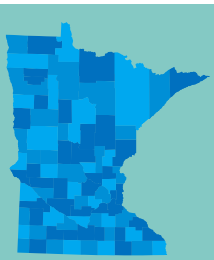
Climate change

September 2022

Greenhouse gas reduction potential of agricultural best management practices (Revised edition)

This technical report provides a description of the greenhouse gas emissions reduction potential from 27 practices related to changing land use, cropping practices, and nutrient reduction.

MINNESOTA POLLUTION CONTROL AGENCY



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Climate change is a worldwide problem that is already affecting Minnesota. In the coming decades, Minnesota may experience warmer temperatures and wetter weather due to climate change. To reduce the impacts of climate change, Minnesota has set a goal to reduce greenhouse gas emissions by 80% by 2050, but we are behind schedule.

Agriculture accounts for approximately one-quarter of Minnesota's greenhouse gas emissions, so strategies to reduce emissions from this sector are critical to reaching statewide goals. In addition to greenhouse gas reduction benefits, some strategies may help farmers maintain soil health and reduce erosion which will help them adapt to warmer and wetter climate conditions. A new technical report estimates the impact of 21 different agriculture best practices on greenhouse gas emissions.

What do we know?

Twenty-five acres of cover crops remove as much atmospheric carbon as taking one car off the road!

Many Minnesota farmers already implement best management practices like planting shelterbelt trees and reducing tilling to protect soil health and water quality. Agriculture creates greenhouse gas emissions, but through best practices, it can reduce emissions or even remove greenhouse gasses from the atmosphere and be part of our climate solution.

This report quantifies the climate co-benefits of certain agricultural practices based on existing research. The report estimates greenhouse gas reductions for 27 agricultural best management practices[1]. The emission reductions per acre range are small, but implementing best management practices across the 20 million acres of Minnesota cropland could reduce overall agriculture emissions by 25%.

What does it mean for Minnesota?

Agricultural practices that protect our water and our soil can also help reduce greenhouse gas emissions and protect our climate. This report provides evidence for practices that have the strongest climate co-benefits. Minnesota should support farmers with funding and technical assistance to implement these practices. Widespread implementation of these practices will be good for farmers, good for Minnesota's water quality, and good for the global environment.

Early adopters of these practices are already making a difference. Water and soil conservation programs from the Board of Water and Soil Resources have reduced cropland agriculture emissions by 600,000 tons per year, approximately 1% of cropland emissions. This report could help focus future work to achieve water quality, soil health, and greenhouse gas reduction goals statewide.

What impact can agricultural best practices make?

Some agricultural practices are more effective than others at reducing greenhouse gases. Practices that take land out of agricultural production have the highest reductions per acre, but may not be widely implemented. Cropping and fertilizer changes may achieve smaller emission reductions per acre, but could be implemented on millions of acres while maintaining or improving agricultural production. Four practices are highlighted below.

Riparian grass buffers

Riparian grass buffers are already required for lakes, rivers, streams, and public ditches in Minnesota. Grass buffers help filter out phosphorous, nitrogen and sediment and protect water quality. This report estimates that riparian grass buffers reduce greenhouse gas emissions by 0.77 tons/acre.

Cover crops

Cover crops are planted in the fall after harvest and grow slowly through the winter. The crops capture excess soil nutrients and are plowed under in the spring. The most common cover crop in Minnesota is cereal rye. Winter cover cropping can reduce greenhouse gas emissions by 0.27 tons/acre.

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Biochar

Biochar is charcoal produced from crop residues. When placed in soil, it can improve soil fertility and reduce greenhouse gas emissions by 1.27 tons/acre. Biochar is a relatively new technique with limited field research, so this estimate is preliminary and will be updated as more research is available.

Agricultural best practices: Terms to know

Avoided conversion of upland grassland to cropland: conversion of unmanaged grassland to agricultural use that would have occurred but is avoided through the use of easements, set-asides, and other measures

Avoided conversion of wetlands to cropland: drainage and conversion of mineral wetlands and peatlands to agricultural use that would have occurred but is avoided through the use of easements, land purchase and retirement, and governmental protections

Biochar: charcoal produced through low-temperature pyrolysis from crop residues and its placement in cropland soils to improve soil fertility and essential soil properties.

Constructed/restored mineral wetlands: Constructed and restored wetlands intercept the flow of nutrients and sediments from croplands to water bodies.

Constructed wetlands are engineered wetlands constructed on former croplands to intercept the flow of nutrients and sediments from croplands to lakes, rivers and streams.

Restored mineral wetlands are drained mineral wetlands that have been hydrologically restored, typically by blocking drainage ditches or disconnecting drainage piping. Like constructed wetlands, restored wetlands act to intercept the flow of nutrients and sediments from croplands to water bodies.

Controlled release fertilizer: urea fertilizer coated with polymers that delay the onset of urea hydrolysis until later in the crop season, thereby delaying availability of nitrogen to the plant until the time of greatest crop nutrient need.

Crop residue retention: post-harvest retention in cultivated fields of aboveground crop residues like wheat straw or corn stover

Corn-soybean rotation replacing continuous corn: conversion from corn monoculture to corn and soybeans in a two-year rotation.

Cropland idling in restored grassland: conversion of upland cropland to unmanaged grassland, without harvest removals or grazing, usually through a long-term or short-term easement.

Cropland idling in trees: conversion of upland cropland to forested acres, without harvest removals or grazing, usually through a long-term or short-term easement.

Cropland to hayland conversion: conversion of upland or lowland cropland to alfalfa, other hay or perennial grassland leys for forage production.

Field borders, contour buffer strips, vegetative and herbaceous barriers: Buffers are used to intercept nutrients and sediments and reduce wind erosion of soils.

Field borders are strips of permanent vegetation placed at field edges.

Contour buffer strips and vegetative barriers are intra-field strips of permanent vegetation that follow the contour of the land, particularly the contour of sloping hills. Farmers often alternate contour buffer strips with strips of annual row crops.

Herbaceous wind barriers are narrow strips of perennial or annual grass placed across the path of prevailing winds.

Forested riparian and multispecies buffers: vegetated strips along streams and rivers that are planted to trees or trees, bushes and grass in combination and act to intercept agricultural nutrients and sediments in surface run-off. Multispecies buffers include, from stream edge to farm field, tall stature trees, medium stature bushes and perennial grasses.

Grassland riparian buffers: vegetated strips along streams and rivers that are planted to perennial grasses and act to intercept agricultural nutrients and sediments in surface run-off.

Nitrification and urease inhibitors: chemicals added to ammonia and urea-based fertilizers to delay the conversion in soils of urea to ammonium (urease inhibitors) and ammonium to nitrate (nitrification inhibitors), thereby delaying the availability of nitrogen until it is needed by the crop. In well-aerated soils, nitrification is the principal process through which nitrous oxide is produced in soils.

No-till tillage: tillage practice in which cropland soil is left undisturbed, before and during planting and after harvest. Seeding is done through direct drilling. Weeds are controlled with herbicides. Crop residues are left on the soil surface to decompose. For purposes of analysis, in this study, the effects of no-till are evaluated against either conventional tillage with moldboard plow or reduced tillage.

Restored/rewet peatlands: Restored/rewet peatlands are formerly cropped, drained peatlands on which agricultural activities have been discontinued and that have been hydrologically restored. Typically, this is accomplished by blocking drainage ditches. As in the case of restored mineral wetlands, restored peatlands act to intercept the flow of nutrients and sediments from cropland or pastureland to water bodies.

Perennial grass added to annual crop rotation: in a crop rotation with one or more annual crops, one to three years of alfalfa, other hay or grass leys added to the rotation to build soil organic carbon (SOC) and to improve other soil physical characteristics.

Reduced tillage: Tillage practice that avoids full soil inversion, but still results in some disturbance and some soil mixing. Variants of reduced tillage include: chisel till, ridge till, mulch till, sweep till, disk tillage, and subsoiling.

Conservation tillage, in which a certain percentage of crop residue is left on the soil surface, is a variant of reduced tillage. For purposes of analysis, in this study, reduced tillage is anything that does not fall into the categories of: conventional tillage with moldboard plow and no-till.

Shelterbelts/hedgerows: tall and medium stature trees and shrubs in a linear array at the edges of agricultural fields, typically two or three threes deep, perpendicular to prevailing winds to provide shelter.

Short rotation woody crops: hybrid poplar or willow woody crops grown in rotations of three to ten years and harvested for bioenergy feedstocks or fiber

Split fertilizer application: application of cropland fertilizers in two or three treatments spaced to make nutrient available at the time of greatest crop nutrient need. This is *in lieu* of single application of nitrogen fertilizer at, before, or immediately after planting.

Subsurface placement of nitrogen fertilizer: shallow or deep placement of nitrogen fertilizer, through either incorporation, injection, or nesting, near the crop root zone. This can be done in bands or, in the case of incorporation, evenly across the field. This is *in lieu* of surface broadcast or surface spraying of fertilizer.

Winter cover crop/catch crop: an intercrop that typically is established in the fall after cash crop harvest to take-up or scavenge excess soil nutrients. Cover crops grows slowly in cold climates and typically are plowed under in the spring. Cereal rye is the most commonly used cover crop in the US Midwest.

Fifteen percent fertilizer use reduction: starting with average per acre nitrogen fertilizer use, a 15 percent reduction in annual per acre applications.

I. Introduction and summary

Climate change, forced by accumulating atmospheric greenhouse gases (GHGs), is a widely recognized environmental problem. The state of Minnesota has statutory greenhouse gas emission reduction goals of 15 percent from 2005 levels by 2015, 30 percent from 2005 levels by 2025, and 80 percent by 2050. The state did not meet its 2015 goal.[1]

Based on the most recent emission inventory totals, GHG emissions from agriculture, forestry and land-use comprise 22 percent of state-level emissions. About two-thirds of these are produced from cropland soils, from nitrate leached from croplands to the state's surface waters, or from petroleum-based fuels combusted in farm equipment during crop production. The scientific literature is replete with suggestions that, with improved agricultural practices, emissions from agricultural cropland sources can be reduced.

In this report, we review the greenhouse gas emission reduction potential of 27 agricultural best management practices designed to slow rates of soil erosion and reduce the movement of nutrients from cropland to groundwater and surface water and sediments from cropland to surface water. Our intent is to determine the effectiveness, if any, of these 27 practices in reducing greenhouse gas emissions.

We used a conventional lifecycle framework for estimating the emissions-avoidance potential of the 27 practices evaluated here. Emissions-avoidance was estimated for all direct cropland sources of GHGs, as well as indirect cropland sources, emissions from fuel use in cropland farm equipment, and emissions from the manufacture of fertilizers, other agricultural chemicals and fuels used in crop production. Total avoided-emissions are the sum of avoided-emissions from all sources. These are calculated in carbon dioxide-equivalent (CO_2-equivalent) short tons per 100,000 acres per year. Given some specific practice, they represent the estimated annual emissions-avoidance in the present that would result from the implementation of that practice. So long as the practice remains in place, these estimated co-benefits should persist at roughly this level for at least 20 years, the window of time that we used to develop this analysis. Most field and modeling studies of GHG-avoidance are conducted within roughly a 20-year window of time (2 to 20 years).[2][3]

Greenhouse gases emitted to the atmosphere during crop production include nitrous oxide (N_2O) and carbon dioxide (CO_2). N_2O is produced in fertilized and tilled cropland rich in ammonium (NH_4^+), nitrate (NO_3^-), and organic nitrogen. Tillage and fertilization with synthetic nitrogen and manure act to stimulate the microbial production of nitrous oxide in soils and its subsequent emission. N_2O can be produced in surface water from nitrate leached from cropland. Nitrous oxide also can be produced microbially in soils downwind of fertilizer application as a result of ammonia (NH_3) volatilization and deposition.

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[1] MPCA, *Greenhouse gas emissions in Minnesota: 1990-2016, January 2019,* available at: https://www.pca.state.mn.us/sites/default/files/lraq-2sy19.pdf

[2] In practice, physical changes in soils may, with time, reduce the rate at which certain agricultural and conservation practices impinge on GHG emissions. For instance, with many best agricultural practices, cropland soils saturate with respect to soil organic carbon, slowing with time the rate at which they remove CO_2 from the atmosphere. But this usually occurs only after 20 to 25 years from the initiation of those practices. (Marland *et al*., 2003; West and Six, 2007) For some practices like cropland conversion to permanent grassland, soils begin to saturate with respect to soil organic carbon only after 40 to 50 years after conversion. (Poeplau *et al*., 2011) Less is known about soil emissions of N_2O and CH_4 (or soil CH_4 oxidation), besides some initial indications that, with time, cropped soils under no-tillage practice may become progressively lower emitters of N_2O. (Six *et al*., [3])

CO_2 is produced during tillage-induced oxidation of soil organic matter, again through microbial action, and also during fuel use in farm equipment used in crop production. Small amounts of carbon dioxide are emitted during urea fertilizer hydrolysis and the use of crushed limestone to raise soil pH levels.

Carbon dioxide also can be removed from the atmosphere and stored in cropland soils and plant biomass. During photosynthesis, CO_2 is removed from the atmosphere and fixed in plant biomass and, in the form of root biomass and crop residues, some of this makes its way to and is retained in soils. During the removal of CO_2 from the atmosphere, cropland soils and plant biomass act as negative emissions sources.

Most well-drained cropland soils oxidize atmospheric methane (CH_4). In this, again, they act as negative emission sources.

Finally, carbon dioxide and methane are both produced in large amounts during the manufacture of nitrogen fertilizers, as well as other fertilizers, herbicides and insecticides, and agricultural fuels. Nitrous oxide also is produced. Large amounts of CO_2 are released in processes that convert CH_4 in natural gas to ammonia-based fertilizer by replacing CH_4 carbon with nitrogen, with waste CO_2 vented to the atmosphere as a pollutant. Most of this occurs out-of-state.

The list of practices that we reviewed is shown in Table 1, along with the Natural Resources Conservation Service (NRCS) practice standard number for each. Some practices involve the idling of cropland in conservation plantings like unmanaged grasses or trees or the conversion of cropland to a cropland supporting role in the form of riparian buffers, shelterbelts, field borders, in-field vegetative barriers and related land-uses. Of the practices that fall into this category, analyses are presented for six practices.

Ten of the practices that were reviewed involve tillage and cropping change or the use of biochar as a soil amendment. Under these practices, cropland remains in production.

Nutrient reduction practices comprise a further category of best practices. These practices generally act to improve the efficiency of nitrogen fertilizer use, resulting in reduced fertilizer use and reduced N_2O emissions to the atmosphere. Six nutrient reduction practices are examined in this report.

The avoided conversion of unmanaged landscapes to agricultural use will result in fewer emissions of greenhouse gases to the atmosphere. The effects of avoided conversion are considered for three ecosystem types: upland grasslands, peatlands, and mineral wetlands.

We define the emissions-avoidance potential of these practices as the difference, on 100,000 acres, of emissions under each practice and average cropland emissions. In many cases, this difference was calculated using the estimated percentage change in emissions with each practice from baseline emission levels or, in the case of biogenic carbon sequestration, the absolute change in sequestration on an area basis (per acre, per hectare or per square meter basis). Estimates of the change in emissions with each practice, again either percentage changes or changes in absolute units, were taken from the scientific literature. In the case of some practices, no estimates were available. For these practices, estimates of average rates of emission in absolute units were developed from the scientific literature and, in combination with estimates of average cropland emission rates, were used to develop practice-based estimates of emissions-avoidance.

Table 1. Agricultural practices examined in this study

Practice	NRCS Conservation Practice Standard	Principal GHG Impacted
Practices that Involve Land-Use Change from Cropland to Cropland-Supporting Role or Long-term Idling [a]		
Land Retirement/Long-term Idling: Grassland Restoration	327	N_2O, CO_2 (carbon sequestration)
Land Retirement/Long-term Idling: Afforestation	327	N_2O, CO_2 (carbon sequestration)
Shelterbelts, Hedgerows	380, 422	N_2O, CO_2 (carbon sequestration)
Field Borders, Contour Buffer Strips, Vegetated Barriers, Herbaceous Wind barriers	386, 601, 332, 603	N_2O, CO_2 (carbon sequestration)
Grassland Riparian Buffers	390	N_2O, CH_4, CO_2 (carbon sequestration)
Forested and Multispecies Riparian Buffers	391	CH_4, CO_2 (carbon sequestration)
Constructed and Restored Mineral Wetlands	656, 657, 658	CH_4, CO_2
Retired/Rewet Peatlands	657	N_2O, CH_4, CO_2
Cropping and Tillage Practices [a]		
No-Till Tillage	329	N_2O, CO_2 (carbon sequestration, fuel use)
Reduced Tillage	345	CO_2 (carbon sequestration, fuel use)
No-Till Tillage-Reduced Tillage Counterfactual	329	N_2O, CO_2 (carbon sequestration)
Winter Cover Crops/Catch Crops	340	CO_2 (carbon sequestration)
Cropland to Hayland	328	N_2O, CO_2 (carbon sequestration)
Add a Perennial Grass to Crop Rotation	328	N_2O, CO_2 (carbon sequestration)
Corn-Soybean Rotation Replacing Continuous Corn	NA	N_2O, CO_2 (carbon sequestration)
Short Rotation Woody Crops	NA	N_2O, CO_2 (carbon sequestration)
Crop Residue Return	NA	N_2O, CO_2 (carbon sequestration)
Biochar Soil Amendments	NA	N_2O, CO_2 (carbon sequestration)
Nutrient Reduction Practices [a]		
15% Fertilizer Use Reduction	590	N_2O
Split Fertilizer Application	590	N_2O
Nitrification Inhibitors	590	N_2O
Urease Inhibitors	590	N_2O
Controlled Release Fertilizers	590	N_2O
Subsurface Fertlilizer Placement	590	N_2O
Avoided Conversion of Unmanaged Lands to Cropland		
Avoided Conversion of Peatlands	NA	N_2O, CH_4, CO_2
Avoided Conversion of Mineral Wetlands	NA	N_2O, CH_4, CO_2
Avoided Conversion of Uplamd Grasslands	NA	N_2O, CO_2

[a] often also result in reduced nutrient run-off and leaching to surface and groundwater

In developing these estimates, most attention was paid to emissions-avoided from soils, either in terms of avoided (or increased) emissions of N_2O or CH_4 or biogenic carbon sequestration. Emissions from fuel use in crop production are small, as are emissions in the form of CO_2 from the use of urea fertilizer or crushed limestone. The same is true for indirect N_2O emissions from leached nitrate or NH_3 volatilization and downwind deposition.

In the case of the out-of-state manufacture of agricultural chemicals and fuels, it is conventional to estimate emissions using simplified methods based on national-level emission factors per unit of fertilizer, herbicide, insecticide or fuel output. (Eagle *et al*., 2012; Liebig *et al*., 2019; Mosier *et al*., 2006; Sainju *et al*., 2014). In the case of each of these sources, a simplified method was applied to estimate emission-avoidance, again following conventional practice. In the case of avoided indirect emissions from nitrate leached from cropland, we deferred to the analysis on nitrate control found in the Minnesota Pollution Control Agency (MPCA), *Minnesota Nutrient Reduction Strategy*. (MPCA, 2014)

For emissions-avoided from cropland soils, we compiled a database of results for practices for which we have final results from 2,914 published scientific studies. Using the results of these 2,914 studies, we developed a set of rates of GHG-avoidance on an area-basis (per acre, per hectare or per square meter basis) or, in the case of practices for which we calculate emissions-avoidance as the difference between practice emissions and average cropland emissions, a set of practice cropland emission rates. In many instances, these were taken from meta-analyses of study results found in the published literature. Meta-analysis is a powerful statistical tool used in ecology and other disciplines to aggregate results from studies with widely divergent designs and draw overall conclusions across studies. When the results from meta-analyses were not available, we used simple arithmetic averaging of study results from the larger literature.

For each practice, we developed a GHG-avoidance budget with an itemized accounting of GHG-avoidance by emission source and gas. For each source of emissions or emissions-avoidance, we also developed descriptive statistics of the relevant study results from the database, including standard errors and confidence intervals. We accompany each budget with an extended discussion of the physical, biological and biochemical processes that underlie estimated emissions or emissions-avoidance.

The results of the analysis are shown in Table 2 in abbreviated form. Of these practices, all but two of these 27 practices result in GHG-avoidance. Of practices that involve cropland idling or conversion of cropland to buffers, shelterbelts, field borders and other land-uses that indirectly support crop production, all result in net GHG-avoidance, with avoidance falling into an estimated range of 0.8 to 14.8 CO_2-equivalent short tons per acre of practice. Of practices involving tillage and cropping change, eight of ten deliver GHG-avoidance benefits. Only the conversion of cropland from corn monoculture to corn-soybean in a two-year rotation results in increased estimated GHG emissions. These estimates, it should be noted, are for average per acre avoidance. Not all acres will experience these estimated levels of GHG-avoidance or do so consistently.

Of nutrient reduction practices, one practice – subsurface nitrogen fertilizer placement – results in increased emissions. According to the analysis, GHG emissions are avoided in five of the nutrient reduction practices that were considered.

Table 2. Estimated annual greenhouse gas-avoidance from agricultural practices (CO_2-equivalent short tons per 100,000 acres per year)

Cropland Idling or Related Conservation Land-Uses	**tons per 100,000 acres per year [a,b,c]**	**Tillage and Cropping Changes**	**tons per 100,000 acres per year [a,b,c]**
Retired/rewet peatlands	(1,478,636)	Short rotation woody crops	(157,447)
Shelterbelts/hedges	(298,377)	Cropland to hayland conversion	(120,897)
Cropland idling in trees	(255,863)	Crop rotation with perennial forages	(41,392)
Retired/rewet mineral wetlands	(221,637)	Cover crops	(26,712)
Forested riparian buffers	(220,528)	No-till, reduced tillage counterfactual [d]	(20,259)
Cropland idling in grass	(159,184)	Crop residue return	(17,171)
Field borders and related	(157,810)	No-till	(14,291)
Riparian grass buffers	(76,872)	Reduced tillage	(7,019)
		Corn and soybean in rotation replacing continuous corn	34,883
Avoided Loss and Other	**tons per 100,000 acres per year [a,b,c]**	**Nutrient Management Practices**	**tons per 100,000 acres per year [a,b,c]**
Avoided peatland conversion	(1,529,415)	Nitrification inhibitors	(30,097)
Avoided upland grassland conversion	(377,861)	Urease inhibitors	(18,368)
Avoided mineral wetlands conversion	(209,256)	Controlled release fertilizers	(17,722)
		Split fertilizer application	(11,296)
Biochar soil amendments (annualized)[e]	(127,582)	15% fertilizer reduction	(5,205)
		Subsurface N fertilizer application	27,746

[a] negative = emissions-avoided; positive = emissions increase

[b] descriptive statistics for the soil organic carbon, direct soil N_2O and soil CH_4 oxidation components of each emissions-avoided estimate are shown in Tables 12-14, 16-18, 20-22, 25-27, 29-31, 34-39, 41-44, 47-49, 52-54, 56-58, 60-61, 65-66, 68-69, 72-73, 74-76, 78, 81-82, 84-85, 87, 89, 91-92, 94, 97-98, and 101-102

[c] for terrestrial carbon sequestration, assumes 20 years of sustained storage of newly sequestered organic carbon in soils and biomass

[d] counterfactual = base tillage condition against which the effect of no-till is evaluated

[e] while most emissions-avoidance from biochar soil amendments occurs during the year of application, here they are annualized using 20 year annualization to make them comparable to other practices where a change, made in a single year, yields a 20-year stream of future emissions-avoidance

All avoided-conversion practices – avoided conversion of peatlands, mineral wetlands and upland grassland to cropland – yield emissions-avoidance benefits, in the range of 2.1 to 15.3 CO_2-equivalent short tons per acre of practice

The resulting analysis is intended to answer the question: based on best available science, what general level of annual GHG-avoidance might be expected from different agricultural best management practices implemented today? Uncertainties notwithstanding, and they can be substantial, what is the best estimate of emissions-avoidance of the practices?

Practices that require a change in land use will continue to produce annual emissions-avoidance over the 20 years of the forecast window. In many instances, for GHG-avoidance to continue, no further action is required once land is converted to conservation practices. By contrast, to realize a persistent 20-year benefit, the cropping, tillage and nutrient best practices listed in Table 2 would need to remain in place each year of this 20-year window.

Biochar use as a soil amendment is the one exception to this pattern. Once biochar is applied to soils, most emissions-avoidance from soil application is realized in the year of application, with the result that cumulative 20-year emissions-avoidance is roughly equal to avoidance in the initial year of application. To make the results for biochar comparable to 20-year cumulative emissions-avoidance for the other 26 practices, we annualize using a 20-year window of time. The values given in Table 2 (as well as those given in Tables 7, 8, 9 and 103 below) reflect this annualization.

Some of the results should be treated with caution, as they may change as the analysis is better developed. For nutrient reduction practices, in particular, there exists a dearth of research, excepting the results for nitrification inhibitors and 15 percent nitrogen fertilizer reduction, For some of the practices considered in this report, other researchers may have come to conclusions different from ours based on different choices in how the problem is set-up and in data.

The estimates given in Table 2, in Section II below (Tables 7, 8 and 9) and throughout this report for annual GHG- avoidance are roughly comparable to those reported in the published literature. Published studies that address GHG-avoidance across multiple practices report, for best cropping and tillage practices, annual avoidance of 0.72 to 0.85 CO_2-equivalent short tons per acre and, from cropland idling in grass or trees and related conservation land-use, annual avoidance of 1.23 to 1.92 CO_2-equivalent short tons per acre. (Eagle *et a*l., 2012; Gelford and Robertson, 2015; Robertson *et al*., 2000; Swan *et a*l., 2015) For cropland idling in upland grasses or trees and related conservation land-use change, the annual avoidance estimates reported in this study range from 0.77 to 2.99 CO_2-equivalent short tons per acre, while those for tillage and cropping practices[4] range from 0.07 to 1.57 CO_2-equivalent short tons per acre. Estimates of total GHG-avoidance taken from the published literature are provided throughout this report by practice (see Tables 11, 33, 46, 51, 64 and 71).

In general, agricultural practices, if well designed, can reduce GHG emissions to the atmosphere. Leaving aside retired/rewet peatlands, the average rate of avoidance for the seven practices that involve cropland idling or conversion of cropland to a supporting role in the form of buffers and related land-uses, is an estimated 1.99 CO_2equivalent tons per acre. If implemented in Minnesota on half a million acres, these practices would result in the avoidance of about 995,000 CO_2-equivalent short tons of GHG emissions annually. For retired/rewet formerly drained, cropped peatlands, average GHG-avoidance is an estimated 14.8 CO_2-equivalent short tons per acre of restoration. At an estimated 400,000 acres of drained peatlands currently in cultivation in Minnesota, 90 percent restoration would result in the avoidance of 5.9 million CO_2-equivalent short tons annually. For cropping and tillage practices, the average rate of avoidance is about 0.5 CO_2-equivalent short tons per acre. If implemented on 10 million acres, these practices would result in the avoidance of about 5 million CO_2-equivalent short tons of GHGs per year. These totals seem generally indicative of at least a modest potential for GHG-avoidance from improved cropland practices, on the order of 7 million CO_2-equivalent short tons annually, or about 25 percent of estimated 2016).[5]

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[4] All cropping and tillage practices shown in Table 2 except cropping change from continuous corn to corn and soybeans in rotation, a practice not treated in Eagle *et al*. (2012), Gelford and Robertson (2015), Robertson *et al*. (2000), or Swan *et al*. (2015).

[5] MPCA Greenhouse Gas Emissions data for 2016, available at: https://www.pca.state.mn.us/air/greenhouse-gas-emissionsdata

II. Methodology

Greenhouse emissions-avoidance from the implementation of an agricultural or land-use practice is calculated as the sum of the changes in GHG emissions by gas for each practice from each of the individual emissions sources from agriculture. In crop production, emitted greenhouse gases include: CO_2, N_2O and CH_4. Sources of GHG emission include cropped soils, fuel use, surface waters, land surfaces downwind of crop production on which volatilized ammonia might be deposited, and the mostly out-of-state manufacture of agricultural chemicals and fuels used in crop production. Emissions and emissions-avoidance are expressed on an area-basis in a common unit, CO_2-equivalent short tons, which cumulatively give the net impact of the practice on emissions in the form of a single value. In this analysis, these are annualized to give the average annual change in GHG emissions – whether an increase or a decrease - associated with the establishment of some practice. The change in emissions is calculated on a 100,000-acre basis. The results for each practice are reported as the change in CO_2equivalent emissions per year on 100,000 acres. The quantification is set up so that a negative change in total annual average emissions indicates net GHG emissions-avoidance and a positive change indicates a net emissions increase from some change in agricultural practice.

The boundaries to this analysis were selected following the practice, now widely accepted, of Robertson *et al*. (2000) and Mosier *et al*. (2005, 2006). This limits the frame of analysis to the change in emissions from soils, vegetation, surface waters, fuel use, and agricultural chemicals manufacture, omitting downstream emissions and emissions-avoidance resulting from land-use changes of a more international nature that might result, through the market price mechanism, from changes in crop production in North America. Also not considered are changes in net emissions or net emissions-avoidance as a result of specific downstream uses of field commodities, for instance, in livestock operations or biofuels production. Changes in albedo or surface reflectance also are not considered

The estimates that are developed in this analysis reflect present-day experience with different agricultural practices. In general, in Minnesota, we are most interested in mitigating GHG emissions on a decadal timeframe; with the state's statutory 2025, 30 percent GHG reduction targets now just three years off and the state's progress in reducing emissions about 5 percent as of 2015, the first target year given in state statute. For policymaking, the relevant window of effectiveness of different practices, then, is a decade or two, which in assembling data on the effectiveness of practices we generalize to 20-years, excluding responses that fall outside of that window. This is important because response rates of GHG to different practices can be quite different in the out-years following the introduction of an improved practice, 20 to 50 years after introduction, than in the initial 20 years.

As noted in the introduction, in most cases emissions-avoidance is evaluated against a cropland counterfactual; emissions under changed practice less emissions from upland cropland under average current conditions gives the level of emissions-avoidance for each practice. Rewet peatlands and rewet mineral wetlands constitute a notable exception. Emissions-avoidance for retired/rewet peatlands is evaluated against a drained, cropped peatland counterfactual, while emissions-avoidance for retired/rewet mineral wetlands is evaluated against a drained, cropped mineral wetland counterfactual. Emissions-avoidance resulting from the avoided conversion of peatlands or mineral wetlands to cropland is calculated against an undisturbed wetland counterfactual. A restored upland counterfactual is used in the estimate of emissions-avoidance resulting from the avoided conversion of undisturbed upland grassland. Due to a scarcity of published research, in most cases it was not possible to evaluate emissions-avoidance against a pastureland counterfactual, particularly with respect to changes in soil carbon.[6]

The estimates of emissions-avoidance account for net changes in emissions that result from soil carbon sequestration. During photosynthesis, CO_2 is removed from the atmosphere and incorporated into plant biomass and, potentially, through roots and crop residue inputs to soil, to soil organic carbon (SOC). This results in a net drawdown of atmospheric CO_2 levels, which, as with most other researchers, we treat as a negative emission.

CH_4 is treated similarly. Atmospheric methane is oxidized in cropland soils, removing it from the atmosphere. An increase in CH_4 oxidation from a change in agricultural practice results in a drawdown of atmospheric CH_4 levels, which again we treat as a negative emission

The avoided-emissions estimates (or estimates of increased emissions) contained in this report are calculated using the Global Warming Potential Index values drawn from the 2007 IPCC Fourth Scientific Assessment. (IPCC, 2007) This index provides relative weightings of greenhouse gases that allow us to express the emission of any one GHG in terms of its equivalent in units of emitted CO_2. This allows us to add emissions of GHGs with quite different warming capacities to derive net GHG emission (or net emission-avoidance) totals. To maintain a common reference point, it has become something of an agreed convention in science to continue to use the 2007 version of this index. We follow this practice. In 2013, and again in 2021, the 2007 weightings were superseded by an updated version in the IPCC's fifth and sixth scientific assessments. (IPCC, 2013, IPCC, 2021)

In converting nominal units of sequestered soil carbon (or rates of sequestration) to CO_2-equivalent units, we used a global warming potential value of 0.4. This corresponds to a period of persistent storage of newly sequestered carbon in agricultural landscapes of about 20 years. This is the longest period over which, in our judgment, persistent storage safely can be assumed. The larger calculation of the 0.4 global warming potential value derives from an estimate of CO_2 retention in the atmosphere for emitted CO_2 from fossil fuel combustion. Once emitted to the atmosphere, a unit of mass of CO_2, e.g., ton, kilogram, lbs., is only partially retained in the atmosphere. One-hundred years after emission, an estimated 38 percent of that mass will remain in the atmosphere. Expressed in ton-years, an emission of one ton of CO_2 to the atmosphere will, over the one hundred year period, result in 52 ton-years of atmospheric retention. To offset one ton of emission, a ton of sequestered organic carbon must remain in storage an equal 52 years. At 20 years, storage of organic carbon would offset only 20-ton-years of emissions or about 40 percent what might be needed to offset a ton of emitted CO_2 from oil or coal combustion.

Organic carbon stored in soils or on the landscape in tree biomass is subject to rapid loss with a change to more intensive tillage, changed cropping patterns or land-clearing or conversion from less intensive land uses, like conservation purposes or hayland, to more intensive uses of the land, like row crop cultivation. Past changes in land use have proven very difficult to predict, making it difficult to conclude much about the likelihood of the persistence of carbon storage beyond a decade or two.[7]

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[6] Pastureland soils are more like native grassland or forest soils than cropland soils. However, unlike the effect of changes in cropland or former cropland soil carbon under different land-use practices, relatively little work has been published on the change in organic carbon from land retirement from pastureland to unmanaged grassland or from pastureland or unmanaged grassland to forestland or wetland.

[7] Perhaps the best example might be Conservation Reserve Program lands in Minnesota, which include lands that are temporarily idled, mostly as unmanaged grassland. These lands stored large amounts of organic carbon, which, as is often noted, will be quickly reemitted to the atmosphere as CO_2 if placed back into intensive cultivation. (Gelfand *et al*., 2011) Based

Regarding the larger lifecycle approach using GWP-weightings, this is a longstanding approach in the scientific literature stretching back to 2000. (Adviento-Borbe *et al*., 2007; Amadi *et al*., 2017; Archer and Halvorson, 2010; Del Grosso *et al*., 2005; Dendooven *et al*., 2012; Gan *et al*., 2011; Gan *et al*., 2014;

Gelfand and Robertson, 2015; Hernandez-Ramirez *et al*., 2009; Johnson *et al*., 2011; Kaye and Quemada, 2017; Kim and Dale, 2008; Kusterman *et al.*, 2008; Liebig *et al*., 2010; Merbold *et al*., 2014; Robertson *et al*., 2000; Sainju *et al*., 2014; Six *et al*., 2004; Smith *et al*., 2008; Soussana *et al*., 2007) Recent applications have been in meta-analysis of the results of published lifecycle analyses using GWP weightings (Sainju, 2016) and in related comparative assessments of net emissions-avoidance by practice, built-up emissions source by emissions source from statistical analyses of study results of GHG-avoidance taken from the scientific literature. (Eagle *et al*., 2012; Fargione *et al*., 2018; Swan *et al*., 2015)

In this report, we mainly follow the practice pursued in Eagle *et al*. (2012), Swan *et al*. (2015) and Fargione *et al*. (2018) in aggregating results across a large number of published studies to come to a set of conclusions about the relative effectiveness of agricultural practices in mitigating GHG emissions.

Table 3 lists emission sources or sources of emissions-avoidance for the 27 agricultural and land-use practices for which we have results. Of these, the sources with the greatest influence on estimated GHG-avoidance, across all evaluated practices are: soil carbon sequestration, soil N_2O emissions, and soil CH_4 emissions from wet anoxic soils. In the following subsections, we focus on these sources, including how in each case response rates for emissions-avoided (or, if this is the case, emissions increases) are estimated and the issues associated with that estimation. Response rates are at the heart of the analysis presented here.

The remainder of emissions and emissions-avoidance--from indirect N_2O emissions from surface waters and volatilization and deposition, fuel use, urea and liming, and upstream chemical manufacture--are treated separately near the end of this section on Methodology.

Finally, as noted above, the emissions-avoidance estimates are annual estimates of avoidance applicable to a period of roughly the next 20 years. In the case of biochar, emissions-avoidance is experienced in the year of biochar manufacture and its land application, roughly as a single pulse event. Here we annualize the results over a twenty period to render them roughly comparable to the average annual avoidance associated with the other 26 best practices, particularly with those that involve a land-use change that, after land conversion, yields a continuing stream of avoidance. Both annualized results and unannualized results are reported.

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on the most recently available statistics, once enrolled in CRP, only about 10 percent of these idled lands were re-enrolled beyond the initial 15-year contract period. (USDA-FSA, 2017) If, at initial enrollment, it had been assumed that this organic carbon build-up would be retained indefinitely, that would have been an incorrect assumption.

Table 3. Sources of emissions-avoidance or increase for agricultural practices

Greenhouse Gas	Emission Source or Sink	Dominant Term in Calculation
CO_2	carbon accumulation in soils and biomass	all practices but one evaluated
N_2O	soils	9 out of 13 practices evaluated
CH_4	soils	grassland and forested riparian buffers
N_2O-indirect leaching	indirect emissions-surface waters from leached soil nitrate	cover crops
N_2O indirect volatilization	indirect emission-downwind soils from nitrogen volatilization/redeposition	none
CO_2	lime and urea use (soils)	none
CO_2, N_2O, CH_4	fossil fuel and electricity use in crop production	none
CO_2, CH_4	upstream agricultural chemicals and fossil fuel production	grass riparian buffers, perennials added to rotation, continuous corn to corn-soybean rotation

A. Terrestrial carbon sequestration response rates

As just noted, average response rates of emissions and terrestrial carbon sequestration to specific agricultural and land-use practices are at the heart of the analysis presented here. With different practices, organic carbon can be sequestered in soils or in live biomass and surface litter or detritus. Derived from the pool of atmospheric carbon, each increment of additional carbon storage represents a net drawdown of atmospheric CO_2 levels, which with most other researchers we treat as a negative emission.

In this study, response rates of terrestrial carbon sequestration to different practices are developed from review of the scientific literature, principally from the review of results taken from long-term and short-term controlled experiments of sequestration potential using side-by-side experimental plots, or, more often, derivative statistical studies of those results. The results from literature reviews and studies that propose mean values for response rates based on expert judgment also are used, as are results from numerical modeling studies. The same is true for the results from a small number of longitudinal time series studies. Side-by-side experiments include long-term soil sampling experiments under controlled conditions, eddy covariance studies of net carbon exchange, and studies of total ecosystem carbon using a combination of soil sampling and biometric approaches to biomass estimation.

Regarding derivative statistical studies, it is now common practice for scientists to produce and publish derivative statistical analyses of the results of controlled side-by-side studies, time-series analyses, and modeling studies, collapsing large numbers of study results down to a single mean practice response rate. The side-by-side studies particularly suffer from high variability in response rates across environmental and soil conditions. Rates of terrestrial sequestration vary within agricultural fields, across county and state lines, across soil types, and, in response to decadal climatic fluctuations, across time. Because of this high variability in results, to determine response rates to individual practices, a very large number of experimental results, spanning a wide range of environmental and edaphic conditions and often decades of observations, often are required. Using the body of published side-by-side experimental work, derivative statistical analyses extract their results from just such a large number of studies spanning the necessary range of environmental and edaphic conditions.

Derivative statistical analyses include formal meta-analyses. Meta-analysis is a powerful statistical tool used to evaluate and integrate results from experiments of different designs and draw overall conclusions about response rates. (Luo *et al*., 2010; Du *et al*., 2017) Beginning with initial studies in the early 2000s, meta-analysis has taken on an ever more central role in the analysis of GHG response rates to different practices.

Literature reviews and studies that propose mean values for response rates based on expert judgment serve a similar function to meta-analyses, albeit on a less quantitative basis. In integrating across expert knowledge, these types of studies act as distillations of what is known scientifically, with estimates of likely mean response rates an extension of that corporate wisdom.

Modeling studies mathematically describe the biological, biochemical and physical processes involved in sequestration and integrate across the interactions.

In selecting response rates, we give preference to the results of meta-analyses, if any, followed by the mean of the results for all studies across study type. Meta-analysis was designed specifically to address the problem of mean response rate under conditions of wide variability in environmental and other conditions and divergent study designs. Use of a mean value of the results from all studies is an obviously second best choice, but in absence of results from formal meta-analyses, is the best alternative. The studies that fall under the category ‘statistical summaries and other derivative analyses’ are a mixed lot, sometimes simple data compendia, with and without averaging. The utility of modeling studies is generally constrained by limited numbers of available studies, as are literature reviews and reviews that, in advancing estimates of mean response rates to practices, rely on expert judgment.

The mean response rate used to estimate net carbon sequestration, if developed from a set of meta-analyses study results, is the simple arithmetic average of those results.

For some practices, no changes occur in organic carbon storage beyond those in soils. Generally, these retain cropland in production without land-use change. For these, it is sufficient in evaluating the effects on biogenic carbon storage to report on changes solely in soil organic carbon. For some practices, substantial land-use changes are involved. For these, sequestration is measured by the change in total ecosystem carbon, including, besides soils, carbon in aboveground and belowground live biomass, woody detritus and aboveground litter. Almost without exception, practices that add trees to the landscape add large amounts of new carbon to existing carbon pools, resulting in substantial carbon sequestration. The same is true, though to a lesser extent, for practices like grassland restoration, in which large stores of biogenic carbon are maintained year-round in aboveground vegetation and litter or belowground in live roots.

Finally, many or most of the studies on carbon sequestration in soils, regardless of the practice involved, report results in tons of carbon sequestered per hectare or acre per practice, either over some set of years or per year, rather than percentage changes. This is true for empirical site studies using paired plots. (Dean and Kataki, 2003; Gelfand and Robertson, 2015; Olson *et al*., 2013). It is also true for expert reviews (Chambers *et al*., 2016; Conant *et al*., 2017; Lal *et al*., 1998; Misnasny *et al*., 2017; Smith *et al*., 2005), modeling studies (Del Grosso *et al*., 2005; Desjardin *et al*., 2005) and derivative statistical analyses like meta-analyses. (Angers and Ericksen-Hamel, 2008; Congreves *et al*., 2014; Luo *et al*., 2010; Puget and Lal, 2005; Six *et al*., 2002b; Virto *et al*, 2012; West and Post, 2002) There are some notable exceptions.

The same is true for studies of carbon sequestration in aboveground and belowground biomass and surface detritus like forest litter or downed dead trees.

Given the limits of the literature, we follow general practice in estimating sequestration response rates to different agricultural or land-use practices in absolute units, typically metric tons of carbon per hectare (megagrams of carbon per hectare). Annually avoided emissions are calculated on 100,000 acres.

B. N_2O and CH_4 response rates

N_2O and CH_4 response rates are estimated differently than those for terrestrial carbon sequestration. For agricultural practices that involve a change in land use, response rates are estimated as the difference between annual emission or flux rates under the improved practice and average cropland net annual flux rates. Practices that involve a change in land-use include grassland restoration, avoided grassland conversion to cropland, afforestation on idled croplands, shelterbelts, field borders and vegetative barriers, riparian buffers and cropland to hayland conversions. Annual flux rates for the cropland counterfactual are, for N_2O, drawn from the MPCA Greenhouse Gas Emission Inventory, and, for CH_4, from Aronson and Helliker (2010) for average temperate cropland soils.

Emissions-avoidance from the retirement of peatlands from agricultural use and their rewetting is calculated in the same manner as that for practices involving a change in upland land-use. The same is true for mineral wetlands. In the case of peatland and mineral wetland retirement, emissions-avoidance is calculated as the difference between emissions from retired/rewet peatland soils and those from drained, cropped peatlands or, in the case of mineral wetlands, between emissions from retired/rewet mineral wetlands soils and those from drained, cropped mineral wetland soils. Emissions-avoidance from the avoided conversion of peatlands to cropland is calculated as the difference between emissions from undisturbed peatland soils and those from peatlands in crop production. Emissions-avoidance from the avoided cultivation of mineral wetlands is similarly treated.

Most emission estimates for N_2O emissions under these practices derive from empirical site studies, with relatively few meta-analyses available for the results of these empirical studies. In estimating average annual emissions rates per acre, we use a simple average of the results from all available studies, though in practice these results tend to derive overwhelmingly from empirical site studies.

CH_4 is produced in and emitted from wet soils in which anaerobic conditions predominate, while, in well-drained upland soils, CH_4 generally is oxidized. CH_4 fluxes can be expressed in terms of emissions or oxidation. As in the case of N_2O, most estimates of CH_4 fluxes under improved land-use practice, whether upward fluxes to the atmosphere or net negative fluxes, which denote oxidation, derive from empirical site studies.

For agricultural practices that involve a change in cropping or tillage practice, response rates for N_2O and CH_4 are the product of average cropland net annual flux rates and the estimated percentage change in that annual flux under the new practice. The same is true for nutrient reduction best practices, as well as biochar use. Practices that involve a change in cropping tillage practice include: use of cover crops, conversion from conventional tillage to no-till and reduced tillage, crop residue retention, cultivation of short rotation woody crops in place of grains or forage grasses, and rotational change from continuous corn or a corn-soybean rotation to an extended rotation with two years of alfalfa or another hay, or from continuous corn to a corn-soybean rotation. Nutrient reduction best practices include: split nitrogen fertilizer application, deep fertilizer placement, use of nitrification and urease inhibitors and controlled release fertilizers, and a prescribed per acre percentage reduction in nitrogen fertilizer application amounts.

To calculate response rates, for the cropland counterfactual we use flux or emission rates from, for N_2O, the MPCA Greenhouse Gas Emission Inventory, and, for CH_4, from Aronson and Helliker (2010) for average temperate cropland soils. Estimated flux rates for cropland under improved tillage or rotations most often are taken from meta-analysis-type studies. For the reasons discussed above with respect to terrestrial carbon sequestration, in estimating average flux rates for N_2O and CH_4, preference is given to the results of meta-analyses, if any, followed by the mean of the results for all studies across study type.

Finally, in developing estimates for flux rates by practice or the change in flux rates with the implementation of different practices, a simple arithmetic average of study results by study is used. Given a set of derived response rates, annually avoided emissions are calculated on 100,000 acres.

C. Database practices

To understand the potential role of agriculture in GHG emission mitigation, we examine, on a practice-by-practice basis, the GHG-avoidance-potential of practices that, in the scientific literature, have been identified as potentially effective in mitigating emissions. To date, we have assessed the effect of 27 practices on greenhouse gas emission-avoidance. The results of that analysis are reviewed in abbreviated form in the following section and, at length, on a practice-by-practice basis, in the section following that.

To support this analysis, we have assembled a database of the results of 2,914 studies for the 27 practices reviewed thus far. While not exhaustive, the database accounts for a substantial percentage of published studies on the effects of different agricultural practices on GHG emissions.

GHG emissions from agriculture, regardless of species, are highly variable both spatially and temporally. This is as true for emissions from practices introduced to mitigate emissions as it is for emissions under conventional agricultural practices. This variability results from the large number of environmental controls on emissions. To be useful, the set of studies used to support analysis needs to be broadly representative of that variability, with results across a wide range of environmental conditions roughly analogous to those encountered in and across agroecosystems. With analysis based largely on observational data, the more representative is the data, the more robust the conclusions are likely to be.

The results included in the database are from studies of one of five types: empirical site studies, modeling studies, meta-analyses, statistical summaries or other derivative statistical analyses, and literature or expert reviews. The results from empirical site studies are generally limited to those from field studies and, within the class of field studies, to studies with observations covering at least two-thirds of a growing season. With but a few exceptions, the results of laboratory experiments are excluded from the database. Studies involving flooded field rice paddy agricultural also are excluded as involving fundamentally different soil conditions than found in upland croplands.

To estimate changes in soil carbon sequestration, CH_4, or N_2O with changed practices against a conventional agricultural practice baseline, side-by-side studies under controlled condition are required. This is true regardless of whether changes are presented in absolute units of change, e.g., tons per acre per year, as in the case of terrestrial soil carbon, or in terms of percentage changes from a baseline. The vast majority of study results housed in the database are from side-by-side studies conducted under controlled conditions. In the studies housed in the database, changes in soils carbon typically are evaluated over periods of time of five to twenty years. We determined that, to be included in the database, sequestration studies had to include enough information to for observed changes in carbon levels to be annualized. We also determined that, to be included in the database, the results of studies of soil carbon sequestration had to have been developed on a mass, as opposed to a concentration, basis, accounting for changes in bulk density over time. In general, we include in the database only the results from studies that provide clear information on the units in which results are reported, as well as on experiment duration, and location.

Modeling studies can be forward or backward looking, while most other study types are backward looking, developing information based on experimentation and long-experience. The set of studies that are included in the database are largely, but not completely, limited to those providing results from a 20-year window of time either side of the present year. The database excludes model forecast results for practices implemented in the later years of this century, beyond 2040 or 2045.

Meta-analyses often report results at multiple spatial scales and geographies, soil sampling depths, and study lengths. In populating the database, wherever possible, study results were selected at the smallest relevant spatial scale available, preferably those for the US Midwest or the continental United States, but more frequently for temperate climates or cool, humid climates. Many meta-analyses report results at a global level, but in actuality these results reflect North American or European practice or practices common generally to developed temperate climate economies. The response rates taken from meta-analyses are classified in the database as annual rates of response, as opposed to response rates limited to the growing season.

To simplify the data housed in the database, wherever possible within studies we average results across environmental and management conditions. For cropping and tillage best practices, as well as those practices that remove land from agricultural use to conservation uses, we average results across soil type, crop residue treatment, and fertilizer nitrogen amounts, placement and timing. Depending on the practice under inquiry, we also average results across tillage practice, so long as the study inquiry is not into the effect of tillage practice on emissions or sequestration, likewise for cover crop treatments, and crops and crop rotations.

For nutrient reduction practices, we average across fertilizer application amounts. For split nitrogen application, we average results across inhibitor use and depth of fertilizer placement. For inhibitor use, we average results across nitrogen fertilizer application timing and number of applications, fertilizer placement, and other practices and environmental conditions. Averaging for deep placement follows a similar practice.

In assembling the database, we did not request information on all study replicates, but restricted our analysis to the data presented in the studies themselves.

Because of this averaging, the ratio of numbers of studies to numbers of study results in the database is near to, though not exactly, unity. Some notable exceptions include studies that report results using multiple study types, or where, in the case of cover crops, results are reported for both nonleguminous cover crops and leguminous cover crops and for cover crop incorporation or non-incorporation. Other notable exceptions include tillage studies that report multiple results based on cover crop treatment and cover crop studies that report multiple study results based on different tillage practices. It is increasingly common in field research to investigate the effects of different tillage and cover crop treatments jointly, due to the perceived soil benefits of joint implementation of these practices. Because of the importance of cover cropping to tillage results, and tillage to cover cropping results, research results are retained in the database for tillage practices across different cover crop treatments (with and without cover crops) and for cover crop practices across different types of tillage.

Multiple study results also are retained when given for buffer types (forested riparian buffer practice), forage type (cropland to hayland practice), grassland restoration by participation or nonparticipation in CRP, and grassland and forestland status as newly restored or existing mature systems (grassland restoration and afforestation practices.) Multiple study results also are retained for rewet peatlands by post-drainage use (cropland, pastureland).

For belowground sequestration, we include results for the deepest soil layer reported. Where a series of estimated rates of sequestration are reported for multiple sets years, we include only the results from the longest experiment duration consistent with our general 20-year window for results. Where, particularly with meta-analyses, it is possible to calculate an average 15- or 20-year rate of emission or sequestration, we do so, using this *in lieu* of point estimates of sequestration or emission in the 5th, 10th or 20th year after experiment initiation. Regarding cropping, in selecting results we use results reported at the multi-year rotation level, rather than for individual crop years within a rotation.

While we attempt to limit our database to studies that report experimental or other results that fall within our 20-year window of applicability, we are not always successful in doing so. Due to a paucity of experimental results, in some instances, like cropland afforestation, study results may be reported for periods of time substantially longer than 20 years.

Changes in soil carbon may be examined on a fixed-depth basis or a soil mass-equivalent basis. In the scientific literature, the latter approach generally is the preferred approach. Wherever possible, results developed using the latter approach are included in the database. Similarly, given a choice between sequestration results developed using long-term soil sampling and those developed from observed respiration rates, again the former are used as, again, seemingly the preferred alternative.

It is a convention in the literature to calculate annual rates of sequestration from study endpoints, assuming linearity between endpoints. Where individual studies provide multi-year estimates of sequestration, but do not provide annualized estimates, we follow general convention in annualizing using total sequestration mass and experiment duration in years.

Often in older experimental plots, carbon mass was not measured in the initial years. In these older studies, results were reported using the difference in soil carbon mass in the terminal year of the experiment, working from the assumption that, since side-by-side plot were involved, initial levels of soil carbon must have been similar if not identical. Again, where individual studies provide multi-year estimates of sequestration, but provide neither annualized estimates nor estimates of soil carbon mass in the initial experiment years, we follow standard conventions in estimating sequestration rates from the annualized difference in reported soil organic carbon mass in the experiment’s final year.

Finally, regarding geographical range, generally we limit the study results included in the database to those from temperate climates. While a number of studies from subtropical climates are included in the database, including studies from subtropical Australia, Brazil, Mexico and China, the bulk of the results housed in the database derive from North American and European sources. In general, the geographical range of the data in the database has to be broad enough to capture enough studies under a wide enough array of environmental conditions so that, in terms of mean response to different practices, the mean of the database studies is in fact roughly representative of the mean in nature.

In practice, this means that the results given here have general applicability rather than local applicability. They give the average response of emissions to these practices at large spatial scales, rather than small spatial scales, like the land area of the state of Minnesota, for which only a small number of published studies, about 40, exist for GHG-avoidance across the 27 agricultural and conservation practices considered in this study. The small number of available Minnesota-specific studies probably now precludes the development of estimates of GHG-avoidance tailored narrowly to Minnesota.

D. Weight of evidence test

As already noted, flux rates of GHGs from agricultural soils are highly variable. The same is true for changes in flux rates resulting from alternative agricultural practices that are implemented to lower emission rates or to offset emissions.

Given this endemic high variability, for N_2O and CH_4 emissions-avoidance and CO_2-avoidance in the form of carbon sequestration, we use a weight of the evidence test in assessing how well an estimate of mitigation potential is known. Throughout this study, we provide estimates of the numbers of study results for each practice by study type, the ratio of positive-to-negative results, again by study type, along with standard errors and confidence intervals. We also provide in the case of each practice and soil emittant (or sequestered gas) a discussion of the underlying science at the process level, including what the science tells us should be happening, based on underlying scientific understanding. The corporate judgment of the community of involved scientists, as expressed in expert reviews, is particularly informative of the larger state of the science.

We also identify estimates that, based on width of confidence intervals and odd anomalies in the results, are somewhat or substantially uncertain and for which caution in their use is warranted.

We accept that, because of the need to act to reduce GHG emissions, which is nearly universally acknowledged, in the end it is a matter of best presently available science. What does best available science tell us and, very high levels of uncertainty aside, is it known well enough at a probabilistic 'weight of the evidence' level to underpin action? Is it good enough? We provide the underlying factual basis for judging that issue.

E. Response rates: Indirect N_2O emissions, emissions from fuel use and upstream manufacturing emissions

Finally, in most instances, the contribution of indirect N_2O sources to changes in emissions under changed practices is small. The same is true for fuel use sources of emissions and minor sources of CO_2 like urea fertilizer and crushed limestone. In certain instances, the contribution of out-of-state manufacture of agricultural chemicals and fuels can be significant, but generally, the effects are small.

Response rates for these sources to alternative agricultural practices are estimated using simple methodologies and, typically, using a single, albeit authoritative, data source for estimated mitigation potential or in some cases several sources. By its nature, the standard methodology for estimating emissions change from the avoided manufacture of agricultural chemicals and fuels – the amount of these commodities produced multiplied by the average US GHG emission per unit produced – is simplified.

Table 4 delineates the simplified calculative approaches taken with respect to response rates of emissions in the case of each of these minor sources. In the case of indirect N_2O from leached nitrate or NH_3 volatilization and redeposition, response rates are the product of average emission rates from these sources at a statewide level and estimated percentage rates of emission reduction per practice. For the most part, the reduction rates are, in the case of nitrate loading, taken from MPCA, *Minnesota Nutrient Reduction Strategy* (MPCA, 2014). For NH_3, reduction rates are taken from a broad set of meta-analyses of experimental results reported in the scientific literature. These are listed in Table 4. In some instances, response rates for these sources are calculated as the difference in average N_2O flux rates statewide from these sources, on a per acre basis, and emissions per acre under alternative practices, like grassland restoration or shelterbelt establishment. Estimated average flux rates for cropland are from the MPCA GHG emission inventory, while, for idled land in upland or riparian grass or trees, they are taken from Bouwman *et al*. (1997).

Table 4. Calculative basis for emissions-avoided or emissions-increase estimates: indirect N_2O, urea and liming CO_2, GHGs from fuel use and agricultural chemical and fuels manufacture

GHG	Calculative Approach to Emissions-avoidance	Base emission level
N_2O-Indirect, nitrate leaching, NH_3 redeposition	% reduction in NO_3- runoff to surface waters [a, b]; % reduction in NH_3 volatilization and redeposition [a, c] (N_2O-leaching under changed land-use) – (average N_2O-leaching rate from cropland) [d]; (N_2O-NH_3 deposition under changed land-use) – (average N_2ONH_3 deposition to cropland) [d] Data sources for reduction potential: nitrate leaching -- MPCA (2014),[e] MPCA GHG emission inventory (MPCA GHG EI) [f]; Pan *et al*. (2016)[g], Borchard *et al*. (2019)[g], Christianson and Marmel (2015)[g], Li *et al.* (2021)[g], *Liu et al.* (2018)[g], Quemada *et al.* (2013)[g], Xia *et al.* (2017)[g], Zhang *et al.* (2019)[g] NH_3 redeposition—Bouwman et al. (1997)[h], Pan *et al*., (2016)[l,j], MPCA GHG EI[j], Liu *et al.* (2018)[j], Saggar *et al.* (2017)[j], Sha *et al.* (2017)[j], Silva et al. (2017)[j], Wu *et al.* (2021)[j], Xia *et al.* (2017)[j], Yang *et al.* (2016)[j], Zhang *et al.* (2019)[j]	Minnesota N_2O emissions from NO_3^- leaching and from NH_3 deposition to cropland, 2012-2015 average [m] Data source: MPCA GHG emission inventory
CO_2-urea use, liming	urea: (no urea use, idled cropland) – (CO_2 from urea use on cropland) [k]; liming: (CO_2 from crushed limestone applications to alfalfa) – (CO_2 from crushed limestone applications to average MN cropland) [l] Data source for reduction potential: Russelle (1997)	Minnesota N_2O and CO_2 emissions from Nitrogen fertilizer and limestone use, respectively, 2012-2015 average Data source: MPCA GHG emission inventory
GHGs-fuel use in crop production	(per acre fuel use intensity of changed practice) – (per acre fuel use intensity baseline practice). For cover cropping, subtraction or addition of emissions from crop production operations foregone or added beyond baseline. Data source for per acre fuel use intensity by practice and fuel use rate per operation: Camargo *et al*. (2013)	Minnesota fuel use emissions, 2012-2015 average, using a weighted average of fuel use per rotation from Camargo *et al*. (2013)
GHGs-manufacture of fertilizer, other agricultural chemicals and fuels	subtraction or addition of emissions from upstream fertilizer, chemicals and fuel use from crop production operations foregone or added beyond baseline Data source for emissions rates per lbs. of N, P and K fertilizer, herbicides, insecticides and fungicides manufactured: Camargo *et al.* (2013)	Minnesota average per acre fertilizer and agricultural chemical use on cropland, using a weighted average across major crops, from most recent USDA-NASS fertilizer and chemical use summaries (NASS, 2018)

[a] assumes that the reduction in N_2O from surface waters and NH_3 volatilization and downwind redeposition is the same as the estimated percentage reduction in NO_3^- runoff and volatilization, respectively, after IPCC (2006) methodology

[b] cover crops, no-till, reduced tillage, riparian buffers, crop residue retention, biochar, rewet peatlands and mineral wetlands, nitrification and urease inhibitors, controlled release fertilizers, split nitrogen application, deep nitrogen placement, 15% nitrogen reduction, avoided peatland and mineral wetland conversion to cropland

[c] no till, reduced tillage, crop residue retention, biochar, nitrification and urease inhibitors, controlled release fertilizers, split nitrogen application, deep nitrogen placement, 15% nitrogen reduction

[d] field borders, grassland restoration, afforestation on cropland, shelterbelts, riparian buffers, cropland conversion to hayland, expanded rotations with perennials, short rotation woody crops, avoided conversion of grasslands to cropland

[e] MPCA (2014): riparian buffers, rewet peatlands and mineral wetlands, no-till, cover crops, nitrification inhibitors, split nitrogen fertilizer application, avoided peatland and mineral wetland conversion to cropland

[f] MPCA GHG EI: grassland restoration, afforestation of idled cropland, shelterbelts, grass borders, cropland to hayland conversion, extended rotations with perennials, short rotation woody crops, avoided upland grassland conversion to cropland

[g]

GHG	Calculative Approach to Emissions-avoidance	Base emission level
biochar: Liu *et a*l.(2018), Borchard *et al*. (2019); crop residue retention: Li *et al*. (2021); reduced tillage: Pan *et a*l. (2016); no-till [reduced tillage counterfactual]: Pan *et al*. (2016); deep nitrogen placement: Christianson and Harmel (2015); controlled release fertilizer: Quemada *et al.* (2012); Quemada *et al.* (2013), Xia *et al.* (2017), Zhang *et al.* (2019)		
[h] Bouwman *et al.* (1997): grassland restoration, afforestation of idled cropland, shelterbelts, grass borders, riparian buffers, cropland to hayland conversion, short rotation woody crops, avoided upland grassland conversion to cropland		
[i] Pan *et al.* (2016): no-till, reduced tillage, crop residue retention, split nitrogen application, deep nitrogen placement		
[j] extended rotations with perennials: MPCA GHG EI; biochar: Liu *et al*. (2018), Sha *et al*. (2019); nitrification inhibitors: Pan *et al.* (2016), Saggar *et al.* (2013), Silva *et al.* (2017), Wu *et al.* (2021), Xia *et al.* (2017), Yang *et al.*(2016); controlled release fertilizers: Pan *et al.* (2016), Xia *et al.* (2017), Zhang *et al.* (2019		
[k] grassland restoration, afforestation on idled upland cropland, shelterbelts/hedges, field borders/vegetative barriers, cropland to hayland conversion, expanded rotations with perennials, short rotation woody crops, avoided conversion of grassland to cropland		
[l] cropland to hayland conversion, extended rotations with perennials		
[m] 0.75 percent of leached nitrogen is assumed to be emitted to the atmosphere as N_2O, after the IPCC (2006) methodology. 1 percent of nitrogen that is redeposited on land surface after ammonia volatilization is assumed to be emitted to the atmosphere as N_2O, again after IPCC (2006)		

In most instances, avoided-emissions from fuel use are calculated using the crop-based and tillage-based fuel use intensity factors given in Camargo *et al*. (2013). These are converted to avoided-emissions using standard conversion values. Camargo *et al*. (2013) is likewise the source of the emission intensity of avoided agricultural fertilizer and chemical manufacture, which, using a weighted average for crop production and average chemical and fertilizer use rates for Minnesota crops from USDA-NASS (2018), is expressed as a rate of emission intensity per acre of cropland for use in calculation.

Fuel use-avoided from the retention in the field of aboveground crop residues is calculated from data for in-field fuel use in US corn production given in Jayasundara *et al.* (2014), while fuel use in short rotation woody crop production (SRWC) is estimated using the data on fuel use in SRWC production, processing and transport given in Thomsky *et al.* (2015). Nitrogen fertilizer use-avoided in SWRC cultivation is calculated using the data on SWRC fertilizer use given in Fabio and Smart (2018).

Tables 5 and 6 show the equations used to calculate fuel and agricultural chemicals and fertilizer use-avoided in this report, by agricultural practice.

Table 5. Fuel use changes by agricultural or land-use practice

Practice	Equations Giving the Basis for the Calculated Change in Emissions from Fuel Use
No-till, Reduced tillage	(weighted fuel intensity per acre, no-till or reduced tillage) – (weighted fuel intensity per acre, conventional tillage) for corn, soybeans, corn silage, wheat and alfalfa
No-till with Reduced tillage counterfactual	(weighted fuel intensity per acre, no-till) – (weighted fuel intensity per acre, conventional till) for corn, soybeans, corn silage, wheat and alfalfa
Cover Crops	add 1 seed drill operation, 1 roller packer operation
Cropland to Hayland Conversion	(weighted fuel use intensity per acre, alfalfa) – (weighted fuel use intensity, all Minnesota cropland)
Extended Rotations with Alfalfa or Other Hay or Grass	(weighted fuel use intensity per acre, corn-corn-alfalfa-alfalfa rotation) – (weighted fuel use intensity, all Minnesota cropland)
Continuous Corn to Corn-Soybean Rotation	(weighted fuel use intensity per acre, continuous corn) – (weighted fuel use intensity, corn-soybean rotation)
Crop Residue Retention	-1 * (per acre fuel use in crop residue shredding, raking, baling, and hauling)
Short Rotation Woody Crops (SRWCs)	(per acre fuel use intensity, SRWC [tillage, planting, fertilizing, harvest, chipping; 3-year average]) - (weighted per fuel use intensity per acre, cropland)
Biochar	1 * (per acre fuel use intensity, corn stover shredding/milling, raking, baling, loading and hauling)
Enhanced Efficiency Fertilizers [a], 15% Less Applied Cropland Nitrogen	no change in per acre fuel use
Split Synthetic Nitrogen Applications	add 1 nitrogen fertilizer application
Deep Nitrogen Fertilizer Placement	(per acre fuel use, knife down placement) - (weighted fuel use intensity for cropland)
All Other	(no fuel use) - (weighted fuel use intensity, all Minnesota cropland)

[a] nitrification inhibitors, urease inhibitors, controlled and slow release nitrogen fertilizers

Table 6. Assumed changes in fertilizer and agricultural chemicals use by agricultural or land-use practice[a]

Practice	Equations Giving the Basis for the Calculated Change in Emissions from Avoided Manufacture of Agricultural Chemicals
Cover Crops	- (nitrogen credit for cover crops) - (-15% reduction, herbicide use) + (energy input to cover crop seed production)
Cropland to Hayland Conversion	(P,K and lime applications to alfalfa) - (N,P,K, lime, herbicide, insecticide applications to cropland)
Extended Rotations with Alfalfa or Other Hay or Grass	(P,K and lime applications to alfalfa) - (N,P,K, lime, herbicide, insecticide applications to cropland), 2 years of 4-year rotation - N credit to corn after alfalfa, 140 and 70 lbs. per acre, first and second years after alfalfa
Continuous Corn to Corn-Soybean Rotation	no N applications to soybean phase of corn-soybean rotation, plus N credit 35 Lbs N/acre to corn after soybeans
Short Rotation Woody Crops (SRWCs)	(nitrogen applications to SRWCs (in 3-year rotation) - (synthetic nitrogen applications to cropland)
Enhanced Efficiency Fertilizers, [a] Split Synthetic Nitrogen Applications, Deep Nitrogen Fertilizer Placement, Crop Residue Return	no N credit for nutrient management practices [b]
15% Less Applied Cropland Nitrogen	(rotation weighed per acre synthetic nitrogen applications to corn-soybean rotations * -0.15)
All Other	(no fertilizer or chemical use) - (N, P, K, lime, herbicide, insecticide applications to cropland)

[a] nitrification inhibitors, urease inhibitors, controlled and slow release nitrogen fertilizers

[b] no empirical basis was identified for a change in nutrient application rates on the part of crop producers in response to the implementation of nutrient management best practices, biochar or crop residue return

III. Results

As noted in the Introduction, 27 agricultural practices have been reviewed, falling into four basic categories: practices that involve long-term cropland idling or a land-use change from cropland to a cropland-supporting role in buffers and related land-uses; practices that retain land in crops with changes in tillage and cropping rotations; nutrient reduction practices; and practices that involve the avoided conversion of undisturbed peatlands to croplands, as well as the avoided conversion of mineral wetlands and upland grasslands to cropland.

The results of the analyses are shown in Table 7. Results are given in CO_2-equivalent short tons of GHGs-avoided for each practice per 100,000 acres per year. Emissions-avoided are shown for both in-state sources of avoidance and total avoidance, both in-state and out-of-state. Results are reported for the year of biochar manufacture and its placement in soils, as well as on an annualized basis, using a 20-year annualization period. Annualized results are given for biochar to render them comparable to the results reported for the other 26 practices.

Of the 27 practices that have been reviewed, all but two result in per acre greenhouse gas reductions. Subsurface placement of nitrogen fertilizer and rotational change from continuous corn to 2-year corn-soybean rotation act to increase GHG emissions. Seven of the ten largest estimated per acre emission reductions involve land-use change from cropland to a cropland supporting role, like that played by riparian buffers or shelterbelts, or long-term cropland idling in unmanaged grasses or trees. The other three practices are associated with the avoided conversion of wetlands and unmanaged grasslands to cropland.

Of the 27 practices considered in this report, the practices that yield the largest per acre greenhouse gas-avoidance are, in descending order: peatland retirement from agricultural use and rewetting; avoided peatland conversion to cropland; the avoided conversion of unmanaged upland grassland to cropland; long-term idling of cropland in shelterbelts and in upland forest; mineral wetland retirement from agricultural use and its rewetting; long-term cropland idling in forested riparian buffers; and the avoided conversion of mineral wetlands to cropland. Peatlands and mineral wetlands contain large amounts of organic carbon, as do unmanaged upland grasslands. Upon cultivation, a substantial part of this is oxidized and emitted to the atmosphere as CO_2. With set-asides, these emissions are avoided or reversed.

In the case of shelterbelts or the long-term idling of cropland in forested riparian buffers or upland forest plantations, land that was formerly in annual crop production is planted to trees, which enables the storage of large amounts of organic carbon in the form of aboveground and belowground tree biomass. Organic carbon is fixed in plant biomass during photosynthesis, effectively removing it from the atmosphere.

Expressed as emissions-avoided per acre, average annually avoided emissions with shelterbelts, afforestation on idled cropland, forested riparian buffers, upland grassland restorations, field borders and related grass barriers, and grassland riparian buffers are an estimated 3.0, 2.6, 2.2, 1.6, 1.6, and 0.8 CO_2-equivalent short tons per acre, respectively. Annually avoided emissions from retired/rewet peatland soils and retired/rewet mineral wetland soils are an estimated 14.8 and 2.2 CO_2-equivalent short tons per acre, respectively.

Per acre emissions-avoidance resulting from the conversion of cropland to hayland is estimated to be 1.21 CO_2-equivalent short tons per acre per year, while that for the conversion of cropland to the cultivation of short rotation woody crops is an estimated 1.57 CO_2-equivalent short tons per acre per year. Annualized per acre emissions-avoidance for biochar is an estimated 1.27 CO_2-equivalent short tons per acre per year.

Per acre emissions-avoidance associated with cropping and tillage best practices is substantially lower, in the range of 0.2 to 0.4 CO_2-equivalent short tons per acre per year. These practices, it should be noted, do allow cropland to remain in production, which enables them to be implemented across the Minnesota landscape potentially on millions of acres of cropland. While cropland idling, buffer establishment and related practices might be established in Minnesota on tens of thousands to hundreds of thousands of acres, these practices are unlikely to be implemented in Minnesota on millions of acres. Tillage and cropping practices that were examined include: no-till tillage, reduced tillage, cover crops, crop residue retention, the addition of one or two years of forage perennials to annual crop rotations, and rotational change from continuous corn to a 2-year corn-soybean rotation.

Expressed as emissions-avoided per acre, average annually avoided emissions with no-till tillage, reduced tillage, no till tillage with a reduced tillage counterfactual, cover crops, crop residue retention, the addition of one or two years of forage perennials to annual crop rotations, and rotational change from continuous corn to two-year corn-soybean rotation are an estimated 0.14, 0.07, 0.20, 0.27, 0.17, 0.41 and (-) 0.35 CO_2-equivalent short tons per acre, respectively.

Best nutrient management yield annual GHG emissions-avoidance in the range of 0.1 to 0.3 CO_2-equivalent short tons per acre. In the case of subsurface nitrogen placement, greenhouse gas emissions are projected to increase.

Lastly, emissions-avoidance from the avoided conversion of upland grassland and wetland soils to agricultural use, including the avoided conversion of undisturbed peatland soils to cropland uses, ranges from 2.1 to 15.3 CO_2-equivalent short tons per acre per year. GHG emissions-avoidance from the avoided conversion of undisturbed peatland soils to cropland are an estimated 15.3 CO_2-equivalent short tons per acre per year.

As noted above, the largest avoidance potential shown by practice in Table 7 is associated with the retirement and rewetting of formerly cropped or pastured peatland or with a related practice, the avoided conversion of undisturbed peatland to cropland. This is largely explained by the present-day scope of GHG emissions from drained peatland soils in agricultural use, which the Minnesota Pollution Control Agency, in its most recent greenhouse gas inventory for Minnesota, estimates at some 11 million CO_2-equivalent short tons on approximately 800,000 acres.

Table 8 provides an itemized accounting of GHG-avoidance, practice-by-practice and by gas. The totals shown in Table 8 are the same as appear in Table 7. Sequestration of biogenic carbon in soils and biomass typically is the largest contributor to greenhouse gas-avoidance. If we exclude the five nutrient reduction practices, for which we have no estimates for soil carbon sequestration, avoidance through sequestration typically accounts for 40 to greater than 100 percent of total GHG-avoidance under the practices shown in Table 8. Expressed as an offset of emitted CO_2 from fossil fuel combustion, rates of sequestration fall into a range of 0.5 to 1.3 tons of CO_2 per acre for practices that idle cropland or move cropland to a supporting role in production, as is the case with shelterbelts or riparian buffers. As noted in the Methodology section of this report, sequestration rates, expressed as emission offsets, are calculated assuming a 20-year period of persistent storage of newly sequestered biogenic carbon. With 50 years of assumed storage, these rates of annual sequestration roughly double. Sequestration under changed tillage and cropping practices are smaller than those involving land-use change, 0.1 to 0.9 CO_2-equivalent tons per acre per year (13,000 to 86,000 CO_2-equivalent short tons per 100,000 acres), or in short tons of carbon, 0.04 to 0.23 tons of carbon per acre per year. Adding in biochar broadens the range to 0.1 to 1.37 tons of CO_2 per acre per year.

Table 7. Emissions-avoided from agricultural practices (short CO_2-e tons per 100,000 acres per year)

	Emissions-avoided [a,b]	
	in-state plus out-of-state	in-state-only [c]
	CO_2-e short tons	CO_2-e short tons
Practices that Involve Land-Use Change from Cropland to Cropland-Supporting Role or Long-term Idling [d,e]		
Retired/Rewet Peatlands	(1,478,636)	(1,458,452)
Shelterbelts, Hedgerows	(298,377)	(278,193)
Land Retirement/Long-term Idling: Afforestation	(255,863)	(235,679)
Retired/Rewet Mineral Wetlands and Constructed	(221,637)	(201,453)
Forested and Multispecies Riparian Buffers	(220,528)	(200,344)
Land Retirement/Long-term Idling: Grassland	(159,184)	(138,999)
Field Borders, Contour Buffer Strips, Vegetated Barriers, Herbaceous Wind Barriers	(157,810)	(137,626)
Grassland Riparian Buffers	(76,872)	(56,688)
Cropping and Tillage Practices		
Short Rotation Woody Crops	(157,447)	(148,819)
Cropland to Hayland	(120,897)	(107,526)
Add a Perennial Grass to Crop Rotation	(41,392)	(29,504)
Winter Cover Crops/Catch Crops	(26,712)	(25,525)
No-Till Tillage-Reduced Tillage Counterfactual	(20,259)	(20,026)
Crop Residue Return	(17,171)	(16,735)
No-Till Tillage	(14,291)	(13,690)
Reduced Tillage	(7,019)	(6,651)
Biochar Soil Amendments	(2,466,039)	(2,468,968)
Biochar Soil Amendments (annualized) [f]	(127,582)	(130,511)
Corn-Soybean Rotation Replacing Continuous Corn	34,883	52,179
Nutrient Reduction Practices		
Nitrification Inhibitors	(30,097)	(30,097)
Urease Inhibitors	(18,368)	(18,368)
Controlled Release Fertilizers	(17,722)	(17,722)
Split Fertilizer Application	(11,296)	(11,296)
15% Fertilizer Use Reduction (corn-soybean rotation)	(5,205)	(3,099)
Subsurface Fertlilizer Placement	27,746	27,656
Avoided Conversion of Unmanaged Lands to Cropland		
Avoided Conversion of Peatlands	(1,529,415)	(1,509,231)
Avoided Conversion of Upland Grasslands	(377,861)	(357,677)
Avoided Conversion of Mineral Wetlands	(209,256)	(189,071)

[a] positive = emissions increase, negative = emissions reduction

[b] descriptive statistics for the soil organic carbon, direct soil N_2O and soil CH_4 oxidation components of each emissions-avoided estimate are shown in Tables 12-14, 16-18, 20-22, 25-27, 29-31, 34-39, 41-44, 47-49, 52-54, 56-58, 60-61, 65-66, 68-69, 72-73, 74-76, 78, 81-82, 84-85, 87, 89, 91-92, 94, 97-98, and 101-102

[c] emissions-avoided within the borders of Minnesota

[d] often also result in reduced nutrient run-off and leaching to surface and groundwater

[e] for terrestrial carbon sequestration, assumes 20 years of sustained storage of newly sequestered organic carbon in soils and biomass

[f] while most emissions-avoidance from biochar soil amendments occurs during the year of application, here they are annualized using 20 year annualization to make them comparable to other practices where a change, made in a single year, yields a 20-year stream of future emissions-avoidance

Avoided losses of soil carbon through the avoided conversion of undisturbed peatland, mineral wetland, and upland grassland soils range from 2.9 to 14 tons of CO_2 per acre per year. As soil carbon losses that would have occurred upon land conversion to cropland, avoided losses can be seen as just another form of soil carbon sequestration.

After sequestration, avoided direct emissions of N_2O are next in importance, often accounting in best cropping and tillage practices and practices that retire cropland for conservation purposes for between 5 and 30 percent of total GHG-avoidance. For nutrient reduction practices, this value is closer to 70 to 95 percent.

N_2O emissions do not always decline under the practices that were examined. Emissions of N_2O in soils tend to increase in saturated soil, in which rates of denitrification are accelerated. This occurs most obviously in riparian buffer soils, particularly buffer soils in trees, offsetting a part of the mitigating effects of enhanced biogenic carbon sequestration in buffer soils and in aboveground and belowground buffer live biomass. This largely explains the advantage that idled upland soils enjoy over wet riparian soils with respect to GHG-avoidance or mitigation (see Table 8). Based on the analysis, N_2O emissions increase with the use of cover cropping, and likewise with a change in tillage practice from conventional tillage to no-till, at a rate of about 0.07 and 0.08 CO_2-equivalent short tons per acre, respectively (7,000 and 7,500 CO_2-equivalent short tons per 100,000 acres).

Additionally, N_2O emissions increase with the deep placement of nitrogen fertilizers, with the result that this practice is a net greenhouse gas emitter.

Avoided-emissions from the avoided out-of-state manufacture of agricultural fertilizers, chemicals and fuels generally are the third largest source of avoided-emissions. In most instances, avoided-emissions of CH_4 are small and either positive or negative. Large new emissions of CH_4 result from the retirement and restoration of drained peatland and mineral wetland soils.

Finally, the results given in Tables 7 and 8 were calculated using the index developed in 2007 by the IPCC to express emissions of CH_4 and N_2O as equivalent emissions of CO_2. (IPCC, 2007) In 2013, and again in 2021, the 2007 version of this index was superseded by an updated version. (IPCC, 2013, IPCC, 2021) Using the updated 2021 version of this index, we recalculated the estimates given in Tables 7 and 8 for emissions-avoidance. The results of this recalculation are shown in Table 9. For most practices, the effects of recalculation are minor.

Table 8. Emissions-avoided from Agricultural Practices (short CO_2-e tons per 100,000 acres per year) [a,b]

	N_2O-direct	N_2O-indirect volatilization	N_2O-indirect leaching	CH_4	CO_2-carbon sequestration	CO_2-urea, liming	GHGs-energy	Out-of-State Upstream GHGs	In-State Upstream GHGs	Total
Practices that Involve Land-Use Change from Cropland to Cropland-Supporting Role or Long-term Idling										
Retired/Rewet Peatlands	(251,663)	NK	(7,186)	151,092	(1,341,038)	(2,808)	(6,849)	(20,184)	-	(1,478,636)
Shelterbelts, Hedgerows	(47,288)	(2,148)	(14,020)	(73)	(205,007)	(2,808)	(6,849)	(20,184)	-	(298,377)
Land Retirement/Long-term Idling: Afforestation	(47,288)	(2,148)	(14,020)	(73)	(162,493)	(2,808)	(6,849)	(20,184)	-	(255,863)
Retired/Rewet Mineral Wetlands and Constructed Wetlands	(18,970)	not known (NK)	(7,186)	276,183	(441,823)	(2,808)	(6,849)	(20,184)	-	(221,637)
Forested Riparian Buffers	5,208	(2,148)	(13,653)	33,466	(213,560)	(2,808)	(6,849)	(20,184)	-	(220,528)
Land Retirement/Long-term Idling: Grassland Restoration	(42,756)	(2,107)	(11,703)	520	(73,297)	(2,808)	(6,849)	(20,184)	-	(159,184)
Field Borders, Vegetated Barriers	(42,756)	(2,107)	(11,703)	520	(73,297)	(2,808)	(5,475)	(20,184)	-	(157,810)
Grassland Riparian Buffers	(9,405)	(2,107)	(13,653)	27,176	(49,042)	(2,808)	(6,849)	(20,184)	-	(76,872)
Cropping and Tillage Practices										
Short Rotation Woody Crops	(48,446)	(2,148)	(14,020)	NK	(85,839)	NK	1,635	(8,628)	-	(157,447)
Cropland to Hayland	(52,012)	(2,107)	(11,703)	NK	(42,625)	(2,786)	3,706	(13,371)	-	(120,897)
Add a Perennial Grass to Crop Rotation	(1,599)	(1,053)	(6,826)	NK	(25,518)	(1,393)	6,886	(11,888)	-	(41,392)
Winter Cover Crops/Catch Crops	7,511	NK	(7,329)	22	(26,248)	-	519	(1,187)	-	(26,712)
No-Till Tillage-Reduced Tillage Counterfactual	(6,597)	553	-	NK	(12,927)	-	(1,054)	(234)	-	(20,259)
Crop Residue Return	-	586	(1,725)	332	(20,208)	-	(1,969)	(436)	-	(17,171)
No-Till Tillage	7,071	553	-	(283)	(18,319)	-	(2,713)	(601)	-	(14,291)
Reduced Tillage	21	553	-	52	(5,619)	-	(1,658)	(367)	-	(7,019)
Biochar Soil Amendments	(16,279)	76	(4,455)	NK	(2,731,796)	NK	13,224	2,929	270,262	(2,466,039)
Biochar Soil Amendments (annualized) [c]	(16,279)	76	(4,455)	NK	(136,590)	-	13,224	2,929	13,513	(127,582)
Corn-Soybean Rotation Replacing Continuous Corn	(958)	NK	NK	NK	54,046	-	(909)	(17,296)	-	34,883
Nutrient Management Practices										
Nitrification Inhibitors	(25,908)	448	(4,389)	(248)	-	-	-	-	-	(30,097)
Urease Inhibitors	(17,111)	(1,072)	NA	(185)	-	-	-	-	-	(18,368)
Controlled Release Fertilizers	(12,585)	(1,210)	(3,927)	NK	-	-	-	-	-	(17,722)
Split Fertilizer Application	(11,173)	108	(1,006)	206	-	-	568	-	-	(11,296)
15% Fertilizer Use Reduction	(2,528)	(253)	(569)	NK	636	(385)	-	(2,106)	-	(5,205)
Subsurface Fertilizer Placement	33,436	(1,187)	(4,999)	NK	-	-	405	90	-	27,746
Avoided Conversion to Crop Production										
Avoided Conversion: Peatlands	(240,215)	(2,169)	(7,186)	147,061	(1,397,065)	(2,808)	(6,849)	(20,184)	-	(1,529,415)
Avoided Conversion: Upland Grasslands	(42,756)	(2,107)	(11,703)	520	(291,974)	(2,808)	(6,849)	(20,184)	-	(377,861)
Avoided Conversion: Mineral Wetlands	(66,914)	(2,169)	(7,186)	338,701	(441,847)	(2,808)	(6,849)	(20,184)	-	(209,256)

[a] positive = emissions increase, negative = emissions reduction

[b] descriptive statistics for the soil organic carbon, direct soil N_2O and soil CH_4 oxidation components of each emissions-avoided estimate are shown in Tables 12-14, 16-18, 20-22, 25-27, 29-31, 34-39, 41-44, 47-49, 52-54, 56-58, 60-61, 65-66, 68-69, 72-73, 74-76, 78, 81-82, 84-85, 87, 89, 91-92, 94, 97-98, and 101-102

[c] while most emissions-avoidance from biochar soil amendments occurs during the year of application, here they are annualized using 20 year annualization to make them comparable to other practices where a change, made in a single year, yields a 20-year stream of future emissions-avoidance

Table 9. Emissions-avoided from Agricultural Practices, 6th Assessment GWPs (short CO_2-e tons per 100,000 acres)

	Emissions-avoided [a,b]	
	in-state plus out-of-state	in-state-only [c]
	CO_2-e short tons	CO_2-e short tons
Practices that Involve Land-Use Change from Cropland to Cropland-Supporting Role or Long-term Idling [d,e]		
Retired/Rewet Peatlands	(1,443,622)	(1,423,438)
Shelterbelts, Hedgerows	(293,058)	(272,874)
Land Retirement/Long-term Idling: Afforestation	(250,544)	(230,360)
Retired/Rewet Mineral Wetlands and Constructed	(195,136)	(174,952)
Forested and Multispecies Riparian Buffers	(216,692)	(196,508)
Land Retirement/Long-term Idling: Grassland	(154,390)	(134,206)
Field Borders, Contour Buffer Strips, Vegetated Barriers, Herbaceous Wind Barriers	(153,017)	(132,833)
Grassland Riparian Buffers	(72,367)	(52,183)
Cropping and Tillage Practices		
Short Rotation Woody Crops	(152,023)	(143,396)
Cropland to Hayland	(115,377)	(102,005)
Add a Perennial Grass to Crop Rotation	(40,599)	(28,711)
Winter Cover Crops/Catch Crops	(26,726)	(25,539)
No-Till Tillage-Reduced Tillage Counterfactual	(19,752)	(19,519)
Crop Residue Return	(17,570)	(17,134)
No-Till Tillage	(14,955)	(14,354)
Reduced Tillage	(7,062)	(6,694)
Biochar Soil Amendments	(2,462,444)	(2,465,373)
Biochar Soil Amendments (annualized) [f]	(125,756)	(128,685)
Corn-Soybean Rotation Replacing Continuous Corn	34,963	52,259
Nutrient Reduction Practices		
Nitrification Inhibitors	(27,615)	(27,615)
Urease Inhibitors	(16,859)	(16,859)
Controlled Release Fertilizers	(16,235)	(16,235)
Split Fertilizer Application	(10,266)	(10,266)
15% Fertilizer Use Reduction (corn-soybean rotation)	(4,924)	(2,818)
Subsurface Fertlilizer Placement	25,459	25,370
Avoided Conversion of Unmanaged Lands to Cropland		
Avoided Conversion of Peatlands	(1,495,534)	(1,475,350)
Avoided Conversion of Upland Grasslands	(373,068)	(352,884)
Avoided Conversion of Mineral Wetlands	(173,049)	(152,865)

[a] positive = emissions increase, negative = emissions reduction

[b] descriptive statistics for the soil organic carbon, direct soil N_2O and soil CH_4 oxidation components of each emissions-avoided estimate are shown in Tables 12-14, 16-18, 20-22, 25-27, 29-31, 34-39, 41-44, 47-49, 52-54, 56-58, 60-61, 65-66, 68-69, 72-73, 74-76, 78, 81-82, 84-85, 87, 89, 91-92, 94, 97-98, and 101-102

[c] emissions-avoided within the borders of Minnesota

[d] often also result in reduced nutrient run-off and leaching to surface and groundwater

[e] for terrestrial carbon sequestration, assumes 20 years of sustained storage of newly sequestered organic carbon in soils and biomass

f while most emissions-avoidance from biochar soil amendments occurs during the year of application, here they are annualized using 20 year annualization to make them comparable to other practices where a change, made in a single year, yields a 20-year stream of future emissions-avoidance

IV. Detailed results and discussion

Below we treat in depth the GHG emission reduction potential of the 27 practices that were assessed, including itemized GHG-avoidance budgets by emission source and gas for each practice. We also provide detailed discussion of the physical, biological and chemical processes that, in the case of each practice, underlie emissions-avoidance or, in some cases, increased GHG emissions. We identify what, in the case of each emissions source, is, in our judgement, the best estimate of emissions-avoidance based on best available science and identify alternative estimates and their physical basis. To support this discussion, we present descriptive statistics for the body of published results for emission-avoidance for individual GHGs and sources. With these descriptive statistics, we build-up a picture of the state of the published literature on these issues.

The budgets of emission-avoidance include avoidance from all sources, including all direct GHG emissions from and removal mechanisms (sinks) in soils, emissions from fuel used in cropland field operations and indirect emissions from surface waters and downwind soil surfaces resulting from nitrate leaching and ammonia volatilization and redeposition. Emissions that result from the manufacture of agricultural chemicals and fuels used in crop production also are included. Detailed discussion of GHG-avoidance is limited to GHG-avoidance resulting from carbon sequestration in soils and plant biomass and changes in direct N_2O soil emissions and CH_4 emission from or oxidation in soils. As noted in earlier sections, with the exception of avoided out-of-state emissions from the manufacture of agricultural fertilizer, most of these non-soil sources of emissions-avoidance (or increase) are small. In the case of agricultural fertilizer manufacture, the methods conventionally used to estimate emissions-avoidance are throughput-based calculations based on a set of simplified emission factors that might be described in a sentence or two.

The methods and sources used to estimate avoided indirect N_2O emissions from nitrate leaching and ammonia volatilization, avoided-emissions from fuel use, and avoided-emissions from foregone agricultural chemicals and fuels manufacture are discussed above in Section II, Subsection E.

We begin the discussion with practices that involve cropland idling or the conversion of cropland to a supporting role in crop production in the form of buffers, shelterbelts, field borders and herbaceous barriers. Subsections A through H house this discussion. These are followed by Subsections I through R, which house the discussion of per acre emission-avoidance potential of ten cropping and tillage practices. These are in turn followed by Subsections S through X, which contain a discussion of nutrient management best practices, and Subsections Y through AA, which treat the impacts on GHG emissions of the avoided conversion of wetlands and upland grasslands.

Earlier in the Methodology Section of this report, we provided a generic description of the calculative methods used to evaluate emissions-avoidance from upstream agricultural chemical and fertilizer manufacture, field fuel use, and indirect N_2O emissions. As was noted there, for nitrate control, the source of emissions-avoidance for indirect N_2O from nitrogen run-off and leaching, we defer to the expertise on nitrate control embedded in the MPCA, Nutrient Reduction Strategy. (MPCA, 2014)

A. Land retirement/Long-term idling: Grassland restoration

Under land retirement or long-term idling, land that historically has been managed as cropland or pastureland is sown to grass or planted to trees and, for periods of a decade to many decades, is idled. In Minnesota, about 1.13 million acres of lands are idled or temporarily retired under the Federal Conservation Reserve Program (CRP), most of it as restored grassland. In addition, 250,000 acres of environmentally sensitive agricultural lands have been permanently retired under the Reinvest in

Minnesota Program (RIM) in more than 6,000 easements. The CRP is a US Department of Agriculture program that, under contracts typically 15 years long, pays agricultural producers temporarily to retire lands to grass, trees, wetlands or other conservation uses.

We estimate that, for each 100,000 acres of cropland retired to grass, 159,000 CO_2-equivalent short tons of greenhouse gases would be avoided annually within the 20-year window of analysis discussed in the preceding sections, or 1.6 short CO_2-equivalent tons per acre. Of this, a little less than 90 percent of emissions annually avoided through grassland restoration would be avoided in state at the field level. The remainder would be avoided out-of-state. Out-of-state avoidance is associated with the mining and manufacture of agricultural fertilizer, chemicals, and fuels that, as a result of land retirements or idling in Minnesota, does not otherwise occur. Of total avoided-emissions from cropland idling in unmanaged grass, roughly 85 percent derives from soil organic carbon (SOC) accumulation in soils and live biomass, avoided-emissions of N_2O from soils, and avoided GHGs from unneeded out-of-state production of agricultural chemicals and fertilizer. The emissions-avoidance effects of the temporarily idling of 100,000 acres of cropland as restored grassland are shown In Table 10 by greenhouse gas and emissions source.

As discussed in the Methodology section of this report, in calculating avoided-emissions associated with biogenic carbon sequestration in soils or live biomass, a 20-year timespan for storage was assumed. In our judgment, this is the longest that continuous storage safely can be assumed for grassland restoration for purposes of calculating the effects today of cropland retirement to grass.[8] Under this assumption, avoided-emissions are an estimated 159,000 CO_2-equivalent short tons. Had a 40-year period of assured storage been assumed, avoided-emissions from grassland restoration would have totaled 232,000 CO_2-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 452,000 CO_2-equivalent short tons (see Table 10). The approach that we use in converting observed rates of sequestration to avoided-emissions was addressed above in the Methodology section (Section II).

Currently, using the values shown in Table 10, on the roughly 1.13 million acres in Minnesota in CRP (as of September 2017), an estimated 1.8 million CO_2-equivalent tons of emissions are avoided annually through grassland restoration. (USDA-FSA, 2017) Additional grassland retirements beyond these 1.13 million acres would add to this annual total. Under the Conservation Reserve Enhancement Program (CREP), participation in which requires permanent retirement of cropland or pastureland, an additional 30,000 CO_2-equivalent tons of annually avoided emissions on 80,000 acres also might reasonably be expected. Of the 107,000 CREP acres in Minnesota, about three-quarters are grassland and the remaining one-quarter are restored wetlands.

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[8] As of September 2017, of the 1.128 million acres currently idled in Minnesota under the Conservation Reserve Program, only about 10 percent have been idled for more than 20 years, the remainder for 20 years or less. As of September 2017, half of all CRP acres in Minnesota had been enrolled in the program for less than 10 years. The CRP program was initiated roughly 30 years ago, in 1987. (USDA-FSA, 2017)

Table 10. Land retirement/Long-term idling - Grassland restoration: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(42,756)	crop production
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	(2,107)	crop production
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(11,703)	crop production
CH_4 [b]	soils	520	crop production
CO_2 [c,d]	carbon accumulation in soils and biomass	(73,297)	crop production
CO_2	cultivated soils from lime or urea use	(2,808)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	(6,849)	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(20,184)	crop production
Total		**(159,184)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass			
40 year storage	all sources and sinks	**(232,481)**	crop production
100 year storage	all sources and sinks	**(452,372)**	crop production

[a] positive = emissions increase, negative = emissions reduction

[b] reduction in soil CH_4 oxidation = relative increase in emissions

[c] carbon accumulation in soil and biomass = net removal of CO_2 from the atmosphere = net emission reduction

[d] assumes 20 years of sustained storage of newly sequestered organic carbon in soils and biomass

A number of estimates have been published of the net change in greenhouse gas emissions resulting from the conversion of cropland to unmanaged grassland. These are shown below in Table 11 in CO2-equivalent short tons per 100,000 acres. With the exception of one outlying modeling study, they support a range of emissions reductions of 75,000 to 240,000 short CO2-equivalent tons for each 100,000 acres of conversions.

Biogenic carbon sequestration from grassland restoration on idled soils is discussed below, as are avoided direct emissions of N2O from soils and the effects of grassland restoration on soil CH4 oxidation. The methods and sources used to estimate avoided indirect N2O emissions from nitrate leaching and ammonia volatilization, avoided-emissions from fuel use, and avoided-emissions from foregone agricultural chemicals and fuels manufacture were discussed in the Methodology section (Section II, Subsection E) of this report.

Table 11. Published estimates of greenhouse gas-avoidance from cropland idling in unmanaged grassland [a]

		emissions avoided [a]	
Study	**Type of study**	**CO_2-eq. short tons per acre per year**	**CO_2-eq. short tons per 100,000 acres per year**
Gelfand and Robertson (2015)	site study	1.92	192,007
Miao *et al.* (2015) [b]	site study	1.09	108,916
Robertson *et al.* (2000)	site study	1.23	122,653
Del Grosso *et al.* (2002)	modeling study	0.10	9,561
Del Grosso *et al*. (2005)	modeling study	0.83	83,350
Desjardins *et al.* (2005) [b]	modeling study	1.80	180,129
Grant *et al.* (2004)	modeling study	1.14	113,733
Robertson (2011) [b]	modeling study	0.74	73,544
Smith *et al.* (2008) [b,c]	modeling study	2.39	239,061
Fargione *et al*. (2018)	literature review/expert judgment	1.94	194,482
ICF International (2013)	literature review/expert judgment	1.20	120,130
Swan *et al.* (2015) [b]	literature review/expert judgment	1.39	138,866
Eagle *et al*. (2012)	other derivative statistical analysis [e]	1.59	159,226
Kim and Kirschbaum (2015) [b,d]	other derivative statistical analysis [e]	1.18	117,573
This report	literature review	1.59	159,184

[a] results as reported without adjustments

[b] partial difference, accounting for direct soils emissions and soil sequestration-only

[c] reversion to natural site vegetation, including grasses, wetlands or trees

[d] annual soil sequestration calculated from using a 20 year cumulative total annualized

[e] statistical analyses other than meta-analyses

a. Carbon sequestration in soils and biomass

In long-term idling of cropland through grassland restoration, cropland is converted to unmanaged grassland. During cultivation, cropland soils are tilled, which acts to disrupt soil structure and expose soil organic matter in soil macroaggregates and microaggregates to microbial decomposition. In an undisturbed grassland or forestland soil, biogenic carbon is deposited in the soil profile through the growth and decay of plant roots and rhizodeposition in the form of sloughed-off plant cells or root exudates. Some biogenic carbon is also deposited into deep soil layers in the form of leached dissolved organic carbon. In undisturbed grassland or forestland, soil organic carbon is physically protected from soil decomposing bacteria by soil macroaggregates, mostly in soil pores that, due to small size, are inaccessible bacteria and fungi (or water soluble enzymes) or are too anaerobic for aerobic soil bacteria. (Jones and Donnelly, 2004) Soil carbon is also chemically protected by clay and silt particles, which bind to soil organic matter and, in the very long-term, by various metals and mineral anions and cations which biochemically bind to organic matter to form organomineral complexes. (Follett *et al*., 2001; Nair, 2010; Six *et al*., 2002a) Once adsorbed on to mineral surfaces, organic matter is highly recalcitrant and remains resident in the soil profile for hundreds to thousands of years.

Cropland cultivation disrupts soil structure, breaking up protective soil macroaggregates and exposing soil organic carbon (SOC) to microbial decomposition. (Six *et al*., 2002a) It is estimated that, upon conversion of native grassland to arable cropland, 20 to 60 percent of soil organic carbon is oxidized and is released to the atmosphere in the form of CO_2. (Guo and Gifford, 2002; Mann, 1986; Post and Kwan, 2000) These losses occur quickly, over period of less than 20 years. (Davidson and Ackerman, 1993; Poeplau *et al*., 2011) In general, cultivated soils are more highly aerated and warmer than unmanaged grassland soils, which accelerates microbial decomposition of organic matter. Cultivated soils also are exposed to higher rates of soil loss from wind and water erosion.

Cropland idling in the form of grassland restoration reverses the processes of soil degradation, slowly building carbon in grassland soils through renewed physical and biochemical protection of soil organic matter, as well as enhanced allocation of carbon to roots, and other processes. Upon cropland idling as restored grassland, soil organic carbon accumulates for 50 to 100 years, eventually stabilizing at levels somewhat lower than those of never disturbed grassland. (Don *et al*., 2009; Poeplau *et al*., 2011) In the US, soil organic carbon (SOC) storage on croplands is estimated to be about 45 short tons of carbon per acre (100 metric tons of carbon per hectare), while organic carbon storage in native grassland soils is 59 short tons per acre (132 metric tons per hectare). (Follett, 2009). This suggests that, on average in the US, with grassland restorations, an additional 10 to 15 short tons of carbon per acre might be stored.

In addition to reduced disturbance, factors that promote sequestration of organic carbon in converted grassland soils include: absence of harvest removals (Omonode and Vyn, 2006; Vuichard *et al*., 2008), enhanced allocation of carbon to roots and rhizomes in perennial grasses (Bell *et al*., 2012), rooting depth (Knops and Bradley, 2009), and inherent recalcitrance of root portions. (Guzman and Al-Kaisi, 2010)

On croplands in annual rotations, harvest removals account for between 40 and 45 percent of cropland net primary productivity (NPP). (West *et al*., 2011) Little of this is available as input to soils. This only partially compensates for the generally lower net primary productivity of grasslands in comparison to croplands.

Regarding the allocation of net primary productivity, in unmanaged grasslands, about two-thirds of net primary productivity is allocated belowground to root growth and rhizomes, where it is made available for storage in SOC. By contrast, only about 20 percent of the net primary productivity of annual crops is allocated belowground. Extensive, deep rooting promotes deep deposition of plant carbon in the form of root turnover and exudation; in general, the degree of SOC stabilization or recalcitrance is greater at deeper soil levels. The inherent recalcitrance of root portions lengthens root carbon residence time in soils.

The capacity of grassland soils to store carbon varies depending on soil texture, soil wetness and temperature, soil clay content, the degree of prior carbon loss, plant productivity, and, again, rooting depth. In general, wet, fine textured soils with high clay contents store more carbon than do coarse, dry soils, particularly where cool climatic conditions prevail. By limiting aeration, wetness inhibits microbial decomposition of soil organic matter (SOM) in soils, as do cool temperatures. As discussed above, soil clay acts to physically protect soil aggregates, inhibiting microbial decomposition of soil organic matter. Regarding prior carbon loss, as an empirical matter, soil scientists have consistently noted that the highest rates of soil carbon sequestration occur on soils that, due to prior land uses, have experienced large losses of soil organic carbon. Finally, since plant primary productivity determines the input of carbon to soils, highly productive grasses with deep roots are often associated with high rates of observed carbon sequestration.

In addition to the sequestration of carbon in soils, organic carbon also is stored in aboveground and belowground live and dead biomass. Between 2.25 and 9 short tons of carbon per acre (5 to 20 metric tons of carbon per hectare) are allocated to aboveground and belowground biomass in reconstructed prairies. (Guzman and Al-Kaisi, 2010; Tufekcioglu, *et al*., 2003) Unlike aboveground and belowground biomass on croplands, much of which is removed at harvest or otherwise rapidly decomposes, grassland biomass is largely retained after the growing season as belowground live roots or aboveground in the form of litter and plant detritus.

In Table 10, an estimate for annual carbon sequestration in restored grasslands of 73,297 short tons of CO_2 or 20,003 tons of carbon was given, covering 100,000 acres of restorations. As discussed above, this was developed using an average rate of sequestration per acre, discounted to account for an assumed 20-year persistence of storage. In aggrading grasslands, CO_2 is removed from the atmosphere and incorporated into the roots and aboveground live biomass of perennial grasses and, eventually, into grassland litter and soils. This offsets emissions of CO_2 from fossil fuel combustion. In developing the sequestration estimates, the calculations were done initially in metric units and then converted to English or common units.

The sequestration estimate given in Table 10 was developed from 23 studies of total ecosystem carbon in restored grasslands. As discussed in the Methodology section of this report, total ecosystem carbon accounting is probably the best approach for approximating rates of carbon sequestration in natural and managed ecosystems. Total ecosystem gain or loss of carbon is estimated as the difference between gross primary productivity and ecosystem respiration, adjusting for, in unmanaged natural systems, the export of organic carbon in the form of DOC (dissolved organic carbon) or methane, and in the case of cropland, the import of manure and harvest removals, in additional to losses in the form of DOC and CH_4.

The mean value from total ecosystem carbon studies for carbon sequestration in restored grassland is an estimated 1.17 ± 0.25 metric tons of carbon per hectare (0.52 ± 0.11 short tons of carbon per acre), implying that, on a per acre basis, carbon storage in grassland that is temporarily idled in grass annually offsets about 2 tons of CO_2 emissions elsewhere in the economy. This is the estimated rate prior to truncation to accommodate an assumed 20-year persistence of newly stored organic carbon in grasslands. Of the total ecosystem carbon studies, 14 were eddy-covariance-based, while the remainder were chamber-based studies.

Overall, 147 studies were reviewed. Most of these studies (123 studies) reported on changes in soil organic carbon only and, as such, were of limited utility. Only a handful of the 147 studies that were reviewed reported reductions in carbon storage after conversion of cropland to grassland; slightly less than 95 percent reported increased carbon storage.

By study type, 15 meta-analyses and other derivative statistical summaries or analyses were reviewed, as were the 57 soil sampling-type site studies, 26 modeling studies, the 14 eddy-covariance, and 28 literature reviews or studies relying on expert judgment. The meta-analyses were limited to studies of soil carbon change with grassland restoration, as were most of the statistical summaries or other derivative statistical analyses. By study type, estimated rates of carbon sequestration ranged from 0.6 to 1.25 metric tons of carbon per hectare (0.27 to 0.56 short tons of carbon per acre).

The average sequestration rate for the literature and expert reviews was 0.74 metric tons per hectare per year.

The descriptive statistics for the studies by study type, by soil sampling depth, and by age of grassland restoration are shown in Table 12.

Table 12. Descriptive statistics: Land retirement/Long-term idling - Grassland restoration, carbon sequestration in soils and biomass

	biogenic carbon sequestration (Mg C/ha/yr)	number of study results [a]	ratio of sequestration to emission: number of studies [b]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
total ecosystem carbon (soil organic carbon, above and belowground biomass)	1.17	23	22/1	0.25	0.67	1.66
soil organic carbon-only	0.55	123	115/8	0.04	0.47	0.64
meta-analyses	0.68	7	7/0	0.16	0.37	1.00
other derivative statistical analyses or statistical summaries [c]	0.64	8	8/0	0.12	0.40	0.89
eddy covariance empirical site studies (NECB/NBP)	1.25	14	13/1	0.37	0.53	1.97
modeling studies	0.66	26	25/1	0.11	0.45	0.87
empirical site studies-soil sampling	0.43	57	50/7	0.07	0.30	0.57
literature reviews/expert judgment	0.74	28	28/0	0.06	0.61	0.86
other study types	0.90	7	7/0	0.37	0.17	1.63
restored grasslands	0.64	140	131/9	0.06	0.53	0.75
existing grasslands	0.81	9	9/0	0.27	0.27	1.35
10 to 30 cm soil sampling/modeling depth [e]	0.54	62	60/2	0.06	0.41	0.66
> 40 cm soil sampling/modeling depth [e]	0.50	20	16/4	0.16	0.17	0.82
15 to 25 year annual sequestration rate	0.53	41	37/4	0.10	0.34	0.73
0 to 14 year annual sequestration rate	0.65	49	44/5	0.11	0.43	0.87
25 year-plus annual sequestration rate	0.34	16	16/0	0.06	0.23	0.44

[a] 147 study results, 147 studies (7 meta-analyses, 8 statistical summaries or derivative statistical analyses, 26 modeling studies, 57 soil sampling-type empirical site studies, 14 eddy covariance type empirical site studies, 28 literature reviews, and 7 other study types)

[b] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[c] statistical summaries or analyses other than meta-analyses

[d] NECB = Net Ecosystem Carbon Balance; NBP = Net Biome Productivity

[e] results for lowest reported sampling depth

In the studies that were reviewed, existing grassland sequestered slightly more on an annual basis than restored grassland, but the data set for existing grasslands is quite limited. Additionally, the studies of existing grassland tend to focus on total ecosystem carbon storage, while most of the restored grassland studies, as noted above, report changes in soil carbon only. Within the soil sampling subgroup of studies, the effect of sampling depth had little observable effect on the results. Within our 20-year window for evaluating the effects of carbon sequestration, sequestration was more rapid in younger grassland restorations (0 to 14 years old), but not substantially.

The overwhelming weight of evidence supports a positive response rate for carbon sequestration in grassland restorations, before truncation for 20 years of assumed storage, generally in a range of 0.4 to 1.2 metric tons of carbon per hectare per year (0.18 to 0.54 short tons per acre), with a best estimate near 1.15 metric tons per hectare per year.

b. Nitrous oxide

Nitrous oxide is produced microbially in soils during nitrification, during which ammonium (NH_4^+) is oxidized to nitrate (NO_3^-), and denitrification, during which nitrate is reduced to N_2O. N_2O is produced in converted grassland soils and cropland soils. N_2O emissions from croplands are often four-fold higher than those of unmanaged restored or existing grasslands. In croplands, emissions are sustained by large inputs of mineral and organic nitrogen in the form of synthetic fertilizer, manure and crop residues. A large amount of nitrogen also is made available to soil bacteria in cropped soil through soil nitrogen mineralization, in part due to tillage. Land idled as unmanaged grasslands is typically untilled and unfertilized.

As discussed above, avoided nitrous oxide emissions from the conversion of cropland to grassland are calculated as the difference on 100,000 acres between estimated emissions from restored grassland and average annual Minnesota cropland N_2O emissions, taken from the MPCA Greenhouse Gas Emission Inventory. For each 100,000 acres of cropland converted to grassland, an estimated 41,000 CO_2equivalent short tons of emissions are avoided or some 138 tons of N_2O.

N_2O emissions from restored grassland were estimated using emission rates developed on a per hectare basis from the scientific literature, and converted to lbs. per acre for use in the calculation. In developing the average N_2O emission rate for unmanaged grasslands, 59 studies were reviewed with 62 study results. These included 39 empirical site studies, 12 modeling studies, five derivative statistical summaries or analyses and three literature reviews or studies that depend on expert judgment.

An average value for all of the studies that were reviewed was selected as the best estimate of annual emissions from restored grassland. No formal meta-analyses were available for N_2O from restored grassland. No other study attribute pointed to one study type as clearly superior in estimating N_2O annual emissions from unmanaged grassland. Using the average value for the studies that were reviewed, restored grasslands were estimated to emit on an annual basis 1.59 ± 0.58 kg N_2O per hectare (1.42 ± 0.52 lbs. N_2O per acre).

By contrast, the estimated annual rate of N_2O emission from Minnesota cropland, from the MPCA GHG emission inventory, was, for 2013-2015, 4.8 kg N_2O per hectare (4.3 lbs. N_2O per acre).

The descriptive statistics for the various studies that were reviewed are shown in Table 13. In these studies, annual emission rates for restored and existing grasslands ranged from 0.7 to 3.8 kg N_2O per hectare (0.62 to 3.39 lbs. N_2O per acre). The results for studies that report results on an annual basis were three times higher than those that report growing season-only emissions. The results for studies that were conducted over more than one year were about one-quarter of those studies conducted over a single year, although not too dissimilar to both the mean value reported in Table 13 for all studies and the value used in this analysis to calculate N_2O emissions from cropland converted to grass. The results from restored grassland were about 40 percent of those from existing grasslands, and were within 30 percent of the mean value reported in Table 13 for all studies.

Thirty-six studies reported on the difference in emissions from cropland (or pastureland) and land idled as restored grassland. In these studies, on an annual basis, unmanaged grassland emitted 3.0 kg

N_2O per hectare (2.68 lbs. N_2O per acre) less than cropland or pastureland. In the calculation of avoided N_2O emissions shown in Table 10, the difference between cropland emissions and emissions from restored grassland is some 3.2 kg N_2O per hectare per year (2.85 lbs. N_2O per acre per year), or quite near the literature estimate.

The weight of the evidence supports an N_2O emission from restored grassland that is one-quarter to 40 percent that of fertilized cropland. Given the high variability of N_2O from different land surfaces, it is not clear that additional research can do much to further narrow this estimate.

Table 13. Descriptive Statistics: Land Retirement/Long-term Idling - Grassland Restoration, N_2O

	emissions (kg N_2O/ hectare/yr) [a]	number of study results [b,c]	ratio of positive-to-negative results: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	1.59	63	63/0	0.58	0.45	2.72
empirical site studies	1.84	41	41/0	0.77	0.33	3.36
modeling studies	1.17	13	13/0	0.34	0.50	1.84
derivative statistical analyses or statistical summaries [d]	1.00	5	5/0	0.29	0.43	1.57
literature reviews/expert judgment	1.35	3	3/0	0.58	0.21	2.49
grassland restorations	1.13	37	37/0	0.20	0.75	1.52
existing grasslands	2.68	19	19/0	1.64	(0.53)	5.89
annual flux monitoring/modeling	2.08	40	40/0	0.79	0.53	3.63
growing season and subgrowing season flux monitoring/modeling	0.72	21	21/0	0.12	0.49	0.96
1 year of observations or simulations	3.84	12	12/0	2.55	(1.16)	8.84
> 1 year of observations or simulations	1.04	41	41/0	0.20	0.65	1.43
grassland restorations against cropland or pastureland counterfactual	(3.03)	36	36/0	0.85	(4.70)	(1.36)

[a] negative emissions = removal from atmosphere and destruction in soils

[b] 62 study results, 59 studies (5 statistical summaries or derivative statistical analyses, 12 modeling studies, 39 empirical site studies, 3 expert reviews)

[c] 2 studies report multiple results by study type or grassland status (existing vs restored)

[d] statistical summaries or analyses other than meta-analyses

c. Methane

Methane is produced in saturated soils in anoxic conditions by methanogenic bacteria and is consumed microbially in aerated soils by methanotrophic bacteria. In upland cropland or existing or restored grasslands, methane typically is oxidized. In these soils, methane sources include atmospheric methane and methane produced in deep soil layers. The rate of methane oxidation in cropland soils is typically less than in native grassland. (Dutaur and Verchot, 2007; Jacinthe and Lal, 2005) Tillage in cropland soils acts to disrupt and lessen the diversity of the methanotrophic microbial communities that oxidize methane. (LeMer and Roger, 2001; Levine *et al.*, 2011) Additionally, methane oxidation in well-aerated cropland soils is suppressed in the presence of high levels of ammonium-based nitrogen fertilizer. In the presence of high levels of ammonium, methanotrophic bacteria preferentially oxidize ammonia, shifting oxidation from methane to ammonia and limiting soil methane consumption. (Bayer *et al.*, 2012; Tate 2015)

By converting cropland to grassland, soil CH_4 oxidation is enhanced, but the timeframes for recovery are likely long, as long as 200 years, with limited recovery over periods as short as 20 years. (Allen *et al.*, 2009; Suwanaree and Robertson, 2005) The extra microbial CH_4 destruction that occurs in soils from the conversion of cropland to grassland is calculated as the difference in CH_4 soil oxidation in cropland and methane oxidation in grassland converted from cropland. Average cropland oxidation rates are taken from Aronson and Helliker (2010). In converting 100,000 acres of cropland to grassland, CH_4 oxidation is estimated to decrease slightly, 468 CO_2-equivalent short tons or some 19 tons of CH_4.

In developing the average soil CH_4 oxidation rate for unmanaged grasslands, 33 studies were reviewed with 34 study results. These included 22 empirical site studies, 6 modeling studies, and 5 derivative statistical summaries or analyses.

An average value for all of the studies that were reviewed was selected to best represent soil CH_4 oxidation in restored grassland soils. No formal meta-analyses were available for CH_4 from restored grassland. No other study attribute clearly pointed to one study type as clearly superior to the others in projecting annual rates of CH_4 oxidation in the soils of restored grassland. Using the average value for the studies that were reviewed, restored grasslands were estimated to oxidize on an annual basis 1.38 ± 0.3 kg CH_4 per hectare (1.23 ± 0.27 lbs. CH_4 per acre).

The descriptive statistics for the various studies that were reviewed are shown in Table 14. In the studies, annual CH_4 oxidation rates for restored and existing grasslands range from 0.7 to 3 kg CH_4 per hectare (0.62 to 2.68 lbs. CH_4 per acre). In 85 percent of all observations, upland grassland soils oxidized CH_4. The rate of CH_4 oxidation in restored grassland soils was about one-third that of existing grasslands, but based on a small number of observations (fifteen). Soil oxidation rates for studies that reported CH_4 losses on an annual basis were about three-fold larger than those that limited observations to the growing season. Soil CH_4 oxidation in studies with more than one year of observations was about two-fold higher than those with shorter observational periods. The results from published statistical summaries or derivative statistical analyses generally support higher mean oxidation rates from restored or existing grassland than the mean value reported in Table 14 for all studies, while results from empirical site-studies a somewhat lower value.

Table 14. Descriptive Statistics: Land Retirement/Long-term Idling - Grassland Restoration, CH_4

	soil CH_4 oxidation (kg CH_4/ hectare/yr) [a]	number of study results [b,c]	ratio of positive-to-negative results: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	1.38	34	29/5	0.30	0.79	1.98
empirical site studies	0.82	23	18/5	0.29	0.24	1.39
modeling studies	3.02	6	6/0	1.01	1.04	5.00
derivative statistical analyses or statistical summaries [d]	2.03	5	5/0	0.39	1.26	2.80
grassland restorations	0.67	15	12/3	0.30	0.07	1.26
existing grasslands	2.02	17	16/1	0.49	1.05	2.99
annual flux monitoring/modeling	1.93	19	17/2	0.47	1.01	2.86
growing season and subgrowing season flux monitoring/modeling	0.69	15	12/3	0.26	0.18	1.19
1 year of observations or simulations	0.72	6	5/1	0.31	0.12	1.32
> 1 year of observations or simulations	1.42	19	15/4	0.53	0.45	2.40
grassland restorations against cropland or pastureland counterfactual	0.19	19	8/9/2	0.25	(0.30)	0.68

[a] CH_4 soil oxidation = removal from atmosphere and destruction in soils

[b] 34 study results, 33 studies (5 statistical summaries or derivative statistical analyses, 6 modeling studies, 22 empirical site studies)

[c] 1 study reports multiple results by grassland status (existing vs restored)

[d] statistical summaries or analyses other than meta-analyses

Finally, seventeen studies reported on the difference in CH_4 oxidation from cropland (or pastureland) and land idled as restored grassland. About half of the study results indicated increased soil CH_4 uptake or oxidation as a result of grassland restoration, and about half-reduced uptake, with a mean emission value of -0.2 kg CH_4 per hectare, indicating slight uptake.

B. Land retirement/Long-term idling: Afforestation

Instead of grassland, cropland can be put into trees, which when accumulating carbon annually store, on a per acre basis, about two and one-half times as much biogenic carbon as do grasslands. As described above, as trees grow, CO_2 is photosynthetically removed from the atmosphere and incorporated into live tree biomass and, eventually, into soils and the forest floor. For each 100,000 acres of cropland retired to trees, an estimated 256,000 CO_2-equivalent short tons of GHGs would be avoided annually, much of it in the form of atmospheric CO_2 removal. More than 90 percent of this would be avoided in-state, with the remainder avoided out-of-state from avoided agricultural chemicals (herbicides, pesticides, and fungicides), fertilizer and fuels production.

The budget for greenhouse gas emissions-avoidance from afforestation is shown in Table 15. The largest sources of emissions-avoidance are, in order of significance: biogenic carbon sequestration (64 percent); avoided direct field emissions of N_2O (18 percent); avoided out-of-state emissions associated with the manufacture of fertilizer, agricultural chemicals and fuels no longer consumed in crop production (8 percent); and avoided-emissions of N_2O from nitrate not leached to surface and groundwater (5 percent). As discussed above, during biogenic carbon sequestration, CO_2 is removed photosynthetically from the atmosphere and is sequestered in live tree biomass, soil organic carbon, tree detritus and the forest floor.

In estimating the emissions-avoided from afforestation of cropland, a 20-year timespan was assumed for assured carbon storage in living and dead biomass and soils. Under this assumption, avoided-emissions are an estimated 256,000 CO_2-equivalent short tons. Had a 40-year period of assured storage been assumed, avoided-emissions from afforestation of former croplands would have totaled 418,000 CO_2-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 906,000 CO_2-equivalent short tons (see Table 15). The approach that we use in converting observed rates of sequestration to emissions offsets, and by logical extension to avoided-emissions, was addressed above in the Methodology section (Section II).

Biogenic carbon sequestration on afforested cropland and pastureland is discussed below, as are avoided direct emissions of N_2O from soils and the effects of afforestation of cropland on soil CH_4 uptake and oxidation. The methods and sources used to estimate avoided indirect N_2O emissions from nitrate leaching and ammonia volatilization, avoided-emissions from fuel use, and avoided-emissions from foregone agricultural chemicals and fuels manufacture were discussed in the Methodology section (Section II, Subsection E) of this report.

Table 15. Land retirement/Long-term idling - Afforestation: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(47,288)	crop production
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	(2,148)	crop production
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(14,020)	crop production
CH_4 [b]	soils	(73)	crop production
CO_2 [c,d]	carbon accumulation in soils and biomass	(162,493)	crop production
CO_2	cultivated soils from lime or urea use	(2,808)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	(6,849)	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(20,184)	crop production
Total		**(255,863)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass			
40 year storage	all sources and sinks	**(418,356)**	crop production
100 year storage	all sources and sinks	**(905,834)**	crop production

[a] positive = emissions increase, negative = emissions reduction

[b] increase in soil CH_4 oxidation = relative decrease in emissions

[c] carbon accumulation in soil and biomass = net removal of CO_2 from the atmosphere = net emission reduction

[d] assumes 20 years of sustained storage of newly sequestered organic carbon in soils and biomass

a. Carbon sequestration in soils and biomass

As is true for grassland restoration, afforestation of cropland reverses the processes that, with cropland tillage, lead to the loss of organic carbon from soils. In undisturbed forestland, soil organic carbon (SOC) is physically protected from microbial decomposition by soil macroaggregates, mostly in soil pores too minute for bacteria and fungi (or water soluble enzymes) to access or too anaerobic for aerobic soil bacteria. Soil carbon also is chemically protected by clay and silt particles, which bind to soil organic matter and, in the very long-term, by various metals and mineral anions and cations which biochemically bind to organic matter to form organomineral complexes that are highly recalcitrant. Soil aeration rates and soil temperature also are lower in undisturbed afforested soils.

Tillage disrupts soil structure, breaking up protective soil macroaggregates and exposing soil organic carbon to microbial decomposition. Idling of land in trees reverses the processes of soil degradation, slowly building carbon in afforested soils through renewed physical and biochemical protection of soil organic matter, as well as through enhanced allocation of carbon to roots, reduced soil aeration and temperature, and other processes. At reduced soil aeration and soil temperature, decomposition rates of unprotected organic matter generally slow. Soil aeration and soil temperature are generally lower in undisturbed, untilled soils.

Afforestation of land that was formerly cultivated also leads to the accumulation of large amounts of carbon in aboveground and belowground biomass, effectively removing it from the atmosphere for decades or longer. In the United States, the average forest stores an estimated 74 short tons of carbon per acre (166 metric tons of carbon per hectare), with roughly 45 percent stored in aboveground biomass, roots, standing and down detritus and the forest floor, and the remainder in soils. (US Global Change Research Program, 2018)[9] It is estimated that, during the first 20 years of growth, carbon accumulation in aboveground biomass and live roots accounts for up to 80 percent of the sequestration potential of US Midwest afforested lands, with soil organic carbon and the forest floor accounting about equally for the remainder. (Niu and Duicker, 2006)

Carbon storage in US grasslands is an estimated 59 short tons per acre (132 metric tons per hectare) and on US croplands, 44 short tons per acre (98.5 metric tons of carbon per hectare). (Follet, 2009) Using the numbers cited immediately above, the average acre or hectare of forestland stores 1.7 times as much organic carbon as does cultivated cropland.

In Table 15, an estimate is given for annual carbon sequestration in afforested former cropland, some 162,493 short tons of CO_2 or 44,345 tons of carbon, covering 100,000 afforested acres. As discussed above, this was developed using an average rate of sequestration per acre, discounted to account for an assumed 20-year persistence of storage. This is the longest period of time that, in our estimation, safely can be assumed in calculating the offset value of present-day sequestration. Since much or most of the science on terrestrial carbon sequestration is developed in metric units, this average rate is given in metric tons of carbon and converted to short CO_2-equivalent tons for inclusion in the summary Table 15. During afforestation, CO_2 is removed from the atmosphere and incorporated into tree biomass and, eventually, into woody detritus and soils. This acts to offset emissions of CO_2 from elsewhere in the economy.

The average sequestration rate per acre was developed from 26 studies of total ecosystem carbon in afforested former croplands. Total ecosystem carbon accounting is probably the best approach for estimating carbon sequestration in unmanaged ecosystems with large amounts of carbon stored in aboveground and belowground live biomass, woody detritus, and soils. Total ecosystem gain or loss of carbon is estimated as the difference between gross primary productivity and ecosystem respiration or, in studies that measure changes in individual carbon pools, the change in carbon storage across all important carbon pools. Using the total ecosystem carbon approach, former cropland planted to trees is estimated to annually sequester 2.58 ± 0.41 metric tons of carbon per hectare (1.15 ± 0.18 short tons of

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[9] Due to generally cooler conditions in Minnesota, and slower rates of decomposition of organic matter in Minnesota forested soils, this US average may understate the percentage contribution of forested soils to total forest carbon in Minnesota.

carbon per acre). This is the estimated rate prior to truncation to account for an assumed 20-year persistence of organic carbon stored in and on afforested former cropland.

Overall, 83 studies were reviewed, including nine meta-analyses, five other derivative statistical summaries or analyses, 15 modeling studies, 37 empirical site studies, 15 literature reviews or studies involving expert judgment, and two eddy covariance-types studies (see Table 16). Of the nine meta-analyses, none addressed carbon storage in aboveground or belowground biomass. Excluding the results from the meta-analyses, estimated annual carbon sequestration, by study type, ranged from 1.4 to 3.4 metric tons of carbon per hectare (0.62 to 1.52 short tons of carbon per acre). For studies that treat total ecosystem carbon, aboveground and belowground biomass carbon, or aboveground biomass carbon plus soil carbon, annual sequestration rates ranged from 2.58 to 3.73 metric tons of carbon per hectare (1.15 to 1.66 short tons of carbon per acre per year).

Of the 83 studies that were reviewed, four reported net losses of or no change in organic carbon storage following afforestation, while 79 reported net increases. In general, the evidence supports a positive annual sequestration rate, prior to truncation for 20-years of assumed storage, in the range of approximately 1.5 to 3.5 metric tons of carbon per hectare (0.67 to 1.34 short tons per acre), with a best estimate of 2.6 metric tons per hectare.

Finally, soil-sampling depth does not appear to be a substantial issue. Sequestration appears to have increased faster at sampling depth below 40 cm (16 inches) than in the 10-40 cm (4 to 16 inches) sampling depth. This may result from the much deeper root penetration in forested soils. Soil sequestration rates tended to fall off with afforestation age, from 2.49 to 1.59 metric tons per hectare per year for 0 to 15 year old afforestations and 15 to 25 year old afforestations, respectively.

Table 16. Descriptive statistics: Land retirement/Long-term idling - Afforestation, carbon sequestration in soils and biomass

	biogenic carbon sequestration (Mg C/ha/yr)	number of study results [a]	ratio of sequestration to emission: number of studies [b]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
total ecosystem carbon (soil organic carbon [SOC], above and belowground biomass)	2.58	26	26/0	0.41	1.80	3.37
aboveground forest plus SOC	3.61	11	11/0	0.59	2.46	4.76
above and belowground live biomass	3.73	6	6/0	1.18	1.41	6.04
soil organic carbon-only	0.53	34	27/7	0.18	0.18	0.88
meta-analyses	1.31	11	9/2	0.79	(0.24)	2.87
other derivative statistical analyses or statistical summaries [c]	2.63	6	6/0	0.96	0.74	4.52
modeling studies	2.44	15	15/0	0.51	1.44	3.45
empirical site studies	2.17	37	33/3/1	0.39	1.41	2.92
eddy covariance empirical site studies (NECB/NBP)	3.40	2	2/0	0.14	3.13	3.67
literature reviews/expert judgment	1.44	15	15/0	0.35	0.76	2.13
15 to 25 year annual sequestration rate	1.59	29	27/2	0.29	1.03	2.15
15 to 25 year annual sequestration rate (total ecosystem carbon-only)	2.24	10	10/0	0.40	1.46	3.01
less than 15 year annual sequestration rate	2.49	16	14/2	0.76	1.00	3.98
25 year-plus annual sequestration rate	2.23	22	21/1	0.38	1.48	2.97
10 to 40 cm soil sampling/modeling depth [e]	1.19	20	16/3/1	0.51	0.18	2.19
> 40 cm soil sampling/modeling depth [e]	2.25	17	16/1	0.49	1.29	3.21

[a] 86 study results, 83 studies (9 meta-analyses, 5 statistical summaries or derivative statistical analyses, 15 modeling studies, 37 empirical site studies, 2 eddy covariance type site studies, 15 literature reviews)

[b] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[c] results for lowest reported sampling depth

[d] NECB = Net Ecosystem Carbon Balance; NBP = Net Biome Productivity

[c] statistical summaries or analyses other than meta-analyses

b. Nitrous oxide

N_2O fluxes from forestland are typically one-third those of cultivated cropland. (Dalal and Allen, 2008) Emissions from cropland are sustained by inputs of synthetic and organic nitrogen in the form of mineral fertilizer, manure and crop residues, as well as nitrogen made available through soil nitrogen mineralization. On newly afforested former cropland, most exogenous inputs of nitrogen are foregone, minimizing the pool of soil nitrate and ammonium that sustains N_2O production in soils. Of what remains, a part is immobilized in plant biomass, as a result of the large nutrient needs of young trees, and eventually as organic nitrogen in soils. (Gelfand *et al*., 2016) Immobilized in plant biomass, nitrogen is no longer available for microbial production of N_2O.

Avoided nitrous oxide emissions from the conversion of cropland to forestland are calculated as the difference on 100,000 acres between estimated emissions from forestland converted from cropland and average annual N_2O emissions from Minnesota cropland. Annual Minnesota cropland N_2O emissions are taken from the MPCA Greenhouse Gas Emission Inventory.

N_2O emissions from forestland converted from cropland are estimated using emission rates developed on a per hectare basis from the scientific literature, and converted to lbs. per acre for use in the calculation. In deriving the latter, 43 studies were reviewed. These included 29 empirical site studies, nine modeling studies, and five derivative statistical summaries or analyses.

An average value for all of the studies that were reviewed was selected as the best estimate of annual emissions from afforested former cropland. In this, no study attribute clearly pointed to one study type as clearly superior to the others in estimating N_2O emissions from afforested former cropland. No formal meta-analysis was available for N_2O from restored grassland. Using the average value for the studies that were reviewed, afforested former croplands are estimated to emit on an annual basis 1.25 ± 0.23 kg of N_2O per hectare (1.12 ± 0.21 lbs. of N_2O per acre per year). This value is almost identical to what might be estimated using the reviewed empirical site studies and within 15 percent of the average from the five derivative statistical summaries or analyses. By study type, annual emission rates for afforested and forest soils fall into narrow range of 1.08 to 1.28 kg of N_2O per hectare (0.96 to 1.14 lbs. of N_2O per acre per year).

Average annual cropland N_2O emission rates from the MPCA GHG emission inventory are an estimated 4.8 kg N_2O per hectare (4.3 lbs. N_2O per acre per year).

The flux or emission rates shown in Table 17 derive from studies of both afforested soils and the soils of mature forests. Flux rates are generally quite similar across these two classes of forestland.

Descriptive statistics from the 43 studies that were reviewed are shown in Table 17, including standard errors and calculated upper and lower 95 percent confidence intervals.

Eleven studies evaluated the effect on N_2O emissions of converting cropland to forestland, with a mean annual reduction in emissions across all nine studies of 0.7 kg of N_2O per hectare (0.62 lbs. N_2O per acre per year). Using the mean for all studies for afforested former cropland and average Minnesota cropland N_2O emissions, taken from the MPCA Greenhouse Gas Emission Inventory, we derive a higher value of 3.55 kg N_2O per hectare per year (3.17 lbs. N_2O per acre per year). The estimates agree that, with afforestation, N_2O emissions will decline. Generally there is little sense in the scientific literature that, with cropland abandonment to trees, and nitrogen fertilizer inputs to soils essentially eliminated, N_2O emissions will do anything but decline.

c. Methane

In upland afforested soils, CH_4 generally is oxidized. Due to the large root systems and moisture requirements of trees, afforested soils are typically drier than croplands or grassland, with reduced bulk density, conditions that favor gas diffusion into soils and the oxidation of atmospheric CH_4. (Amadi *et al*., 2017; Dutaur and Verchot, 2007) CH_4 oxidation in forested soils is often inhibited at soil moisture higher than 60 percent or water-filled pore space of 43 percent. (Luo *et al*., 2013) On a per acre basis, soils beneath both established forestland and recently afforested land oxidize more CH_4 than restored grassland and far more than cropland. As discussed earlier, CH_4 oxidation in cropland is likely suppressed by tillage disruptions to methanotroph communities and by the application of ammonium-based synthetic fertilizers.

Table 17. Descriptive statistics: Land retirement/Long-term idling - Afforestation, N_2O

	emissions (kg N_2O/ hectare/yr) [a]	number of study results [b]	ratio of positive-to-negative results: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	1.25	43	43/0	0.23	0.78	1.71
empirical site studies	1.28	29	28/1	0.32	0.65	1.91
modeling studies	1.24	9	9/0	0.48	0.30	2.18
derivative statistical analyses or statistical summaries [c]	1.08	5	5/0	0.28	0.53	1.62
afforestation	1.24	14	14/0	0.44	0.37	2.10
existing forestland	1.25	29	29/0	0.28	0.70	1.81
annual flux monitoring/modeling	1.46	35	35/0	0.28	0.95	1.97
growing season and subgrowing season flux monitoring/modeling	0.30	8	7/1	0.09	0.13	0.47
1 year of observations or simulations	2.11	6	6/0	0.58	0.97	3.26
>1 year of observations or simulations	1.24	27	26/1	0.34	0.57	1.90
afforestation against cropland or pastureland counterfactual	(0.70)	11	10/1	0.98	(2.62)	1.21

[a] negative emissions = removal from atmosphere and destruction in soils

[b] 43 study results, 43 studies (5 statistical summaries or derivative statistical analyses, 9 modeling studies, 29 empirical site studies)

[c] statistical summaries or analyses other than meta-analyses

The extra microbial CH_4 destruction that occurs in soils as a result of the conversion of cropland to forestland is calculated as the difference, across 100,000 acres, between average cropland CH_4 uptake and CH_4 uptake in afforested soils. Average uptake of CH_4 per hectare of cropland was taken from Aronson and Helliker (2010) and converted to lbs. per acre for use in calculation.

In developing the estimate for CH_4 uptake in afforested former croplands, we reviewed 35 studies with 36 study results. In this, no study attribute clearly pointed to one study type as clearly superior to the others in estimating CH_4 oxidation in the soils of afforested former cropland. An average value for all of the studies that were reviewed was selected as the best estimate of annual emissions from afforested former cropland. No formal meta-analyses were available for CH_4 from afforested former cropland.

Using the average value for the studies that were reviewed, afforested former croplands are estimated to oxidize on an annual basis 1.92 ± 0.51 kg CH_4 per hectare (1.71 ± 0.46 lbs. CH_4 per acre per year). Applying this to 100,000 acres, only a small amount of additional CH_4 would be oxidized by converting cropland to trees, on an annual basis an estimated 73 CO_2-equivalent short tons or some three tons of CH_4 (see Table 15). The effects of this on the larger emissions-avoidance budget for afforestation on former cropland are negligible.

The descriptive statistics for the various studies that were reviewed are shown in Table 18. Annual emission rates for afforested and forest soils range from 1.33 to 3.06 kg CH_4 per hectare (1.19 to 2.73 lbs. CH_4 per acre per year). In 90 percent of all observations, upland forested soils oxidize CH_4. The derivative statistical summaries reported generally higher rates of oxidation than the mean value taken from all observations, the empirical sites studies slightly lower values. Studies reporting on CH_4 oxidation in existing forest soils tended to report higher values than afforested soils, but not excessively so.

Table 18. Descriptive statistics: Land retirement/Long-term idling - Afforestation, CH_4

	soil CH_4 oxidation (kg CH_4/ hectare/yr) [a]	number of study results [b,c]	ratio of positive-to-negative results: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	1.92	36	32/4	0.51	0.91	2.92
empirical site studies	1.56	24	20/4	0.71	0.17	2.95
modeling studies	2.20	6	6/0	0.81	0.61	3.79
derivative statistical analyses or statistical summaries [d]	3.06	6	6/0	0.81	1.47	4.64
afforestation	1.62	17	16/1	0.50	0.64	2.61
existing forestland	2.18	19	16/3	0.87	0.48	3.88
annual flux monitoring/modeling	2.06	29	26/3	0.59	0.89	3.22
growing season and subgrowing season flux monitoring/modeling	1.33	7	6/1	0.98	(0.59)	3.24
1 year of observations or simulations	2.16	4	4/0	0.64	0.92	3.41
more than 1 year of observations or simulations	1.53	21	18/3	0.80	(0.05)	3.11
afforestation against cropland or pastureland counterfactual	2.87	10	10/0	1.19	0.53	5.21

[a] CH_4 soil oxidation = removal from atmosphere and destruction in soils

[b] 36 study results, 35 studies (6 statistical summaries or derivative statistical analyses, 6 modeling studies, 23 empirical site studies)

[c] 1 study reports multiple results by forest status (existing vs afforested)

[d] statistical summaries or analyses other than meta-analyses

Relatively wide confidence intervals were calculated for each grouping of data by study type or by years of total observations.

Finally, studies that report on the difference in CH_4 oxidation in cropland soils and soils planted to trees indicate a net change in CH_4 oxidation with cropland afforestation of (+) 2.87 kg CH_4 per hectare per year (2.56 lbs. CH_4 per acre per year). This is substantially higher than the 0.07 kg CH_4 per hectare (0.06 lbs. CH_4 per acre per year) additional CH_4 oxidation given in this review.[10]

C. Shelterbelts and hedgerows

Shelterbelts and hedgerows are installed at field edges or around farmsteads to protect soils from crosswinds and, on cropland, wind-driven erosion. In Minnesota, white spruce and poplar are popular tree species for use in shelterbelts or windbreaks. Hedgerow species are shorter-lived and of smaller stature. We estimate that, for each 100,000 acres of cropland retired to shelterbelts or hedgerows, 298,000 CO_2-equivalent short tons of emissions would be avoided. Of this, about two-thirds, results from CO_2 that, during plant growth, is removed from the atmosphere and is photosynthetically incorporated into live biomass and, with time, into standing and down dead tree detritus, the forest floor and soils. Of the remainder, about one-sixth, are avoided direct emissions of N_2O from cropland soils. More than 90 percent of all emissions-avoided through the establishment of shelterbelts and hedges would be avoided in state, with the remainder avoided out-of-state from avoided agricultural fertilizer, chemicals and fuels production. Estimated average annual GHG emissions-avoidance from shelterbelts and hedgerows is shown in Table 19 by source.

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[10] Estimated oxidation in afforested soils (see Table 18) minus oxidation in cropland soils, from Aronson and Heliker (2010): 1.92 kg CH_4/ha/yr – 1.85 kg CH_4/ha/yr

In the preceding section on upland afforestation, the biological and biochemical processes involved in woodland sequestration of biogenic carbon in plant biomass, woody detritus and soils were reviewed, as were the microbial processes involved in the soil production and emission of N_2O and uptake and oxidation of CH_4. (See Section IV, Subsection B) Since the same processes discussed earlier for general upland afforestation of former cropland are operative in recently established shelterbelts and hedges, this discussion will not be repeated. It simply might be noted that, due to the linear array of shelterbelts and hedges, trees in these plantings face fewer competitive pressures than trees in a closed forest. As a result, they may accumulate carbon more rapidly. Shelterbelts and hedges are open on two sides to sunlight and, bordering on fertilized farm fields, are less likely to be nutrient-limited than trees in a closed forest. (Amichev *et al*., 2017)

It also might be noted that shelterbelts in particular are designed to intercept windblown sediment, which is then preferentially deposited in shelterbelt soils, where in stabilized forms it is stored. (Sauer *et al*., 2007) Due to physical disruption and deposition on warm, dry soil surfaces, the organic carbon in wind-blown soils is subject to oxidation.

Due to dense rooting in shelterbelts and hedges, uptake and immobilization of nitrogen in plant biomass and shelterbelt soils also may lead to the production of less N_2O *in situ* in soils and reduced N_2O emission to the atmosphere. (Amadi *et al*., 2017)

In developing the emission-avoided estimates shown in Table 19, a 20-year timespan for continuous biogenic carbon storage was employed. As in the case of other conservation practices that we review in this report, in our judgment, this is the longest period over which continuous storage safely can be assumed for purposes of calculating the more certain effects today of shelterbelt or hedgerow establishment. Under this assumption, avoided-emissions are an estimated 298,000 CO_2-equivalent short tons. Had a 40-year period of assured storage been assumed, avoided-emissions from shelterbelt establishment would have been greater, totaling 503,000 CO_2-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 1,118,000 CO_2-equivalent short tons (see Table 19). The approach that we use in converting observed rates of sequestration to avoided-emissions was addressed above in the Methodology section (Section II).

The estimated average annual rate of carbon sequestration associated with cropland retirement to shelterbelts or hedges is discussed below, as are direct emissions of N_2O that are avoided by cropland conversion and generally enhanced rates of CH_4 oxidation in afforested soils. The methods and sources used to estimate avoided indirect N_2O emissions from nitrate leaching and ammonia volatilization, avoided-emissions from fuel use, and avoided-emissions from foregone agricultural chemicals and fuels manufacture were discussed in the Methodology section of this report, Section II, Subsection E above.

Table 19. Shelterbelts and hedgerows: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(47,288)	crop production
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	(2,148)	crop production
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(14,020)	crop production
CH_4 [b]	soils	(73)	crop production
CO_2 [c,d]	carbon accumulation in soils and biomass	(205,007)	crop production
CO_2	cultivated soils from lime or urea use	(2,808)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	(6,849)	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(20,184)	crop production
Total		**(298,377)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass			
40 year storage	all sources and sinks	**(503,384)**	crop production
100 year storage	all sources and sinks	**(1,118,404)**	crop production

[a] positive = emissions increase, negative = emissions reduction

[b] increase in soil CH_4 oxidation = relative decrease in emissions

[c] carbon accumulation in soil and biomass = net removal of CO_2 from the atmosphere = net emission reduction

[d] assumes 20 years of sustained storage of newly sequestered organic carbon in soils and biomass

a. Carbon sequestration in soils and biomass

As discussed elsewhere, during forest growth, CO_2 is removed from the atmosphere and incorporated into live tree biomass and, eventually, woody detritus, litter and forest soils. This offsets CO_2 emissions from fossil fuel use. Again, as discussed earlier, one ton of biogenic carbon removed from the atmosphere and incorporated into plant biomass and soils acts to offset about 0.4 tons of carbon emitted to the atmosphere from fossil sources. This assumes a 20-year lifetime of that carbon in terrestrial carbon pools before reemission, the longest period that, in our estimation, safely can be assumed in calculating the offset value of present-day sequestration. In this regard, total sequestration is estimated for 100,000 acres of land retired to shelterbelts and hedges using an average per acre sequestration rate truncated to accommodate an assumed 20-year lifetime of carbon in terrestrial carbon pools before reemission to the atmosphere.

Since most of the science on terrestrial carbon sequestration is developed in metric units, this average rate is given in metric tons per hectare per year and then converted to CO_2-equivalent short tons per acre per year for summary Table 19.

From Table 19, with 100,000 acres of shelterbelts and hedges, roughly 205,000 CO_2-equivalent short tons of emissions would be offset annually through the removal of CO_2 from the atmosphere and its sequestration in plant biomass and soils, or 2.05 CO_2-equivalent short tons per acre per year.

In newly established shelterbelts and hedges, as generally in recently established upland forests, a substantial part of sequestered carbon is stored in aboveground biomass, roots and woody detritus. (Amichev *et al*., 2016; Udawatta and Jose, 2011) Because of this, carbon sequestration on forestland is best estimated as the change in total ecosystem carbon, which for shelterbelts and hedges is estimated at an annual rate of 3.26 ± 0.7 metric tons of carbon per hectare (1.45 ± 0.31 short tons of carbon per acre).[11] This estimate was developed from 14 studies that provide information on total ecosystem carbon storage in shelterbelts and hedges. (See Table 20 below) Studies that address only changes in soil carbon report rates of annual sequestration that are less than a one-sixth of this total ecosystem rate.

In general, relatively few studies can be found in the scientific literature that address carbon sequestration in recently established and growing shelterbelts and hedges, which limits, to a degree, the strength of the quantitative conclusions that might be drawn from a review of the published literature. We reviewed 34 studies. Of these, 14 were total ecosystem studies. Of the total ecosystem studies, four were modeling studies, four were site studies that employed soil sampling and a mix of different means to estimate aboveground carbon storage in shelterbelts and hedges, and four were literature reviews or studies that report results developed using expert judgment. One further study was a mixed meta-analysis/other derivative statistical analysis. No pure meta-analysis was available of the results of the published total ecosystem studies.

In the majority of studies that involved literature review or rely on expert judgment, the analysis of biogenic carbon sequestration was confined to shelterbelt soils. As a consequence, the results from these types of studies were generally of limited use in establishing a representative sequestration rate for shelterbelts and hedges. The same is true of the larger class of modeling and empirical site studies.

Of the 34 studies that were reviewed, all reported net sequestration following shelterbelt establishment. While somewhat expansive, the calculated confidence intervals were positive and, in the case of the total ecosystem studies, robustly so. As in the case of upland afforestation, the evidence overwhelmingly supports a positive sequestration response rate, with best estimates for annual sequestration somewhat larger than those for upland afforestation.

The descriptive statistics for the studies that were reviewed are shown in Table 20.

b. Nitrous oxide

N_2O is produced microbially in the soils of shelterbelts and hedges, albeit at rates lower than are observed in the soils of fertilized cropland. Avoided nitrous oxide emissions from the establishment of shelterbelts and hedges are calculated as the difference on 100,000 acres between emissions estimated for forestland converted from cropland and average Minnesota cropland N_2O emissions, as taken from the MPCA Greenhouse Gas Emission Inventory. Emissions from forestland converted from cropland are estimated on a per hectare basis (kilograms of N_2O per hectare), and then converted to a per acre basis (lbs. N_2O per acre) for the calculation of emissions on 100,000 acres.

There exist relatively few published estimates of N_2O fluxes from shelterbelts and hedges. *In lieu* of N_2O emission estimates specific to shelterbelts and hedges, in calculating avoided-N_2O emissions, we use the average emission rate for upland afforestation of former cropland, which is discussed above in Section IV, Subsection B.b. Afforested former croplands are estimated annually to emit 1.25 kg N_2O per hectare (1.12 lbs. N_2O per acre). Estimated average annual cropland emissions of nitrous oxide are 4.8 kg N_2O per hectare (4.3 lbs. N_2O per acre) or roughly four-fold higher.

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[11] Prior to truncation, to accommodate an assumed 20-year persistence of organic carbon stored in shelterbelt and hedgerow live biomass, soils and woody detritus.

Table 20. Descriptive statistics: Shelterbelts and hedgerows - carbon sequestration in soils and biomass

	biogenic carbon sequestration (Mg C/ha/yr)	number of study results [a]	ratio of sequestration to emission: number of studies [b]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
total ecosystem carbon (soil organic carbon, above and belowground biomass)	3.26	14	14/0	0.70	1.89	4.63
above and belowground live biomass	1.70	4	4/0	0.34	1.03	2.36
soil organic carbon-only	0.52	9	9/0	0.24	0.05	0.99
empirical site studies [c]	1.85	12	12/0	0.77	0.35	3.35
modeling studies [c]	2.95	6	6/0	0.97	1.05	4.84
meta-analyses and derivative statistical analyses or summaries [c,d]	2.23	4	4/0	0.99	0.28	4.17
literature reviews/expert judgment [c]	1.00	12	12/0	0.36	0.29	1.71
15 to 25 year annual sequestration rate	1.58	16	16/0	0.37	0.86	2.30
less than 15 year annual sequestration rate	4.96	2	2/0	4.68	(4.22)	14.14
25 year-plus annual sequestration rate	1.41	8	8/0	0.32	0.77	2.04

[a] 34 study results, 34 studies (4 meta-analyses or statistical summaries or derivative statistical analyses, 6 modeling studies, 12 empirical site studies, 12 literature reviews)

[b] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[c] across carbon pools, e.g., total ecosystem studies, soil organic carbon studies-only, studies of live biomass only

[d] statistical summaries or derivative statistical analyses other than meta-analyses

Six studies of N_2O emissions from shelterbelts and hedges were identified in the scientific literature. The mean rate of emission for these six studies was some 0.81 kg N_2O per hectare per year, which is not too different from the average value calculated for upland afforested former croplands. The descriptive statistics for these six studies of N_2O emissions from shelterbelts and hedges are shown below in Table 21.

Table 21. Descriptive statistics: Shelterbelts and hedgerows - N_2O

	emissions (kg N_2O/ hectare/yr) [a]	number of study results [b,c]	ratio, positive-to-negative results: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	0.81	6	6/0	0.56	(0.29)	1.92
empirical site studies	0.94	5	5/0	0.67	(0.38)	2.26
modeling studies	0.18	1	1/0	NA	NA	NA
shelterbelts	0.30	5	5/0	0.10	0.11	0.50
hedgerows	3.61	2	2/0	NA	NA	NA
					-	-
studies with cropland counterfactuals	(1.03)	3	2/0/1	0.68	(2.37)	0.31

[a] negative emissions = removal from atmosphere and destruction in soils

[b] 6 study results, 6 studies (5 empirical site studies, 1 modeling/empirical site study)

c. Methane

Methane is oxidized in both cropland and forested soils. The change in the rate of CH_4 oxidation in soils from establishing shelterbelts and hedges is calculated as the difference in the rate of soil CH_4 oxidation in cropped soils, as taken from Aronson and Helliker (2010), and estimated annual oxidation in shelterbelts and hedges. Relatively few published estimates of CH_4 oxidation rates for soils of shelterbelts and hedges can be found in the literature; we were able to identify six studies. *In lieu* of an adequate set of estimates for soil CH_4 oxidation rates specific to shelterbelts and hedges, in estimating the change in CH_4 uptake resulting from shelterbelts establishment we use the mean rate of CH_4 oxidation for soils afforested former cropland (see Section IV, Subsection B.c above).

In Table 22, we show the descriptive statistics for the six studies that do provide information on mean annual CH_4 oxidation in shelterbelt soils. These are given in metric units, following general scientific conventions. The mean for these studies is lower than was reported in Table 18 for afforested formerly cultivated soils. It is not known whether the difference in the estimates reflects a real difference in soil CH_4 uptake between shelterbelt soils and soils of upland afforested former cropland.

As noted in discussing afforestation on idled cropland, the contribution of changes in soil CH_4 oxidation from land-use change to overall GHG-avoidance is small.

Table 22. Descriptive statistics: Shelterbelts and hedgerows - CH_4

	soil CH_4 oxidation (kg CH_4/ hectare/ yr) [a]	number of study results [b,c]	ratio, positive-to-negative results: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	0.89	6	6/0	0.23	0.45	1.34
empirical site studies	1.00	5	5/0	0.24	0.52	1.48
modeling studies	0.35	1	1/0	NA	NA	NA
shelterbelts	0.66	6	6/0	0.34	0.00	1.32
hedgerows	0.50	2	2/0	NA	NA	NA
studies with cropland counterfactuals	0.92	1	1/0	NA	NA	NA

[a] CH_4 soil oxidation = removal from atmosphere and destruction in soils

[b] 6 study results, 6 studies (5 empirical site studies, 1 modeling/empirical site study)

D. Field borders, contour buffer strips, vegetative barriers, herbaceous wind barriers

Field borders are strips of permanent vegetation at fields edges placed there to intercept nutrients and sediments leaving the field and to reduce soil and wind erosion. Contour buffer strips and vegetative barriers are intra-field strips of permanent vegetation that follow the contour of the land, particularly the contour of sloping hills. They are designed to trap sediment and reduce erosion. Contour buffer strips often are alternated with strips of annual row crops. Herbaceous wind barriers are narrow strips of perennial or annual grasses placed across the path of prevailing winds and designed to reduce wind erosion of soils. Generally planted in deep-rooted perennial grasses, these field borders, strips and herbaceous barriers act similarly to grassland retirements to sequester organic carbon in soils. Emissions of N_2O generally are lower in these unfertilized, mostly perennial plantings, though only a few studies exist to verify this understanding.

Field studies of biogenic carbon sequestration in field borders, as well as in contour buffer strips and vegetative and herbaceous wind barriers, are relatively few. The same is true for field studies of N_2O emission from and CH_4 uptake and *in situ* oxidation in soils under these practices. It is conventional to apply to these practices rates of carbon sequestration taken from studies of restored grassland. The same is true for N_2O emission and CH_4 emission and uptake rates. (Swan *et al*., 2015; Eagle *et al*., 2012) We follow this practice.

Table 23 shows the budget for greenhouse gas-avoidance for field borders, contour buffer strips and vegetative and herbaceous wind barriers. In developing this budget, it was assumed that these grass areas would be mowed at least once per year, so that avoided-emissions are slightly different from those for cropland temporarily retired to grass (see Table 10 above). Using this approach, we estimate that, for each 100,000 acres of cropland converted to contour buffer strips, field borders, and vegetative and herbaceous wind barriers, 158,000 CO_2-equivalent short tons of greenhouse gases that otherwise would have occurred would be avoided. Of this, a little less than 90 percent of total GHG-avoidance would be from in-state sources.

Table 23. Field borders, contour buffer strips, vegetative barriers, herbaceous wind barriers: Emissions- avoided[a]

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(42,756)	crop production
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	(2,107)	crop production
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(11,703)	crop production
CH_4 [b]	soils	520	crop production
CO_2 [c,d]	carbon accumulation in soils	(73,297)	crop production
CO_2	cultivated soils from lime or urea use	(2,808)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	(5,475)	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(20,184)	crop production
Total		**(157,810)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass			
40 year storage	all sources and sinks	**(231,107)**	crop production
100 year storage	all sources and sinks	**(450,998)**	crop production

[a] positive = emissions increase, negative = emissions reduction

[b] reduction in soil CH_4 oxidation = relative increase in emissions

[c] carbon accumulation in soil and biomass = net removal of CO_2 from the atmosphere = net emission reduction

[d] assumes 20 years of sustained storage of newly sequestered organic carbon in soils and biomass

About half of the calculated emission-avoidance potential results from biogenic carbon sequestration, mostly in grassland soils, but also in live roots and aboveground biomass. A value of 0.52 short tons of carbon per acre per year (1.17 metric tons of carbon per hectare per year) was used to calculate emissions-avoidance from soil carbon sequestration, taken from Table 12 above. The relatively few studies that are specific to the practices discussed in this section report annual sequestration values ranging from 0.06 to 0.98 short tons of carbon per acre (0.13 to 2.19 metric tons per hectare), with a mean value of 0.44 short tons of carbon per acre (0.99 metric tons per hectare), or not too different from the 0.52 short ton per acre value cited above. (Blanco-Canqui *et al.*, 2014; Brouchard *et al.*, 2013; Fallon *et al.*, 2004; Lenka *et al.*, 2012; Perez-Suarez *et al.*, 2014; Swan *et al.*, 2015)

Iqbal *et al.* (2014) report annual N_2O flux rates from N_2O production in upland grass filter strips of 0.89 lbs. N_2O per acre (1 kg N_2O per hectare), which is not too different from the 1.42 lbs. N_2O per acre per year (1.59 kg N_2O per hectare per year) value used in Table 23 to calculate avoided N_2O emissions from field borders, contour buffer strips, and vegetative and herbaceous wind barriers.

No similar estimates specific to field borders or intra-field buffers or barriers were available for soil CH_4 uptake and oxidation for use in evaluating our treatment of soil CH_4 oxidation in field borders and similar grass plantings.

E. Grassland riparian buffers

Riparian buffers are vegetative buffers placed along surface waters that are designed to intercept nutrient run-off from cropland and pastureland. Riparian buffers are lands adjacent to streams, rivers and lakes that are in trees or perennial grasses, or a combination. Due to placement between surface waters and fertilized cropland (or fertilized or grazed pastureland), the soils in riparian buffers are typically wetter and more susceptible to N_2O losses than are upland soils. Whereas upland soils generally act to oxidize CH_4, riparian buffer soils often act as net sources of emission of CH_4 to the atmosphere, although field observations of CH_4 emissions from or uptake and oxidation in riparian buffer soils are limited in number.

In Minnesota, as of 2014, there were an estimated 475,000 acres of land in riparian buffers, most of it in grassland-type riparian buffers. Under the state's Nutrient Reduction Strategy, roughly 100,000 additional acres of land will be retired to riparian buffers.

Table 24 shows the estimated net annual greenhouse gas balance from the conversion of cropland to riparian grassland or herbaceous riparian buffers. We estimate that, for each 100,000 acres of cropland retired to grassland buffer, 77,000 CO_2-equivalent short tons of GHGs would be avoided annually, or less than half of what is estimated above for upland soils temporarily idled in grass (see Section IV, Subsection A).

Of total estimated emissions-avoidance from converting cropland to grassland-type riparian buffers, about 75 percent is from in-state sources and about 25 percent from the avoided out-of-state manufacture of agricultural chemicals, fertilizer and fuels resulting from cropland retirement. In state, net emissions of CH_4 from generally wetter riparian soils offset reductions in the emission of N_2O from these soils. The average acre of cropland in Minnesota is heavily fertilized with synthetic and manure-based nitrogen. Emissions of N_2O to the atmosphere result from the application of nitrogen to soils, as well as from enhanced mineralization of organic nitrogen in soils during tillage and the addition to soils of large amounts of crop residues, particularly those high in nitrogen content. Some emissions of N_2O occur downstream of crop production in river, stream and lake sediments as a result of runoff and leaching of nitrate and nitrogen in other forms to surface and groundwater.

Estimated atmospheric removals of CO_2 through biogenic carbon sequestration on 100,000 acres of riparian soils are about 49,000 tons, accounting for two-thirds of all estimated avoided-emissions, both in-state and out-of-state, from use of this practice on 100,000 acres.

In developing the estimates shown in Table 24, it was assumed that 20 years was the longest period of time over which sustained terrestrial carbon storage, once initiated, safely could be assumed. Under this assumption, avoided-emissions are an estimated 77,000 CO_2-equivalent short tons. Had a 40-year period of assured storage been assumed, avoided-emissions from the establishment of grassland riparian buffers would have been greater, totaling 126,000 CO_2-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 273,000 CO_2-equivalent short tons (see Table 24). The approach that we use in converting observed rates of sequestration to avoided-emissions was addressed above in the Methodology section (Section II) of this report.

Table 24. Grassland riparian buffers: Emissions-avoided[a]

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(9,405)	crop production
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	(2,107)	crop production
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(13,653)	crop production
CH_4	soils	27,176	crop production
CO_2 [b,c]	carbon accumulation in soils and biomass	(49,042)	crop production
CO_2	cultivated soils from lime or urea use	(2,808)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	(6,849)	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(20,184)	crop production
Total		**(76,872)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass			
40 year storage	all sources and sinks	**(125,915)**	crop production
100 year storage	all sources and sinks	**(273,042)**	crop production

[a] positive = emissions increase, negative = emissions reduction

[b] carbon accumulation in soil and biomass = net removal of CO_2 from the atmosphere = net emission reduction

[c] assumes 20 years of sustained storage of newly sequestered organic carbon in soils and biomass

A number of estimates have been published of the net change in total greenhouse gas emissions resulting from the conversion of cropland to grassland riparian buffers. These include estimates by Eagle *et al*. (2012) and Swan *et al*. (2015), which report avoided-emissions for cropland conversion to riparian buffers of 1.59 and 1.39 CO_2-equivalent short tons per acre per year, respectively, or 159,000 and 139,000 CO_2-equivalent short tons per year on 100,000 acres. These estimates are generally similar to, if smaller than, the estimates given in Table 24 above.

Biogenic carbon sequestration riparian grassland buffers is discussed below, as are avoided direct emissions of N_2O from the idling of cropland in riparian grassland buffers and the effects of buffer establishment on soil CH_4 oxidation or emission. The methods and sources used to estimate avoided indirect N_2O emissions from nitrate leaching and ammonia volatilization, avoided-emissions from fuel use, and avoided-emissions from foregone agricultural chemicals and fuels manufacture were discussed above in the Methodology section of this report, Section II, Subsection E.

a. Carbon sequestration in soils and biomass

Cropland tillage acts to disrupt soil structure, leading to rapid decomposition of soil organic matter. In uncultivated soil, organic carbon in soil is physically and chemically protected from microbial decomposition by soil macroaggregates, mostly in soil pores too minute for bacteria and fungi (or water soluble enzymes) to penetrate or too anaerobic for aerobic soil bacteria. (Jones and Donnelly, 2004) Soil carbon also is chemically protected by clay and silt particles, which bind to soil organic matter and, in the very long-term, by various metals and mineral anions and cations which biochemically bind to organic matter to form complexes that are highly recalcitrant and persist in soils for hundreds to thousands of years. (Follett *et al*., 2001; Nair *et al*., 2010)

Cropland cultivation disrupts soil structure, breaking up protective soil macroaggregates and exposing soil organic carbon (SOC) to microbial decomposition, in upland soils as well as cropland in the riparian zone. (Marquez *et al.*, 2017; Six *et al*., 2002a) Cropland idling in riparian grassland buffers reverses the processes of soil degradation, building carbon in grassland soils through renewed physical and biochemical protection of soil organic matter, as well as enhanced allocation of carbon to plant roots in unmanaged grassland buffers. (Bell *et al.,* 2012) Plant rooting depth also is important. (Knops and Bradley, 2009)

Of particular note in riparian grassland buffers is absence of harvest removals (Omonode and Vyn, 2006; Vuichard *et al*., 2008), which on cropland limit organic carbon inputs to soils. The amount of carbon in soils is determined by carbon inputs and the degree to which organic carbon in soils is protected from microbial decomposition. On croplands planted to annuals, harvest removals account for between 40 and 45 percent of cropland net primary productivity. (West *et al*., 2011) Little of this is available as input to soils. By contrast, perennial grasses allocate about two-thirds of net primary productivity belowground to root growth and rhizomes, where it is then available for storage as soil organic carbon.

The soils of riparian grassland buffers are generally wetter than upland cropped soils and subject to elevated water tables and periodic inundation. In general, wet, fine textured soils with high clay contents store more carbon than do coarse, dry soils, particularly where cool climate conditions prevail. By limiting aeration, wetness inhibits microbial decomposition of soil organic matter in soils, as do cool temperatures.

The amount of soil organic carbon that, on average, is stored in riparian grassland buffers is about twice that of adjacent croplands. (Marquez *et al*., 1999; Rheinhart *et al*., 2012)

In addition to the sequestration of carbon in soils, carbon also is stored in aboveground and belowground live and dead biomass. Unlike biomass storage in cropland annuals, where aboveground biomass is removed at harvest or rapidly decomposes, biomass storage in unmanaged grassland is retained belowground after the growing season as live roots or aboveground in the form of litter and plant detritus. On an annual basis, carbon storage in riparian grassland buffers in live and dead aboveground and belowground biomass and litter is about 2.25 to 5 short tons per acre (5 to 10 metric tons per hectare), while, again on an annualized basis, corn and soybeans might store 0.65 to 0.9 short tons per acre (1.5 to 2 metric tons per hectare) as aboveground and belowground living biomass and dead roots and litter. (Tufekcioglu *et al*., 2003)

During sustained carbon sequestration, ecosystems remove carbon from the atmosphere photosynthetically and store it in plant biomass or, over longer periods, in soils and aboveground litter. From Table 24, we estimate that, on 100,000 acres in perennial grasses, riparian buffers on former cropland will sequester 49,000 short tons of carbon as CO_2 (13,000 short tons of carbon). As noted above, this estimate was developed using an average per acre sequestration rate truncated to accommodate an assumed 20-year lifetime of carbon in terrestrial carbon pools before reemission to the atmosphere. Since most of the science on terrestrial carbon sequestration is developed in metric units, this average annual rate is given in metric tons per hectare and then converted to CO_2-equivalent short tons per acre for summary Table 24.

In developing our estimate of annual sequestration in riparian grassland buffers, we reviewed fifteen studies, including one micro-meteorological (eddy covariance) site study, five other empirical site studies, one derivative statistical study and eight literature reviews or studies that report results developed using expert judgment (see Table 25). Ten of the studies gave sequestration estimates limited to losses or gains in soil organic carbon; three addressed sequestration at the ecosystem level, including aboveground and belowground biomass and soil organic carbon. No meta-analyses were available to support the calculation. Given the limited number of published studies, we averaged across the results from all of the available 15 studies to derive an estimate of annual carbon sequestration from riparian grassland buffers.

Table 25. Descriptive statistics: Grassland riparian buffers - carbon sequestration in soils and biomass

	biogenic carbon sequestration (Mg C/ha/yr) [a]	number of study results [b]	ratio of sequestration to emission: study numbers [c]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	0.78	15	15/0	0.143	0.50	1.06
total ecosystem carbon (soil organic carbon above and belowground biomass)	0.53	3	3/0	0.052	0.43	0.63
above and belowground biomass, litter, detritus	1.31	2	2/0	0.931	(0.52)	3.13
soil organic carbon-only	0.67	10	10/0	0.066	0.54	0.79
derivative statistical analyses or statistical summaries [b]	0.54	1	1/0	NA	NA	NA
literature reviews/expert judgment	0.55	8	8/0	0.042	0.47	0.63
empirical site study-eddy covariance (NECB/NBP)	0.63	1	1/0	NA	NA	NA
empirical site study-destructive biomass sampling	1.73	2	2/0	0.931	(0.09)	3.56
empirical site studies-soil sampling	0.99	2	2/0	0.094	0.81	1.18
average 20 year rate of sequestration	0.56	2	2/0	0.098	0.37	0.76
average 5 to 10 year rate of sequestration	1.16	6	6/0	0.306	0.56	1.76

[a] estimates for empirical site study-SOC soil sampling, soil organic carbon-only, and average 5 to 10 year rate of sequestration developed against a cropland counterfactual

[b] 15 study results, 15 studies (1 statistical summaries or derivative statistical analyses, 1 eddy covariance type empirical site studies, 3 soil sampling-type empirical site studies, 2 other empirical study types, 8 literature reviews)

[c] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[d] statistical summaries or derivative statistical analyses other than meta-analyses

Based on the fifteen studies, the idling of cropland in riparian grassland buffer is estimated to sequester 0.78 metric tons of biogenic carbon per hectare (0.35 short tons of carbon per acre). This is the estimated rate prior to truncation to accommodate 20-year assumed persistence of carbon in buffers vegetation and soils. By study type, annual sequestration rates taken from these 15 studies range from 0.53 to 1.73 metric tons of carbon per hectare (0.24 to 0.77 short tons of carbon per acre). Grouped by study type and carbon pools treated, the estimates scatter widely without readily apparent pattern. For instance, annual rates of carbon sequestration in site studies that report changes in soil carbon are higher than those that report total ecosystem carbon storage, including storage in belowground and aboveground biomass. The same is true for site studies that report on changes solely in live biomass, excluding soils.

In general, the studies were uniform in their judgment that, with riparian buffer establishment, carbon would be sequestered, offsetting fossil CO_2 emissions elsewhere in the economy. More studies may be needed, particularly at the level of total ecosystem carbon, to more firmly establish, within the range noted above, a mean best estimate for carbon sequestration in these systems.

b. Nitrous oxide

Nitrous oxide is produced in riparian buffers that are adjacent to cropland predominantly by denitrification of nitrate (NO_3^-). (Hinslow and Dahlgren, 2016) During denitrification, nitrate is microbially reduced to N_2O or dinitrogen (N_2) under anaerobic conditions. Riparian buffers are much wetter that the soils of upland croplands. Maximum N_2O production in soils occurs around water-filled pore space of 70 to 80 percent, which is also optimal soil wetness for denitrification. (Hefting *et al.*, 2006; Machefert *et al.*, 2002) Nitrate-laden groundwater flows from cropland to riparian grassland buffer soils sustain substantial emissions of N_2O from buffers to the atmosphere. (Schelde *et al.*, 2012)

Riparian grassland buffers are established in agricultural areas specifically to act as sites of intensive denitrification of nitrate in groundwater flows. N_2O production and emissions are the unintended byproduct of that use of riparian buffers for nitrate control.

N_2O production in riparian buffers also is promoted by periodic flooding and or high water tables, both of which contribute to the formation of anaerobic conditions in buffers. (Fisher *et al.*, 2014; Jacinthe *et* *al*., 2012) The availability of large amounts of organic carbon substrate in riparian buffers also promotes N_2O production, as does the presence of fine textured soils.

In general, N_2O emissions from riparian buffers, grassland or forestland, are higher than emissions from upland unmanaged grassland, but lower than N_2O emissions from adjacent cropland. (Ambus and Christensen, 1995; Dunmola *et al*., 2010; Groh *et al*., 2018; Kim *et al*., 2009; Vllain *et al*., 2012) Riparian grassland buffers are largely unmanaged, with little intentional input of synthetic fertilizer or manure and no tillage, resulting in lower N_2O emissions than are found in adjacent croplands.

Avoided-emissions from the conversion of cropland to riparian grassland buffers are calculated as the difference on 100,000 acres between estimated emissions from riparian grassland buffers and average Minnesota cropland N_2O emissions, as taken from the MPCA Greenhouse Gas Inventory. In developing an emissions estimate for riparian grassland buffers, we reviewed 15 studies, 14 of which were empirical sites studies and one a modeling study. An average of the results from the 15 studies was selected as the best available estimate of annual N_2O emissions from riparian grassland buffers.

Using the average of the results from the 15 studies that were reviewed, riparian grassland buffers are estimated to annually emit 4.1 ± 0.88 kg N_2O per hectare (3.66 ± 0.79 lbs. N_2O per acre), or about three times as much as upland restored grassland.

Based on MPCA emission inventory totals, average annual N_2O emissions from Minnesota cropland are an estimated 4.8 kg N_2O per hectare (4.3 lbs. N_2O per acre), or only marginally higher than what is estimated for grassland riparian buffers.

The descriptive statistics for the 15 studies that were reviewed are shown in Table 26. In most of the studies, emissions were monitored on an annual basis, as opposed to a growing season basis. Of the two, emissions monitored on a growing season basis tend to be much higher. Studies that report results for multiple years tend to produce results that are lower than the 4.1 kg N_2O per hectare per year estimate for all 15 studies, but too few studies report multiple year results for much to be concluded here. Seven studies report on the difference in N_2O emissions in paired, side-by-side experiments between riparian grassland buffers and adjacent cropland. In these studies, on an annual basis, riparian grassland buffers emitted 13.92 kg N_2O per hectare (12.42 lbs. N_2O per acre) less than adjacent cropland, which is directionally consistent with our results, if also more extreme in terms of reported reductions. From Table 24, we estimate annual reductions of 0.72 kg N_2O per hectare (0.63 lbs. N_2O per acre).

A good deal more empirical research needs to be developed, particularly directed toward this latter discrepancy. Based on what admittedly is a very small group of studies, it seems possible that N_2O emissions could decline a small amount or a very large amount as a result of the conversion of cropland to riparian buffers

Table 26. Descriptive Statistics: Grassland Riparian Buffers - N_2O

	emissions (kg N_2O/ hectare/yr) [a]	number of study results [b]	ratio, positive to negative results: number of studies	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	4.10	15	15/0	0.88	2.38	5.82
empirical site studies	4.32	14	14/0	0.91	2.53	6.10
modeling studies	2.63	1	1/0	NA	NA	NA
annual flux monitoring/modeling	3.49	11	11/0	0.68	2.17	4.82
growing season and subgrowing season flux monitoring/modeling	7.33	3	3/0	3.33	0.80	13.86
1 year or less of observations or simulations	4.91	10	10/0	1.23	2.50	7.32
> 1 year of observations or simulations	2.43	4	4/0	0.69	1.09	3.77
grassland riparian buffers against counterfactuals cropland	(13.92)	7	3/4	7.41	(28.44)	0.60

[a] negative emissions = removal from atmosphere and destruction in soils

[b] 15 study results, 15 studies (1 modeling study, 14 empirical site studies)

c. Methane

As just discussed, the soils in riparian buffers tend to be much wetter than those of upland cropland, in part due to periodic high water levels and flooding, in part due to shading and high levels of soil organic matter. (Kim *et al*., 2010) Anaerobic conditions in wet soils promote the production of CH_4 and its emission to the atmosphere. Methane is produced microbially in soils under anaerobic or anoxic conditions by methanogenic bacteria. Across the course of a year, riparian buffers experience wet and dry conditions, During dry seasons, CH_4 is taken up by soils and oxidized by methanotrophic bacteria and, as just noted, under near-saturated conditions, CH_4 is produced by methanogenic bacteria. On an annual basis, the balance between these processes of methane consumption (methanotrophy) and CH_4 production (methanogenesis) determines whether a riparian buffer is a net source or net sink of CH_4. (Jacinthe and Vidon, 2017)

In this report, net CH_4 emissions to or removals from the atmosphere from the conversion of cropland to grassland riparian buffers are calculated as the difference across 100,000 acres in CH_4 uptake and oxidation in temperate croplands, developed from the average rates of cropland CH_4 oxidation given in Aronson and Helliker (2010), and estimated emissions from grassland riparian buffers.

In developing a CH_4 emissions estimate for grassland riparian buffers, we reviewed eleven studies, all empirical site studies. No results from any other study type was available in the published literature. Of the eleven studies, nine reported CH_4 emissions from riparian buffers, while two reported net CH_4 uptake. The mean value for CH_4 emission for these eleven studies was 22.52 kg CH_4 per hectare per year (20.09 lbs. CH_4 per acre per year).

Care should be taken with this mean CH_4 emissions estimate for grassland riparian buffers. Studies that report emissions estimates developed on an annual basis, as opposed to a growing season basis, also report substantially lower rates of CH_4 production than would be indicated by the mean of the results of the eleven studies reviewed, although with only six studies reporting annual flux data, it is not clear what conclusions to draw from this (see Table 27). Many more empirical site studies may be needed for a better sense of the size of net CH_4 emissions from riparian grassland buffers.

Table 27. Descriptive statistics: Grassland riparian buffers - CH_4

	emissions (kg CH_4/ hectare/yr) [a]	number of study results [b]	ratio, positive to negative results: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	22.52	11	9/2	12.36	(1.71)	46.75
empirical site studies	22.52	11	9/2	12.36	(1.71)	46.75
annual flux monitoring/modeling	3.24	6	4/2	2.24	(1.15)	7.64
growing season and subgrowing season flux monitoring/modeling	45.35	5	4/1	24.38	(2.43)	93.13
1 year of observations or simulations	21.53	7	6/1	16.41	(10.63)	53.68
> 1 year of observations or simulations	17.54	5	3/2	17.62	(16.99)	52.07

[a] negative emissions = removal from atmosphere and destruction in soils

[b] 11 study results, 11 studies (11 empirical site studies)

F. Forested and multispecies riparian buffers

Due to the large amounts of carbon that might be stored in living and dead biomass on afforestation lands, forested and multispecies riparian buffers are generally more effective in mitigating GHG emissions from agricultural sources than grassland riparian buffers. Multispecies buffers are a mixture of grassland species, medium-stature shrubs, and trees arranged by stature and placed adjacent to surface waters. For each 100,000 acres of cropland converted to forested or multi-species riparian buffers, an estimated 221,000 CO_2-equivalent short tons of emissions that would otherwise have occurred would be avoided (see Table 28 below). For croplands converted to forested buffers, this is almost three times what would be avoided through the establishment of grassland-type riparian buffers, but only 85 percent that of upland afforested lands.

Forested and multispecies riparian buffers are emission sources of both CH_4 and N_2O, although in the case of N_2O, just barely. Large net emissions of CH_4 from forested and multi-species riparian buffers account for the large advantage of upland afforestation over afforestation in the riparian zone, although, as we will discuss in the subsection on CH_4, the number of studies that address CH_4 emissions from forested buffers is limited. In upland forested acres, soils act to oxidize atmospheric CH_4, thereby offsetting a small part of surface emissions of other GHGs. In much wetter, occasionally inundated riparian soils, anoxic conditions favor the production of CH_4.

As noted above in Section IV, Subsection E.b, the large amounts of nutrients that, by design, are intercepted in buffers sustain high levels of N_2O production in riparian soils. Soil wetness also contributes to relatively high rates of N_2O emission from these soils.

Avoided-emissions from forested and multispecies buffers on former cropland are shown in Table 28 by source of emission-avoidance. Most avoided-emissions from the retirement of cropland to forested riparian buffers or multispecies buffers would occur in state, about 90 percent. The rest are associated with the out-of-state avoided manufacture of fertilizer, fuel and agricultural chemicals no longer used in crop production.

Table 28. Forested and multispecies riparian buffers: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	5,208	crop production
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	(2,148)	crop production
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(13,653)	crop production
CH_4	soils	33,466	crop production
CO_2 [b,c]	carbon accumulation in soils and biomass	(213,560)	crop production
CO_2	cultivated soils from lime or urea use	(2,808)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	(6,849)	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(20,184)	crop production
Total		**(220,528)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass			
40 year storage	all sources and sinks	**(434,088)**	crop production
100 year storage	all sources and sinks	**(1,074,768)**	crop production

[a] positive = emissions increase, negative = emissions reduction

[b] carbon accumulation in soil and biomass = net removal of CO_2 from the atmosphere = net emission reduction

[c] assumes 20 years of sustained storage of newly sequestered organic carbon in soils and biomass

Biogenic carbon sequestration from forested buffer establishment on idled soils is discussed immediately below. Avoided direct emissions of N_2O from soils and the effects of forested riparian buffer creation on soil CH_4 oxidation are discussed in the subsequent two subsections. The methods and sources used to estimate avoided indirect N_2O emissions from nitrate leaching and ammonia volatilization, avoided-emissions from fuel use, and avoided-emissions from foregone agricultural chemicals and fuels manufacture were discussed in the Methodology section (Section II) of this report.

In quantifying avoided-emissions, we assumed a 20-year timespan for carbon storage prior to its reemission to the atmosphere as CO_2. As noted elsewhere in this report, this is the longest period that, in our judgment, sustained terrestrial carbon storage, once initiated, can be assumed in estimating its value as a GHG offset. Under this assumption, avoided-emissions are an estimated 221,000 CO_2equivalent short tons. Had a 40-year period of assured storage been assumed, avoided-emissions from the establishment of forested riparian buffers would have been greater, totaling 443,000 CO_2-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 1,075,000 CO_2-equivalent short tons (see Table 28). The approach that we use in converting observed rate of sequestration to avoided-emissions was addressed above in the Methodology section of this report, Section II, Subsection E.

a. Carbon sequestration in soils and biomass

Owing to continuous water and nutrient supplies, temperate riparian forests are highly productive, storing large amounts of carbon. At maturity an estimated 89 to 172 short tons of carbon is stored per acre (200 to 385 metric tons of carbon per hectare) in riparian forest buffers. (Sutfin *et al.*, 2016) Of this, half to three-quarters is in the form of live biomass and woody detritus and litter, the remainder in the form of soil organic carbon (SOC). In mineral cropland soil, total ecosystem carbon, down to 39 inches (100 centimeters) of soil depth, is rarely more than 45 short tons per acre (100 metric tons per hectare), and often less. Meta-analysis of riparian forests suggest that, on a per acre basis, in wet temperate climates, forests in the riparian zone will accumulate about 89 short tons of carbon beyond what is typically stored on croplands. (Dybala *et al*., 2018)

Besides reduced water deficits and optimal phosphorus and nitrogen supply, factors that contribute to carbon sequestration in forested and multi-species riparian buffers include: enhanced physical and chemical protection of carbon in soils after the cessation of tillage; soil wetness, which slows decomposition of soil organic matter; and imports into the riparian zone of carbon rich sediments and woody debris. (Riegler *et al*., 2017) To the degree that sediments accumulate in a tillage-free environment, sediments imported into the riparian zone contribute to soil carbon sequestration. The absence of tillage acts to stabilize organic carbon in soil macroaggegates and microaggregates and in mineral-organic complexes, leading to the long-term accumulation of organic carbon in soils.

Riparian forest and multi-species buffers can be planted to fast growing hybrid poplars with a 20-year rotation, followed by harvest and replanting. Over 20 years of growth, hybrid poplars in the riparian zone can store 15 to 45 short tons of carbon per acre (33 to 100 metric tons of carbon) in aboveground and belowground biomass, or at annual rates of 0.76 to 2.5 short tons of carbon per acre (1.7 to 5.5 metric tons of carbon per hectare). (Fortier *et al*., 2015)

From Table 28, we estimate that, on 100,000 afforested acres, riparian buffers on former cropland will sequester 214,000 short tons of carbon as CO_2, or 58,000 short tons of carbon. This estimate was developed using an average rate of sequestration per acre, discounted to account for an assumed 20-year persistence of newly stored organic carbon in soils and biomass. This is the longest period of time that, in our estimation, safely can be assumed in calculating the offset value of present-day sequestration. Since much or most of the science on terrestrial carbon sequestration is developed in metric units, this average rate is given in metric tons of carbon and converted to short CO_2-equivalent tons for inclusion in the summary Table 28. During afforestation, CO_2 is removed from the atmosphere and incorporated into tree biomass and, eventually, into woody detritus and soils. This acts to offset emissions of CO_2 from elsewhere in the economy.

The average per acre sequestration rate for forests in riparian areas was developed from 18 studies of total ecosystem carbon in forested riparian buffers on former croplands. Because it addresses carbon storage in aboveground and belowground biomass and woody detritus, in addition to carbon storage in soils, total ecosystem carbon accounting provides the best indication of how carbon storage will change with a change in conservation practice. Carbon gain or loss is calculated in total ecosystem studies as the difference between gross primary productivity and ecosystem respiration, in unmanaged ecosystems, adjusted for the export of organic carbon in the form of dissolved organic carbon (DOC) and methane. Using the total ecosystem carbon approach, forested and multispecies buffers are estimated annually to sequester 3.40 ± 0.63 metric tons of carbon per hectare (1.52 ± 0.28 short tons of carbon per acre). This is the estimated rate prior to truncation to accommodate an assumed 20-year persistence of organic carbon in riparian buffer vegetation and soils.

Overall, 28 studies of carbon sequestration in forested and multi-species buffers were reviewed. None reported carbon losses. Only one meta-analysis was available, yielding an estimate of annual sequestration somewhat lower than that of the mean for the 18 total ecosystem studies. The same is true of the one other derivative statistical analysis, and to a somewhat lesser degree, for the six literature reviews or studies that report results based on expert judgment.

The descriptive statistics for the 27 studies of carbon sequestration in riparian and multi-species buffers that were reviewed are shown in Table 29. Carbon sequestration rates in studies that reported carbon gains solely for riparian soils were about half of those reporting changes in carbon across all pools, including aboveground and belowground biomass, woody detritus and soils. The results for total ecosystem carbon gain from the eddy covariance studies were similar to, if somewhat smaller (15 percent) than, those reported in the larger set of total ecosystem carbon studies. Pooled, the sequestration estimates range from 1.57 to 5.75 metric tons of carbon per hectare per year (0.70 to 2.56 short tons of carbon per acre per year). Given the relatively few studies in each grouping, the confidence intervals were wide.

Of the studies that were reviewed, twenty-four studies provided sequestration data by age of buffer. In these, in terms of sequestration rates by riparian buffer age, the annual rate of sequestration was higher during the first 15 years after buffer establishment than afterwards, but not significantly so. Sequestration measured during the first fifteen years of buffer age was also somewhat higher than the mean rate of sequestration taken from the 15 total ecosystem carbon studies. This may suggest that, for purposes of estimating carbon sequestration for our 20-year window, the mean sequestration rate developed from the 15 total ecosystem carbon studies may be conservative.

In total, the overwhelming weight of the evidence supports a large, positive response rate for sequestration, before truncation for 20-years of assumed storage, in the range of 2.5 to 5.5 metric tons of carbon per hectare per year (1.12 to 2.5 short tons per acre per year), with a best estimate of 3.4 metric tons per hectare per year.

Table 29. Descriptive statistics: Forested riparian buffers and multispecies buffers - carbon sequestration in soils and biomass

	biogenic carbon sequestration (Mg C/ha/yr) [a]	number of study results [b]	ratio of sequestration to emission: study numbers [c]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
total ecosystem carbon (soil organic carbon [SOC], above and belowground biomass)	3.40	18	18/0	0.63	2.17	4.63
soil organic carbon-only	1.57	5	5/0	0.57	0.46	2.68
above and below ground biomass	3.16	5	5/0	0.80	1.58	4.73
empirical site study-eddy covariance (NECB/NBP)	2.92	3	3/0	0.30	2.33	3.52
empirical site study-SOC soil sampling	1.93	3	3/0	0.81	0.34	3.52
empirical site study-soil sampling, bole measurements, destructive biomass sampling, allometric relationships	5.75	6	6/0	1.25	3.31	8.20
meta-analyses	2.60	1	1/0	NA	NA	NA
other derivative statistical analyses or statistical summaries [d]	3.00	1	1/0	NA	NA	NA
modeling studies	2.18	4	4/0	0.30	1.60	2.77
literature reviews/expert judgment	2.33	6	6/0	1.06	0.26	4.40
15 to 25 year annual rate of sequestration	4.07	11	11/0	0.99	2.12	6.02
0 to 15 year annual rate of sequestration	4.72	7	7/0	1.25	2.28	7.17
>25 year annual rate of sequestration	3.91	6	6/0	1.44	1.09	6.72

[a] all estimates developed against cropland counterfactuals except other derivative statistical analysis or statistical summary, empirical site study-eddy covariance (NECB/NBP), and modeling studies

[b] 28 study results, 28 studies (1 meta-analysis, 1 other derived statistical summary or statistical analysis, 4 modeling studies, 3 eddy-covariance type-empirical site studies, 3 soil sampling-type empirical site studies, 10 other empirical site studies, and 6 literature reviews)

[c] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[d] statistical summaries or derivative statistical analyses other than meta-analyses

b. Nitrous oxide

The microbial processes and environmental conditions that, in riparian buffers, give rise to N_2O emission were discussed above in Section IV, Subsection E.b. That discussion will not be repeated.

Avoided-emissions from the conversion of cropland to forested riparian buffers are calculated as the difference in on 100,000 acres between estimated emissions from forested and multispecies riparian buffers and N_2O emissions from Minnesota cropland. N_2O emissions from Minnesota cropland are taken from the MPCA Greenhouse Gas Inventory. N_2O emissions from forested riparian buffers are estimated using emission rates developed on a per hectare basis from the scientific literature and converted to lbs.

of N_2O per acre for use in the calculation. To estimate N_2O emissions from forested and multi-species buffers, 30 studies with 34 discrete study results were reviewed. With one exception, they were all empirical site studies. Slightly less than three quarters reported emissions on an annual, as opposed to a growing season, basis. We used the mean emission rate from the 30 studies (5.20 kilograms N_2O per hectare per year [4.64 lbs. N_2O per acre per year]) as the best estimate of mean annual N_2O emissions from forested riparian buffers.

No meta-analyses were available to support the calculation. Likewise, results from literature reviews and from studies that report results based on expert judgment were not available.

Eight studies were found in the scientific literature that, in side-by-side experiments, compare N_2O emissions from forested riparian buffers with emissions from adjacent cropland. These suggest a difference in emissions between forested buffers and cropland of 6.61 kg N_2O per hectare per year (5.9 lbs. N_2O per acre per year), favoring croplands as by far the higher emitting source. These results contrast substantially with the results we present in Table 28, which suggests that uncertainty still shrouds these issues. Based on the side-by-side studies, few as they are, it seems possible that the estimates given in Table 28 could be high, by a factor of two or more. Clearly, more research is needed on this question.

The descriptive statistics for the studies that were reviewed are shown in Table 30.

Table 30. Descriptive statistics: Forested and multispecies riparian buffers - N_2O

	emissions (kg N_2O/ hectare/yr) [a]	number of study results [b,c]	ratio, positive to negative results: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	5.20	34	33/1	1.89	1.49	8.90
empirical site studies	5.08	33	32/1	1.94	1.27	8.89
derivative statistical analyses or statistical summaries [d]	9.10	1	1/0	NA	NA	NA
annual flux monitoring/modeling	6.52	25	24/1	2.52	1.57	11.47
growing season and subgrowing season flux monitoring/modeling	1.49	9	9/0	0.47	0.56	2.42
1 year or less of observations or simulations	6.50	21	20/1	2.55	1.49	11.50
> 1 year of observations or simulations	3.76	21	21/0	1.75	0.32	7.19
forested riparian buffers against cropland or pastureland counterfactuals	(6.61)	8	3/5	4.29	(15.01)	1.80

[a] negative emissions = removal from atmosphere and destruction in soils

[b] 34 study results, 30 studies (1 derivative statistical analysis, 29 empirical site studies)

[c] 4 studies report multiple results by buffer type (forested, mixed) or vegetation type

[d] statistical summaries or derivative statistical analyses other than meta-analyses

c. Methane

Depending on soil wetness, methane may be produced in soils and emitted to the atmosphere or may be taken up by soils and oxidized. Excess soil wetness in forested riparian soils favors the production of CH_4 by methanogenesis, although conditions buffers are notoriously heterogeneous spatially. It is possible for one part of a buffer to maintain oxic conditions and take up and consume CH_4, while most of buffer is a net producer of CH_4.

Methane production or uptake in forested and multispecies buffers is calculated as the difference on 100,000 acres between estimated emissions from forested and multi-species riparian buffers and CH_4 uptake in temperate cropland, developed using the rates of uptake given in Aronson and Helliker (2010). In developing our estimate of emissions from forested buffers, we viewed 15 studies, nine of which reported forested riparian buffers to be net emitters of CH_4 to the atmosphere, while six reported CH_4 oxidation to dominate in forested and multispecies riparian buffers. Of the 15 studies, 14 were empirical site studies, and one a derivative statistical analysis.

We used the mean of the results taken from all 15 studies as the best available estimate of net CH_4 production in forested and multi-species buffers. Using this mean, forested riparian buffers are estimated to emit 28.16 kg CH_4 per hectare per year (25.12 lbs. CH_4 per acre) on an annual basis. As noted elsewhere, since most of the science on emissions and emissions-avoidance was developed in metric units, this estimate is given in kilograms per hectare and then converted to CO_2-equivalent short tons per acre for use in summary Table 28.

Care should be taken with these estimates, given the number of studies that report net CH_4 uptake in forested riparian buffers. In addition, CH_4 flux estimates from studies that report emissions on an annual basis are 65-fold lower than those that report on a shorter, growing season basis, although on the basis of very few observations. Many more empirical site studies may be needed for a better sense of the true size of net CH_4 emissions from forested and multi-species riparian buffers. With the use of a lower CH_4 emission rate for forested riparian buffers, or even net CH_4 uptake, the conversion of cropland to riparian forest buffers still results in large overall annual greenhouse gas emissions reductions, only more so.

The descriptive statistics for the 15 studies that were reviewed are shown in Table 31.

Table 31. Descriptive statistics: Forested and multispecies riparian buffers - CH_4

	emissions (kg CH_4/ hectare/yr) [a]	number of study results [b]	ratio, positive to negative results: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	28.16	15	9/6	18.13	(7.38)	63.69
empirical site studies	30.19	14	9/5	19.35	(7.74)	68.12
derivative statistical analyses or statistical summaries [c]	(0.28)	1	0/1	NA	NA	NA
annual flux monitoring/modeling	1.04	8	4/4	0.74	(0.42)	2.50
growing season and subgrowing season flux monitoring/modeling	69.78	6	5/1	41.49	(11.54)	151.10
1 year of observations or simulations	41.88	7	3/4	37.49	(31.60)	115.36
> 1 year of observations or simulations	15.81	8	7/1	11.65	(7.02)	38.65

[a] negative emissions = removal from atmosphere and destruction in soils

[b] 15 study results, 15 studies

[c] statistical summaries or derivative statistical analyses other than meta-analyses

G. Retire/rewet cropped peatlands

Peatlands that have been drained for agricultural purposes are extremely large emitters of greenhouse gases on a per acre basis and in aggregate. In the latest Minnesota Pollution Control Agency Greenhouse Gas Inventory, annual emissions of CO_2 and N_2O, were estimated at 9.5 and 1.5 million CO_2-equivalent short tons per year, respectively, equal is aggregate to about 30 percent of all greenhouse gas emissions from the agriculture-forestry-land use sector.

Peatland soils that have been drained and are in agricultural production can be retired and rewet. In rewetting, drainage ditches are filled or blocked or drainage pumps are disabled, leading to a rise in peatland water tables.

According to analysis developed by the USEPA, in Minnesota about 800,000 acres of peatlands are in agricultural production, about half in cropland and half in pasture. (USEPA 2017)

In an undisturbed peatland, large stores of organic carbon and nitrogen accumulate over very long periods of time, many hundreds and thousands of years. Peatland soils are waterlogged. Anaerobic conditions in waterlogged soils protect the accumulated organic carbon and nitrogen stored from decomposition, with the result that, in the case of carbon, the removal of CO_2 from the atmosphere and its photosynthetic fixation in plant matter exceeds ecosystem respiration losses.

With peatland drainage, this protection is removed and ecosystem respiration, that formerly was anaerobically-based, shifts to an aerobic form. Aerobic respiration proceeds at rates that are about an order of magnitude faster than anaerobic rates, leading in the case of peatland drainage to the mineralization of large amounts of often very old carbon and organic nitrogen, and its subsequent emission to the atmosphere in the form of CO_2 and N_2O. Rewetting returns peatland soils to pre-drainage conditions, including generally anaerobic conditions. Upon rewetting, mineralization of stored organic carbon and nitrogen ceases, often within several years.

We calculate greenhouse gas-avoidance from the retirement and rewetting of cropped peatland as the difference, on 100,000 acres, between emissions from drained cropped peatland soils, or more generally histosols, and those from rewet and retired histosols. Important sources of greenhouse gas emissions from drained cropped peatlands include: CO_2 emissions from mineralization, driven largely by drainage, but to which tillage and nitrogen fertilization also contribute; N_2O emissions from mineralization, followed by the linked processes of nitrification and denitrification; and CO_2 emissions from fuel used in crop production and greenhouse gases emitted during the manufacture of synthetic agricultural fertilizers, pesticides and fuels used on-farm.

With peatland retirement, all greenhouse gas emissions from fuel use and from the associated manufacture of fuel, as well as from the manufacture of agricultural chemicals, ceases. Carbon sequestration in peatlands also recommences with the restoration of high water tables. During terrestrial carbon sequestration, CO_2 is removed from the atmosphere photosynthetically and incorporated into plant matter that, with limited respiration, accumulates in peatland soils in only partially degraded forms.

In the case of rewet, retired peatland soils or histosols, CH_4 is the principal greenhouse gas emitted. Methane is the terminal product of anaerobic restoration in waterlogged peatland soils. With the restoration of anaerobic conditions, peatland soils become large sources of CH_4. N_2O emissions from rewet histosols are minor. By contrast, drained cropped peatlands act to oxidize a small amount of atmospheric CH_4, removing it from the atmosphere.

Estimated avoided-emissions from peatland retirement and rewetting are shown in Table 32 for 100,000 acres of retirements/rewetting. For each 100,000 acres of histosols that are retired from cultivation and rewet, 1.48 million CO_2-equivalent short tons of greenhouse gas emissions would be avoided. Of this, about 90 percent results from the avoided emission of CO_2, which, as noted above, results from restoration of anaerobic conditions in peatland soils. With the restoration of water tables, CO_2 emissions cease and carbon sequestration in peatland soils recommences. Avoided-emissions of N_2O account for about 15 percent of total avoided-emissions, and avoided-emissions from the foregone manufacture of agricultural chemicals another 1 percent. With peatland rewetting, CH_4 emissions from peatlands soils rise dramatically, adding back to emissions totals about 150,000 CO_2-equivalent short tons of emissions.

In developing the estimates shown in Table 32, as elsewhere in this report, a 20-year timespan for terrestrial carbon storage was assumed. In our judgment, this is the longest that continuous storage, once initiated, can safely be assumed. Under this assumption, avoided-emissions are an estimated 1.478 million CO_2-equivalent short tons. Had a 40-year period of assured storage been assumed, avoided-emissions from peatland retirement and restoration would have totaled 1.481 million CO_2-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 1.491 million CO_2-equivalent short tons (see Table 32). The approach that we use in converting observed rates of sequestration to avoided-emissions was addressed in the Methodology section above (Section II).

Table 32. Restored/rewet formerly cropped peatlands: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils or sediments	(251,663)	crop production
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	not known	crop production
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(7,186)	crop production
CH_4	soils or sediments	151,092	crop production
CO_2 [b,c]	carbon accumulation in wetland sediments and biomass	(1,341,038)	crop production
CO_2	cultivated soils from lime or urea use	(2,808)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	(6,849)	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(20,184)	crop production
Total		**(1,478,636)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass			
40 year storage	all sources and sinks	**(1,481,851)**	crop production
100 year storage	all sources and sinks	**(1,491,498)**	crop production
Emissions with Rewetting of Former Pastureland			
GHGs	all sources and sinks	**(1,044,682)**	pasture

[a] positive = emissions increase, negative = emissions reduction

[b] carbon accumulation in soil and biomass = net removal of CO_2 from the atmosphere = net emission reduction

[c] assumes 20 years of sustained storage of newly sequestered organic carbon in soils and biomass

We have also estimated the avoided greenhouse gas emissions from the retirement and rewetting of drained, formerly pastured histosols. On 100,000 acres, emissions-avoidance from peatland retirement/rewetting on formerly pastured peatland soils would be 1.04 million CO_2-equivalent short tons.

A number of estimates has been published of the net change in greenhouse gas emissions resulting from the retirement and rewetting of formerly cropped and pastured peatland soils. These are listed in Table 33 for emissions-avoidance on 100,000 acres. For formerly cropped peatlands, these include results from three meta-analyses of the results of published controlled site studies, plus an estimate from a related statistical analysis, which in aggregate support a range of greenhouse gas-avoidance of 1.14 to 1.58 million CO_2-equivalent short tons. Emissions-avoidance was lower from the three empirical site studies that we identified in the scientific literature, ranging 0.71 to 0.88 million CO_2-equivalent short tons per year, while emissions-avoidance from literature review-type studies fell into a range of 0.26 to 1.56 million CO_2-equivalent short tons.

For retirement and rewetting of formerly pastured histosols, published meta-analyses would support a range of greenhouse emissions-avoidance of 0.63 to 11.69 million CO_2-equivalent short tons on 100,000 acres, while site studies would support a range of avoidance of 0.25 to 19.36 million CO_2-equivalent short tons.

Greenhouse gas-avoidance resulting from the retirement of drained wetlands from agricultural use and their restoration should not be confused with the net radiative balance of rewet peatlands. Due to the scale of emissions from drained, cropped peatlands, it is possible for reductions in emissions to result from the rewetting of peatlands soils and their retirement from agricultural uses and for retired, rewet peatland in themselves to have a net warming effect on climate. (Gunther *et al.*, 2018) Integrated over periods shorter than 100 years, the net radiative balance of intact peatlands is generally positive, contributing to a slight warming of the planet, while for longer periods of time, several hundred years or more, peatlands in a natural condition act to cool global climate. (Whiting and Chanton, 2011)

Averaged over the long stretch of time from the early Holocene to the present, peatlands have exerted a net cooling effect on climate, in terms of radiative forcing of climate, equal to -0.2 to -0.5 watts per square meter of added heating to the system. (Leifeld *et al*., 2019)

Terrestrial carbon sequestration in rewet formerly cropped peatlands is discussed below, followed by a discussion of CO_2 emissions from drained cropped peatland soils. We also discuss CH_4 oxidation in drained cropped peatland soils and CH_4 emissions from rewet histosols, as well as N_2O emissions. Small amounts of N_2O emissions from nitrate loading of groundwater and surface water and volatilized and land deposited ammonia contribute to the totals shown in Table 32. Small amounts of avoided-emissions also results from peatland retirement in the form of emissions from avoided fuel use and the manufacture of agricultural chemicals foregone. The methods and sources used to estimate avoided-emissions from these sources were discussed above in the Methodology section (Section II, Subsection E) of this report.

Table 33. Published estimates of greenhouse gas avoidance through peatlands restoration [a]

		emissions avoided [a]	
Study	**Type of study**	**CO_2-eq. short tons per acre per year**	**CO_2-eq. short tons per 100,000 acres per year**
Cropland Counterfactual [b]			
Hemes *et al* . (2019)	site study	7.07	706,898
Knox *et al.* (2015)	site study	8.76	876,410
Evans *et al.* (2017)	meta-analysis	15.78	1,578,429
IPCC (2014) [c]	meta-analysis	11.45	1,145,354
Wilson *et al.* (2016)	meta-analysis	11.42	1,142,232
Tiemeyer *et al.* (2020)	other derived statistical analysis [d]	15.57	1,556,575
Byrne *et al.* (2004)	literature review/expert judgment	1.63	163,418
Gunther *et al.* (2018)	literature review/expert judgment	8.33	832,552
Martens *et al.* (2021)	literature review/expert judgment	15.61	1,561,035
Pastureland Counterfactual [b]			
Audet *et al.* (2013)	site study	0.25	24,531
Beetz *et al.* (2013)	site study	19.36	1,935,971
Hemes *et al.* (2019)	site study	1.07	107,210
Knox *et al.* (2014)	site study	6.28	628,205
Evans *et al.* (2017)	meta-analysis	9.31	930,600
IPCC (2014) [c]	meta-analysis	6.32	631,996
Wilson *et al.* (2016)	meta-analysis	6.36	636,308
Tiemeyer *et al.* (2020)	other derived statistical analysis [d]	11.69	1,168,546
Byrne *et al.* (2004)	literature review/expert judgment	0.73	72,744
Unidentified Counterfactual			
Griscom *et al.* (2017)	literature review/expert judgment	5.97	596,521

[a] results as reported without adjustments

[b] Hemes *et al.* (2019) provides a second estimate, calculated with a GWP = 45 (sustained global warming potential [SGWP]), for both cropalnd and pastureland counterfactuals of 207, 562 and -197,805 CO_2-equivalent short tons per 100,000 acres per year. Fargione, *et al.* (2018) provides an estimate, again calculated with GWP = 45 of 130,744 CO_2-equivalent short tons per 100,000 acres for an unidentified counterfactual.

[c] reported in Wilson, *et al* . (2016)

[d] statistical analyses other than meta-analyses

a. Carbon sequestration in soils and biomass

Avoided CO_2 emissions from the retirement of histosols from agricultural use and their rewetting is calculated as the sum, on 100,000 acres, of CO_2 no longer emitted from what formerly were drained, cropped or pastured histosols plus post-restoration sequestration of CO_2 as organic carbon in peatland soils. The drainage and use of histosols for agricultural purposes unambiguously results in very large per acre CO_2 emissions. (Beyer and Hoper, 2015; Freeman *et al*., 2021; Gunther *et al*., 2018; Knox *et al*., 2015) Globally, the drainage and use of histosols results annually in the release of about seven billion metric tons (7.7 billion short tons) of CO_2 to the atmosphere, or equal to six percent of global CO_2 emissions. Hydrologically restored or 'rewet' histosols that have been retired from agricultural use generally remove CO_2 from the atmosphere and store it in peatland soils or mineral muck, but at relatively low annual rates.

In calculating avoided-emissions, CO_2 no longer emitted from what formerly were drained, cropped or pastured histosols equals: -1 * CO_2 emitted from drained, cropped or pastured histosols prior to retirement and hydrological restoration.

In some cases, hydrologically restored or 'rewet' histosols that have been retired from agricultural use can act as continuing small sources of CO_2 emission to the atmosphere. In this case, emissions-avoidance would equal CO_2 formerly emitted from drained, cropped or pastured histosols less this continuing emission during the post-restoration phase.

Based on our analysis, post-restoration histosols act to remove CO_2 from the atmosphere and to sequester it in peatland soils and muck, albeit at low annual rates.

We discuss post-restoration soil carbon sequestration in the following subsection. We discuss CO_2 emissions from drained or pastured histosols in the subsequent subsection (Section IV, Subsection G.a.ii, "CO_2 emissions from drained peatland soils in agricultural use").

i. Carbon sequestration in retired, rewet peatlands

In natural intact peatlands, continued inundation causes anoxic conditions in which the decomposition of organic matter is inhibited. During photosynthesis, CO_2 is removed from the atmosphere and is incorporated as organic carbon in plant biomass and, through root exudation and senescence and plant litter fall, into soils. Under anoxic or anaerobic conditions, microbial oxidation of accumulated soil organic matter or surface litter is suppressed. Decomposition through anaerobic processes substitutes for decomposition by aerobic processes, but proceed at rates an order of magnitude less than comparable rates in aerobic environments. (Bridgeman and Richardson, 1992) As a result, in undisturbed peatlands, photosynthetic fixation of atmospheric CO_2 in plant biomass outpaces losses from the decomposition of organic matter, allowing organic carbon to accumulate.

In undisturbed peatlands, the imbalance between plant biomass production and anaerobic respiratory losses is small, allowing the accumulation of organic carbon, but only over very long periods of time, e.g., millennia.

Anaerobic conditions in unmanaged peatlands are maintained by continued inundation associated with high water tables. In cropped or pastured peatlands, water tables are lowered, removing the protection from rapid microbial oxidation afforded by anaerobic, waterlogged conditions. In cropped or pastured peatlands, generally aerobic conditions favor rapid oxidation of accumulated histosol carbon, resulting in large soil losses of carbon in the form of CO_2 emissions to the atmosphere.

During peatland restoration, water tables are restored, with the intention to prevent further losses of ancient carbon stores and, beyond this, to restore the annual sink function of these soils. Peatland water tables constitute the principal control on, in the case of a low water table, peatland soil carbon loss, and continued peatland carbon accumulation, in the case of high water tables. (IPCC 2014) The height of the water table determines the boundary in the peat soil column between the oxic layer, in which soil organic matter is oxidized, and the anoxic layer, where microbial oxidation is inhibited by low oxygen conditions. In undisturbed peatlands, in their natural state, the water table is close to the surface.

Other controls on rates of organic carbon sequestration or loss in histosols include: soil temperature, surface run-off, meteorology, primary productivity, and vegetative type. (Blodau, 2002) Rates of microbial respiration increase with increased soil temperature, whether respiration is anaerobic or aerobic. Most global peat deposits are found in boreal climates, with depressed rates of organic matter decomposition. Once the water table is restored, sequestration in or loss of organic carbon from the surface layer depends on the surface water balance, as influenced by rainfall and surface runoff. During episodic drought years, peatland soils that otherwise are carbon sinks, can and often become net carbon sources.

Peatland carbon balance is the difference between carbon gained through plant biomass and respiratory losses of carbon. With rates of ecosystem respiration held constant, high plant productivity promotes enhanced carbon storage in histosols. Of the two major classes of peatland, fens and bog, fens are far more productive, but fen plant biomass also is less recalcitrant to decomposition than is sphagnum, the dominant vegetation in bogs. As a consequence, fens tend to accumulate organic carbon at generally lower rates than bogs. (Lamers *et al*., 2014)

Restoration may include both hydrological restoration and the restoration of peatland vegetation. To rewet peatlands, drainage ditches usually are dammed or filled with peat from surrounding acres, biomass bales or wood brash, or drained are blocked. (Cooper *et al*., 2014) Dykes comprised of peat may be constructed to retain spring runoff on-site, as may open water ponds. (Waddington *et al*., 2010) Spillways may be removed and the topography changes to maintain histosol inundation. (IPCC 2014) To restore peatland vegetation, sphagnum spores or fragments are spread on the peatland surface, covered by a straw mulch. Sometimes companion vascular plants, upon which sphagnum seems to depend, like *Eriophorum spp.,* are added. (Waddington and Day, 2007) Lacking restored peatland vegetation, rewet peatlands soils rarely full attain the full sink function of intact peatlands in their unmanaged, natural state. (Wilson *et al*., 2016; Lazcano *et al*., 2018)

The abandonment of cropped or pastured peatlands without adequate hydrological restoration does not restore peatlands to pre-disturbance conditions. (Glatzel *et al*., 2004)

Peatlands cease almost immediately to act as large CO_2 emitters to the atmosphere with rewetting, usually a year or two. (Wilson *et al*., 2016) The recovery of the carbon sink function through which, in accumulating organic carbon, peatland soils remove CO_2 from the atmosphere on a net basis, takes longer. While there are exceptions (Peacock *et al*., 2019; Samaritani *et al*., 2011), the sense of the scientific literature is that rewet peatlands will attain net sink status within twenty years of peatland restoration, and most will begin to remove carbon from the atmosphere on a net basis within ten years. (Beetz *et al*., 2013; Hemes *et al*., 2019; Hendriks *et al*., 2007; Komulainen *et al*., 1998; Lazcano *et al*., 2018; McNicol *et al*., 2017; Nugent *et al*., 2019; Ployda *et al*., 2016; Renou-Wilson *et al*., 2019; Schrier-Uijl *et al*., 2014; Swenson *et al*., 2019; Urbanova *et al*., 2013; Waddington *et al*., 2010; Wilson *et al.*, 2016)

Some analysts have concluded that rewet peatlands never will not fully recover the sink function of intact, unmanaged peatlands over periods shorter than 50 to 100 years. (Moreno-Mateos *et al*., 2016)

High water tables are generally prohibitive of most cropping activities. Implicit in peatland hydrological restoration is a parallel retirement of these acres from cultivation. In drained, cropped histosols, cultivation, and in particular tillage, acts to accelerate drainage-induced soil organic carbon losses by disrupting soil structure and introducing oxygen deeply into the soil column.

High-yielding pastureland is possible with water table 20 centimeters below the peat soil surface, but with a forfeiture of the full benefits of full inundation at a rate of about some 0.22 metric tons of carbon per hectare per year for each 1 centimeter crop in water table height. (Ployda *et al*., 2016) With partial inundation, the oxic zone in the peatland comes to include the upper 5 to 30 centimeters, which is then subject to continued microbial oxidation, with attendant CO_2 loss.

The long-term trajectory of carbon sequestration in rewet histosols is less clear, some scientists suggesting rising long-term rates of sequestration as sink function on rewet acres approaches that of intact unmanaged peatlands (Baldocchi *et al*., 2013), some suggesting a slow long-term reduction in sequestration rate from initially high levels. (Wilson *et al*., 2016)

Avoided CO_2 emissions from the retirement of histosols from agricultural uses and their rewetting are calculated as the difference between soil organic carbon sequestration in retired, rewet formerly drained, cropped (or pastured) peatland soils and CO_2 emissions from drained peatland soils or muck. After peatland restoration, peatland soils, or histosols, act to sequester carbon, particularly over long period of time. During the growing season, CO_2 is photosynthetically removed from the atmosphere and fixed in plant biomass, which in anaerobic environments accumulates in peat soils with little loss. This removal of CO_2 from the atmosphere acts to offset CO_2 emissions from combustion of fossil fuels like coal and natural gas.

Two published formal meta-analyses of the results of empirical site studies that treat sequestration in rewet histosols were identified in the published scientific literature, along with three other derivative statistical analyses of roughly the same body of site studies. We use the mean rate of soil carbon sequestration from these five studies to best represent post-restoration soil carbon sequestration in histosols and muck. Using this mean rate, retired, rewet peatland soils are estimated to sequester, on an annual basis, 0.05 ± 0.18 metric tons of carbon per hectare (0.02 ± 0.08 short tons of carbon per acre per year). This is the average rate of sequestration prior to truncation for short storage lifetimes.

Meta-analysis is a powerful statistical tool used to integrate results of experiments of different designs and draw conclusions at broad spatial scales. Its use is increasingly prominent in ecological assessment. While governed by a set of specific rules and procedures, and conducted using statistical programs designed around these rules and procedures, the use of the term ‘meta-analysis’ is sometimes broadened to include other types of related statistical analysis.

The five meta-analyses or derivative statistical analyses (other than formal meta-analysis) include six study results (for database practices, see Section II, Subsection C above). Of the six results, four indicated net sequestration in post-restoration peatland soils and muck, two net CO_2 emissions.

Overall, we reviewed 59 studies of post-restoration carbon sequestration in retired, rewet peatland soils, including 60 results. Of these 59 studies, 43 were empirical site studies of sequestration at hydrologically-restored sites. Nine were literature review-type studies or studies that reported results developed on the basis of expert judgment. Finally, two were formal meta-analyses, while three were related derivative statistical analyses of results from published empirical site studies. Of the 60 study results, 42 (70 percent) indicated post-retirement, post-restoration net soil sequestration, while 18 indicated continuing net carbon losses.

Averaged across all 60 study results, net sequestration totaled an estimated 0.8 ± 0.28 metric tons of carbon per hectare per year (0.36 ± 0.12 short tons of carbon per acre per year). By study type, estimated rates of carbon sequestration ranged from -0.03 metric tons of carbon per hectare per year, in the case of chamber-based net ecosystem carbon studies, to 6.54 metric tons of carbon per hectare per year in modeling studies.

The descriptive statistics for the studies by study type, by biomass pool, and by age of histosol restoration are shown in Table 34. Results are given in metric tons of carbon, but converted to short CO_2-equivalent tons for use in calculating avoided CO_2 emissions, as given in summary Table 32. Empirical site studies include: eddy covariance- and chamber-based total ecosystem studies, plus a single soil sampling study. For the eddy covariance studies, annual sequestration is an estimated 1.82 ± 0.58 metric tons of carbon per hectare (0.81 ± 0.05 short tons of carbon per acre per year), while in the 25 chamber-based studies, restored histosols are a slight 0.03 ± 0.31 metric tons of carbon per hectare source of emitted CO_2 (0.01 ± 0.14 short tons of carbon per acre per year). Estimated annual sequestration from the modeling studies was an estimated 6.54 ± 2.04 metric tons of carbon per hectare, while that from the literature reviews was an estimated 0.24 ± 0.49 metric tons of carbon per hectare.

Sequestration in total ecosystem studies, again both empirical field studies and modeling studies, was an estimated 0.99 metric tons of carbon per hectare across some 47 studies, which suggests that the estimate for post-restoration sequestration in the meta-statistical studies may be overly conservative.

Restoration age seems to have little effect on sequestration rate. With the exception of those for the total ecosystem studies, confidence intervals nearly all overlap the zero value, pointing to a substantial degree of uncertainty in the overall rate of post-restoration sequestration. Generally speaking, because post-restoration soil carbon sequestration plays a minimal role in the calculation of greenhouse gas avoidance, accounting for less than half a percent of total greenhouse gas avoidance[12], these uncertainties may be of substantially less importance than uncertainties arising from other sources.

Lastly, the retirement agricultural uses of histosols and their rewetting will result in a decreased CO_2 flux to the atmosphere, which we estimate in Table 32 at 1.34 million short tons of CO_2 per year on 100,000 acres (8.20 metric tons of carbon per hectare per year). Again, this was calculated as the difference, on 100,000 acres, between sequestration in retired, rewet peatland soils and muck, and CO_2 emissions from drained, cropped peatland soils. We identified six studies in the literature that presented a similar calculation, with a mean estimate for histosols formerly in agricultural production of 7.81 metric tons of carbon per hectare, or again quite near our estimate in Table 32 (see Tables 32 and 34).

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[12] 5,216 CO_2-equivalent short tons per 100,000 acres on a base avoidance of 1,478,636 CO_2-equivalent short tons per 100,000 acres.

Table 34. Descriptive statistics: Restored peatlands - carbon sequestration in soils and biomass

	biogenic carbon sequestration (Mg C/ha/yr)	number of study results [a]	ratio of sequestration to emission: study numbers [b]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses and other derivative statistical analyses or statistical summaries [d]	0.05	6	4/2	0.18	(0.29)	0.40
eddy covariance empirical site studies	1.82	17	15/2	0.58	0.69	2.95
chamber empirical site studies (NECB/NBP)	(0.03)	25	13/12	0.31	(0.63)	0.58
empirical site studies-soil sampling	2.14	1	1/0	NA	NA	NA
modeling studies	6.54	2	2/0	2.04	2.55	10.54
literature reviews/expert judgment	0.24	9	7/2	0.49	(0.72)	1.21
all studies	0.80	60	42/18	0.28	0.24	1.35
total ecosystem carbon (NECB/NBP) [c]	0.99	47	35/12	0.34	0.32	1.67
soil organic carbon (SOC) only	0.44	9	6/3	0.27	(0.08)	0.97
1 to 9 year old constructed/restored wetlands	0.91	23	17/6	0.55	(0.16)	1.99
10 year old-plus constructed/restored wetlands	0.96	21	13/8	0.54	(0.11)	2.03
studies with pre-restoration counterfactual:						
total ecosystem carbon, cropland/pastureland counterfactual	7.81	6	6/0	0.89	6.07	9.55
total ecosystem carbon, peat extraction counterfactual	2.73	11	11/0	0.53	1.69	3.77

[a] 61 study results, 59 studies (2 meta-analyses, 3 statistical summaries or derivative statistical analyses, 2 modeling studies, 43 empirical site studies, 9 literature reviews)

[b] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[c] NECB = Net Ecosystem Carbon Balance; NBP = Net Biome Productivity

[d] derivative statistical studies other than meta-analyses

ii. CO_2 emissions from drained peatland soils in agricultural use

Peatland soils are commonly known as histosols. According to the definition in use by the IPCC, in addition to peaty soils, histosols also include mucky mineral soils like gleysols. (IPCC, 2014) Drainage of histosols removes the protection afforded them in waterlogged environments by anaerobic conditions. In a waterlogged, saturated state, oxygen-deprived conditions inhibit aerobic forms of microbial respiration, promoting instead anaerobic respiration, the respiratory pathway by which soil bacteria in peatlands mineralize organic matter. Decomposition through anaerobic processes is very slow, proceeding at rates much slower than comparable rates in oxic environments. (Bridgeman and Richardson, 1992) This low rate of decomposition allows organic carbon to accumulate in large amounts in peat deposits. With drainage, rapid oxidation of peat through aerobic respiratory pathways recommences, resulting in the release of large amounts of CO_2 to the atmosphere.

Peat deposits in the continental US are about 8.3 billion metric tons of carbon on about 8.4 million hectares, or about 990 metric tons per hectare (442 short tons per acre). (USGCRP 2018)

Once initiated, the oxidation of peatland carbon will continue so long as drainage is maintained, up until full complete oxidation of the accumulated peat stock. (Leifeld *et al.*, 2019; Swenson *et al.*, 2019; Taft *et al.*, 2017) This is in contrast to mineral soils, in which after large initial soil organic carbon losses from disturbances, soil organic carbon levels do stabilize, at levels 20 to 60 percent lower than initial levels. (Guo and Gifford, 2002; Mann, 1986; Poeplau *et al.*, 2011)

Subsidence typically accompanies peatland drainage, resulting from shrinkage and compaction, as well as from organic carbon losses from microbial decomposition of organic matter in drained histosols. Present-day rates of subsidence from drained peatlands in mid-latitude climates are an estimated 2.5 centimeters per year (0.98 inches). (Freeman *et al.*, 2021)

The carbon that is emitted to the atmosphere from drained histosol is very old carbon, many hundreds to thousands of years old, and in this is more akin to fossil carbon than fast-cycling biogenic carbon like might be released to the atmosphere attendant to the burning of wood or other biomass.

Water table height is the principal control on rates of CO_2 production in and emission from drained histosols. (Veber *et al*., 2018) Low water tables act to expand the aerobic zone in the peat soil column and to contract the anaerobic zone, promoting accelerated oxidation of peat within the soil column. At relatively high water tables levels, 10 centimeters (0.39 inches) from the surface, rates of carbon loss from drained histosols are relatively low, an estimated 1 metric tons of carbon per hectare per year (0.45 short tons per acre). From German data, at 20 centimeters (7.9 inches) below the surface, this rate of loss rises five-fold to five metric tons per hectare per year, and ten-fold at water tables 60 centimeters below the surface. (Tiemeyer *et al*., 2020) With the water table 30 centimeters below the surface, loss rates estimated from the German data are eight metric tons of carbon per hectare per year (3.57 short tons of carbon per acre per year).

Other controls on carbon loss from histosols in agricultural use include: soil temperature and porosity, peat nutrient content, surface soil moisture, plant primary productivity, crop biomass removals, and local land-use and land management practices. (Norberg *et al*., 2016; Taft *et al*., 2017)

Peatlands are drained for use as cropland and pastureland. Some drained histosols were formerly cropped, but since have been abandoned. In addition, peatlands are sometimes drained for forestry and in some bogs, peat is drained and harvested for horticultural uses.

As noted in the discussion of rewet histosols, the intensive agricultural use of drained peat soil acts to exacerbate losses of carbon resulting from drainage. (Kekkonen *et al*., 2019) Tillage in particular acts to disrupt soil structure, exposing carbon in soil microaggregates to microbial decomposition and enhanced CO_2 emission (see Section IV, Subsection J). By limiting surface inputs of organic carbon to cropped and pastured peatland soils, plant biomass removals also contribute to peatland soil carbon loss. In acres in agricultural use, biomass plant is removed for forage, bedding and use as a feedstock for bioenergy production. Somewhat higher carbon losses are associated with drained cropped histosols than with drained histosols used for pasture, although the differences are not great. (Lohita *et al*., 2004; Norberg *et al*., 2016; Ployda *et al*., 2016)

It may be possible to mitigate some carbon losses from histosols in agricultural use by raising water tables, particularly on pastureland, and through the use of no-till tillage with full crop residue retention. (Kekkonen *et al*., 2019) Some limited mitigation may result from the conversion of peatland from cultivation to pasture.

As noted above, avoided CO_2 emissions from the retirement of histosols from agricultural uses and their rewetting are calculated as the difference between soil organic carbon sequestration in retired, rewet formerly drained cropped (or pastured) sites and CO_2 emissions from drained or pastured peat soils or muck. In estimating CO_2 emissions from drained histosols in agricultural uses, we reviewed 61 studies reporting in aggregate some 72 study results. Of these, 36 study results were from empirical site studies of soil carbon losses at drained cropped or pastured sites. Another four were meta-analyses of the results of these published empirical studies, and nine were other derivative statistical analyses of results from a similar pool of studies. Twelve were literature review-type studies or studies that reported results developed on the basis of expert judgment.

We selected the mean estimate of CO_2 emission from the six meta-analyses and other derivative statistical analyses as the best estimate of emissions from drained, cropped histosols, or 8.18 ± 1.46 metric tons of carbon per hectare per year (3.65 ± 0.65 short tons of carbon per acre). For drained, pastured histosols, we selected a value of 5.95 ± 1.45 metric tons of carbon per hectare per year (2.65 ± 0.65 short tons of carbon per acre). Of the 13 studies upon which we relied, all reported net emissions of CO_2 from histosols drained for agricultural purposes. As noted above in the introduction to Subsection G, even if drained histosols were to be rewet within a decade of drainage and cultivation, rates of carbon accumulation in rewet peatlands are so slow that many hundreds of years would have to pass before peatland restoration would compensate for present-day emissions.

As noted in Section II of this report, in selecting response rates, we give preference to the results of formal meta-analyses, along with those from similar derivative statistical analyses. Meta-analysis was designed specifically to address the problem of mean response rate under conditions of wide variability in environmental and other conditions and divergent study designs. While governed by a set of specific rules and procedures, and conducted using statistical programs designed around these rules and procedures, the use of the term 'meta-analysis' is sometimes broadened to include other types of related statistical analysis.

Descriptive statistics from the 61 studies (72 study results) that were reviewed are shown in Table 35, including standard errors and calculated upper and lower 95 percent confidence intervals. As elsewhere in this report, these estimates are reported in metric units, and have been converted to English units for use in Table 32.

Of the 72 study results for drained histosols, 71 reported net carbon loss from drainage and farm use, one reported a net gain. The mean rate of CO_2 emission from all studies of drained cropped peatland soils or muck was 7.15 metric tons of carbon per hectare per year (3.19 short tons of carbon per acre per year), while that from drained pastured histosols was 4.98 metric tons of carbon per hectare per year (2.22 short tons of carbon per acre per year). For site studies, using the mean of the reported losses from drained cropland, carbon losses per hectare from drained cropland were an estimated 6.83 metric tons of carbon per hectare per year (twelve study results), while those from pastured histosols were an estimated 5.18 metric tons of carbon per hectare per year (see footnotes 'e,' and 'f' to Table 35.

For total ecosystem carbon (TEC) studies, using the mean of the reported losses from drained cropland, carbon losses per hectare, were an estimated 6.86 metric tons of carbon per hectare per year (3.06 short tons of carbon per acre per year), while those from drained pasture are an estimated 5.28 metric tons of carbon per hectare per year. TEC studies report the difference between CO_2 removed from the atmosphere during photosynthesis and CO_2 emitted terrestrially from plant and soil respiration, adjusting for carbon losses through crop harvest, CH_4 emissions and losses of carbon to groundwater in the form of dissolved organic carbon, plus any gains from imported manure.

From the results of the meta-statistical studies, drained cropped histosols are more highly emitting than pastured peaty soils, about 35 percent more emitting. Based on the same mean estimates, the estimates shown in Table 35 are about 20 percent higher than those used in the biennial development of the MPCA greenhouse gas emission inventory.

The empirical work, built-up over ther last two decades, supports a robust estimate of of CO_2 emissions from cropped, drained peatlands generally, in the range of five to ten metric tons of carbon per hectare per year (2.23 to 4.46 short tons of carbon per acre per year), with a best estimate of 8.2 metric tons of carbon per hectare per year. Scientific understanding of emissions is well established. More study is unlikely to narrow the range of potential post-drainage emissions.

Finally, CO_2 emissions from peat extraction are an estimated 2.59 metric tons of carbon per hectare per year, based on 22 study results and from histosols drained for all uses – agriculture, peat extraction, forestry – are an estimated 4.87 metric tons of carbon per hectare per year (7.98 short tons of CO_2 per acre per year), from the mean of 104 study results.

Table 35. Descriptive Statistics: Restored peatlands - Soil carbon emission counterfactual [a]

	CO_2 Emissions (Mg C/ha/yr)	number of study results [b]	ratio of emission to sequestration: study numbers [c]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
Peatland drained for agricultural uses						
meta-analyses and other derivative statistical analyses or statistical summaries [d]	6.98	13	13/0	1.05	4.93	9.03
cropland	8.18	6	6/0	1.48	5.28	11.09
pastureland	5.95	7	7/0	1.45	3.10	8.79
all studies	5.91	72	71/1	0.42	5.10	6.73
literature reviews/expert judgments	5.65	23	23/0	0.54	4.59	6.72
site studies [e]	5.76	34	33/1	0.69	4.42	7.11
total ecosystem carbon studies [f,g]	6.03	48	47/1	0.52	5.01	7.06
MPCA GHG emission inventory - cropland	10.72	1	1/0	NA	NA	NA
MPCA GHG emission inventory - pastureland	2.81	1	1/0	NA	NA	NA
Peatland drained for peat extraction	2.59	22	21/1	0.34	1.93	3.25
Peatland drained for all purposes	4.87	104	100/4	0.35	4.18	5.55

[a] counterfactual = emissions from drained cropped peatlands

[b] 72 study results, 61 studies (13 meta-analyses or statistical summaries or derivative statistical analyses, 36 empirical site studies, 12 literature reviews)

[c] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[d] derivative statistical analyses = statistical analyses other than meta-analyses of study results in the published literature

[e] mean emission rate for drained cropped histosols of 6.83 Mg C/ha/yr, and, for drained pastureland, of 5.18 Mg C/ha/yr

[f] mean emission rate for drained cropped histosols of 6.86 Mg C/ha/yr, and, for drained pastureland, of 5.28 Mg C/ha/yr

[g] studies that treat above and below ground live biomass, SOC, and surface litter

b. Nitrous oxide

We calculate N_2O emissions-avoidance from the retirement of histosols in agricultural use and their rewetting as the difference, on 100,000 acres, of N_2O emissions from retired, rewet formerly cropped or pastured histosols and those from cropped or pastured histosols. In undisturbed histosols, N_2O emissions are inhibited by anaerobic conditions, which act to suppress mineralization of organic nitrogen. N_2O is formed in soils during the nitrification of nitrogen in a mineral form to nitrate. Anaerobic conditions also act to inhibit the emission of N_2O, which in waterlogged anoxic environments is further reduced to dinitrogen (N_2) and emitted to the atmosphere in that form.

Aerobic conditions predominate in drained histosols, leading to the mineralization of stored nitrogen, and large emissions of N_2O. Conditions also are lacking for complete or near-complete reduction of nitrate to N_2, in place of N_2O.

The restoration of peatlands by rewetting restores the low-N_2O forming conditions present in unmanaged peatlands in a ‘natural state.’

We discuss post-restoration emissions of N_2O in the following subsection. We discuss N_2O emissions from drained or pastured histosols in the subsequent subsection (Section IV, Subsection G.b.ii, “N_2O emissions from drained peatland soils in agricultural use”).

i. N_2O emissions from retired, rewet peatland soils

Beyond what was said in the introduction to this subsection, there is relatively little to say about N_2O production in and emissions from rewet, hydrologically-restored peatland soils. Aerobic conditions predominate in drained histosols in agricultural use. In the aerobic conditions, organic nitrogen is mineralized. As will be discussed in the following section, large emissions of N_2O to the atmosphere result. By raising the water table to pre-disturbance level typical of undisturbed peatlands, anaerobic conditions are reestablished, inhibiting the formation of N_2O and its emission to the atmosphere. (Leppelt *et al*., 2014) In rewet peatland soils, N_2O emissions are low or negligible. (Beyer and Hoper, 2015)

In histosols in an oxic condition, pools of organic nitrogen that had been accumulating for hundreds to thousands are years are mineralized. Consequently, N_2O emissions often comprise as much as 15 percent of CO_2-equivalent weighted emissions of greenhouse gas emissions from drained histosols in agricultural uses. (Norberg *et al.*, 2016) Emissions-avoidance from rewetting is similarly large.

In some agricultural peatland acreages, large amounts of synthetic nitrogen are added to soils to improve crop productivity. In cropland, these take the form of synthetic nitrogen applications, while in pastures, manure nitrogen from grazing livestock constitutes the principal source of added nitrogen. N_2O is formed in soils during the nitrification of ammonium (NH_4^+) to nitrate (NO_3^-) and the denitrification of nitrate. Its formation during nitrification depends the presence of a pool of NH_4^+ in excess of plant nutritional needs. N_2O formation during denitrification similarly depends the presence in soils of excess NO_3^-. Fertilizer applications and manure nitrogen excreted from grazing livestock contribute to excess nitrogen in soils in the form of NH_4^+ and NO_3^-

These exogenous inputs of nitrogen to peatland soils cease with the retirement of these acres from agricultural use. Along with rewetting, this contributes to the N_2O emissions-avoidance observed in retired, rewet peatland soils.

N_2O emissions-avoidance from the retirement and restoration of cropped peatland soils or histosols is calculated as the difference between emissions from retired, rewet peatland soils and N_2O emissions from drained, cropped peatland soils. As our best estimate for N_2O emissions from post-retirement, post-restoration histosols, we selected the mean estimate for emissions from five statistically-based studies. These five studies included one meta-analysis of the results of published empirical site studies, and four other derivative statistical analyses of results from a similar pool of studies. Using this mean estimate, our best estimate of N_2O emissions from post-restoration peatlands is 0.26 ± 0.11 kilograms per hectare per year (0.23 ± 0.1 lbs. N_2O per acre per year). The results from these study-types were selected in deference to the place meta-analyses, and similar cross-study statistical analyses, increasingly have assumed in the scientific literature in determinations of response rates for ecological processes.

Overall we reviewed 27 studies with 29 study results, including 18 empirical site studies of N_2O emissions at rewet, formerly cropped or pastured sites, one meta-analysis of the results of these published empirical studies, and five other derivative statistical analyses of results from a similar pool of studies. One modeling study also was reviewed, as were two literature review-type studies or studies that reported results developed on the basis of expert judgment. By study type, the estimates scattered quite broadly, ranging from 0.26 kilograms per hectare per year to 5.59 kilograms per hectare per year. Confidence intervals were calculated. By study, and with few exceptions, the calculated confidence intervals straddled the zero value, indicating that, in a statistical sense, the mean estimates, again by study type, generally could not be said to be significantly different from zero.

Descriptive statistics for the 27 studies are shown in Table 36 by study type, as well as by monitoring period and by age of restoration.

Of the 18 empirical site studies that were reviewed, sixteen were chamber-based site studies, with an estimated mean annual N_2O emission of 5.59 kilograms per hectare per year. This is at substantial variance to the results from the meta-statistical analyses, as well as the mean results given in Table 36 for the other study types. Mean annual N_2O flux rates from post-restoration histosols are, for the modeling, literature review-type, and eddy-covariance site studies, 0.47, 0.26, and 0.54 kilograms of per hectare per year, respectively.

We chose the mean estimate of the six meta-statistical study as the best available estimate, fully aware of the difficulties posed by the flux estimates given in Table 36 by study type and restoration age. It seems possible that differences in water table depth across studies may explain the wide range of N_2O flux estimates with peatland restoration, as may differences in hydroperiod.

Clearly more empirical site studies, particularly those of the eddy covariance type, are needed. The evidence supports a positive rate of emission from rewet peatland soils, but with substantial variability in the estimates by study type and an uncertain central tendency.

Lastly, the retirement of histosols from agricultural uses and their rewetting will result in a decreased N_2O flux to the atmosphere, which we estimate in Table 32 at CO_2-equivalent 251,000 short tons of per year on 100,000 acres (18.93 kilograms of N_2O per hectare per year). Again, this was calculated as the difference, on 100,000 acres, between N_2O emissions from retired, rewet peatland soils and muck, and those from drained cropped peatland soils. We identified ten studies in the literature that presented a similar calculation, with a mean estimate for histosols formerly in agricultural production of -7.79 kilograms of N_2O per hectare per year, or less than half of our estimate in Table 32 (see Tables 32 and 36). This may argue for a substantially higher N_2O flux rate for post-restoration histosols than the 0.26 kilograms per hectare per year in use in this report.

Table 36. Descriptive statistics: Restored peatlands - N_2O

	emissions (kg N_2O/ hectare/yr) [a]	number of study results [b]	ratio, positive to negative results: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses or other derivative statistical analyses or statistical summaries [c]	0.26	8	8/0	0.11	0.05	0.47
all studies	3.23	29	29/0	1.68	(0.07)	6.53
empirical site studies	5.03	18	18/0	2.65	(0.16)	10.22
modeling studies	0.47	1	1/0	NA	NA	NA
literature reviews/expert judgment	0.26	2	2/0	0.26	(0.25)	0.7673
eddy covariance site studies	0.54	2	2/0	0.45	(0.34)	1.42
other site studies	5.59	16	16/0	2.96	(0.21)	11.39
1 to 9 year old constructed/restored wetlands	2.55	11	11/0	0.96	0.67	4.43
10 year old-plus constructed/restored wetlands	10.24	6	6/0	7.74	(4.94)	25.42
growing season and subgrowing season flux monitoring/modeling	1.09	7	7/0	0.71	(0.29)	2.48
annual flux monitoring/modeling	4.09	21	21/0	2.30	(0.42)	8.60
1 year of observations or simulations	1.93	11	11/0	0.79	0.37	3.49
>1 year of observations or simulations	8.72	8	8/0	5.80	(2.64)	20.09
studies with pre-restoration counterfactual:						
restored peatlands: cropland/pastureland counterfactual	(8.63)	10	2/8	2.18	(13.21)	(4.05)
restored peatlands: peatland extraction counterfactual	(0.64)	9	1/8	0.89	(2.38)	1.11

[a] negative emissions = removal from atmosphere and destruction in soils

[b] 29 study results, 27 studies (1 meta-analyses, 5 other statistical summaries or derivative statistical analyses, 1 modeling studies, 18 empirical site studies, 2 literature reviews)

[c] derivative statistical studies other than meta-analyses

ii. N_2O emissions from drained peatland soils in agricultural use

In anaerobic conditions, stocks of soil organic nitrogen (SON) are protected against microbial decomposition. In an immobilized form, these stocks are unavailable for nitrification and denitrification, microbial metabolic processes that produce N_2O. Nitrous oxide is produced as a byproduct of the nitrification of ammonium (NH_4^+) and, along with dinitrogen (N_2), an end product of denitrification. Denitrification depends on the availability of soil nitrate, which is produced in soils during nitrification. Nitrification, in turn, requires that soil organic nitrogen be converted to NH_4^+, a mineral form of nitrogen. In anaerobic environments, soil organic nitrogen is protected against mineralization, an aerobic process, and hence is effectively immobilized in that form.

In intact, undisturbed peatlands, the accumulation of nitrogen in plant biomass and soils outpaces nitrogen losses, leading to large stores of organic nitrogen in these soils. Peatland soils in the US contain an estimated 150 million metric tons of nitrogen[13], or 18 metric tons per hectare (eight short tons per acre).

With drainage, otherwise immobilized organic nitrogen is mineralized, making it available for nitrification and denitrification by soil microbial populations. With large soil organic nitrogen abundances and high mineralization rates, emissions of N_2O are some 14-fold higher from drained cropped and pastured peatland soils than from undisturbed peatland soils, an estimated 15.4 kilograms N_2O per hectare per year (13.7 lbs. per acre), as opposed to the 1.1 kilograms N_2O per hectare per year estimated to be emitted from undisturbed peatland soils. (Leppelt *et al*., 2014)

N_2O production in drained cropped and pastured peatlands soils are highest in peatlands subject to episodic high soil water conditions. Nitrification of NH_4^+ requires aerobic conditions, while denitrification, which utilizes the end-product of nitrification, NO_3^-, requires generally anaerobic conditions. N_2O formation is optimized in drained peatlands with oscillating low and high soil water (Tiemeyer *et al*., 2016), driven either by variations in peatland water table or by episodic surface saturation from precipitation and run-off.

In some agricultural peatland acreages, large amounts of synthetic nitrogen are added to soils to improve crop productivity. In cropland, these take the form of synthetic nitrogen applications, while in pastures, manure nitrogen from grazing livestock constitutes the principal source of added nitrogen. N_2O is formed in soils in the presence of NH_4^+ and NO_3^- in excess of plant needs. N_2O formed as a result of these exogenous inputs of nitrogen adds to already high releases of N_2O beyond from SON mineralization. Of mineralization and these exogenous inputs of nitrogen, mineralization is the dominant of the two in terms of N_2O produced. (Maljanen *et al.*, 2013)

In introducing oxygen deeply into the soil column, tillage promotes SON mineralization. In addition, by accelerating soil organic matter decomposition, it promotes the episodic formation of anaerobic conditions in cultivated peatland soils that are necessary for the formation of N_2O resulting from denitrification.

Water table height is the principal control on N_20 production and emission from drained peatlands in agricultural use. (Leppelt *et al*., 2014) Other controls include: soil pH and bulk density, soil temperature, soil water-filled pore space, carbon to nitrogen ratios in soils, and, as noted above, the presence or absence of a highly dynamic water table. (Kasimir-Klemedtsson *et al.*, 2009; Leppelt *et al*., 2014; Tiemeyer *et al*., 2016)

In drained peat soils in agricultural use, water tables are lowered through surface drainage or with open ditches.

To estimate emissions from drained histosols in agricultural use, we reviewed 58 studies with 74 study results. Some studies reported results for both drained cropland and pastured histosols, some multiple estimates by study type. In developing our database, where results are reported for multiple study types and for both cropland and pastured peatlands soils, we retained both sets of estimates.

In developing the estimates given in Table 32 for N_2O, for emissions from drained, cropped histosols we used the results reported in eight statistical analyses. These included two meta-analyses of the results of published empirical site studies, and six other derivative statistical analyses of results from a similar pool of studies. For pastured, drained histosols, we used mean estimates of the results from nine meta-

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[13] 8.3 billion metric tons of carbon from USGCRP (2018) at 0.019 metric tons of nitrogen per metric ton of carbon, from Leifeld and Menichetti (2018)

statistical analyses, including two meta-analyses and six other derivative statistical analyses. Using the mean of estimates drawn from published meta-analyses and other derivative statistical analyses, drained cropped peatland soils and muck are estimated to emit, on an annual basis, 19.19 ± 2.87 kilograms of N_2O per hectare per year (17.12 ± 2.56 lbs. N_2O per acre per year), while annual N_2O emissions from pastured, drained peaty soils are estimated at 8.67 ± 1.53 kilograms of N_2O per hectare per year (see Table 37).

In aggregate, we reviewed 31 empirical site studies, two modeling studies, eight literature reviews or studies that report results based on expert judgment, four meta-analyses, and 13 other derivative statistical analyses. Mean N_2O emissions across all 58 studies and 74 study results were an estimated 16.17 kilograms of N_2O per hectare per year (14.43 lbs. N_2O per acre per year). Of these 74 study results, 74 reported net N_2O emissions, none an N_2O soil sink.

Table 37. Descriptive statistics: Restored peatlands - N_2O emission counterfactual [a]

	emissions (kg N_2O/ hectare/yr) [b]	number of study results [c]	ratio, positive to negative results: study numbers [d]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
Peatland drained for agricultural uses						
meta-analyses and other derivative statistical analyses or statistical summaries [e]	13.62	17	17/0	2.01	9.68	17.56
cropland	19.19	8	8/0	2.87	13.56	24.82
pastureland	8.67	9	9/0	1.53	5.68	11.66
all studies	16.15	74	74/0	1.88	12.46	19.84
modeling studies	22.05	4	4/0	5.90	10.48	33.61
literature reviews/expert judgments	11.21	17	17/0	1.00	9.24	13.18
site studies [f]	18.62	37	37/0	3.49	11.78	25.46
Peatland drained for peat extraction	2.22	18	18/0	0.67	0.90	3.54
Peatland drained for all purposes	13.40	97	96/1	1.62	10.23	16.57

[a] counterfactual = emissions from drained cropped peatlands

[b] negative emissions = removal from atmosphere and destruction in soils

[c] 74 study results, 58 studies (17 meta-analyses or statistical summaries or derivative statistical analyses, 2 modeling studies, 31 empirical site studies, 8 literature reviews)

[d] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[e] derivative statistical analyses = statistical analyses other than meta-analyses of study results in the publishd literature

[f] mean emission rate for drained cropped histosols of 5.3 kg CH_4/ha/yr, and, for drained pastureland, of 47.27 kg CH_4/ha/yr

The 31 site studies reported 37 study results, the mean of which was some 18.62 kilograms of N_2O per hectare per year (16.61 lbs. of N_2O per acre per year). By agricultural use, mean emission levels from empirical studies were, for cropped histosols, 24.04 kilograms of N_2O per hectare per year, and for pastured drained peaty, mucky soils, 13.50 kilograms of N_2O per hectare per year. Across all drainage purposes, including drainage for peat extraction and forestry, mean annual N_2O emissions per hectare were 13.4 kilograms (12 lbs. N_2O per acre per year).

The evidence supports a positive N_2O emission rate from drained peatland soils in agricultural use, in the range of 10 to 20 kilograms of N_2O per hectare per year (8.9 to 17.8 lbs. of N_2O per acre per year), with a best estimate for cropped peatlands at the upper end of this range, at about 20 kilograms of N_2O per hectare per year.

Descriptive statistics across all studies of drained histosols in agricultural uses are given in Table 37.

c. Methane

In drained peatland soils, CH_4 emissions are inhibited by aerobic conditions, which are toxic to methanogens. In drained, oxic peatlands, organic matter is decomposed through aerobic microbial processes and results in the production of CO_2. In undisturbed histosols, waterlogged conditions, anaerobic conditions prevail. In anaerobic conditions, organic matter is decomposed through a chain of hydrolytic and fermentative processes, resulting finally in CH_4, the end product of the reduction of CO_2 and acetate.

By in-filling of drainage ditches, drained peatlands are hydrologically restored, or rewet. In rewet peatlands, water tables are returned to pre-disturbance levels, resulting in the reestablishment of anaerobic conditions, as well as the processes by which organic matter is decomposed anaerobically. Elevated emissions of CH_4 result.

We discuss post-restoration emissions of CH_4 in the following subsection (Section IV, subsection G.c.i). We discuss CH_4 emissions from drained or pastured histosols in the subsequent subsection (Section IV, Subsection G.c.ii, "CH_4 emissions from drained peatland soils in agricultural use").

i. CH_4 emissions from retired, rewet peatland soils

In undisturbed peatlands, inundation resulting from high water tables inhibits aerobic microbial respiration. In place of aerobic processes, anaerobic processes dominate. In undisturbed peatland, organic matter is decomposed by a consortium of hydrolytic, fermentative, and methanogenic bacteria, resulting in the production of CH_4, the final end production of anaerobic microbial respiration. Drainage removes the inhibition on the microbial oxidation of organic carbon, suppressing CH_4 emissions. The restoration of water levels in peatlands reestablishes anaerobic conditions. As a consequence, CH_4 production, and its emission, recommences, returning to roughly to pre-drainage levels, if somewhat less. (Swenson *et al*., 2016; Urbanova *et al*., 2013)

Methane from rewet peatland is emitted directly from the peatland surface or from incompletely in-filled drainage ditches. Drainage ditches are hotspots for CH_4 emission from peatland soils, comprising as much as two-thirds of CH_4 emissions from rewet peatlands. (Cooper *et al.*, 2014)

CH_4 emissions from the surface itself are the difference between methane production by methanogens in the anoxic peat zone and CH_4 oxidation by methanotrophs in the surface layer. Some CH_4 produced in the saturated anoxic zone are transported to the surface by diffusion or ebullition (bubble formation). As CH_4 diffuses upward, it is made available for oxidation by methanotrophs, soil bacteria that oxidize CH_4, eliminating it. Methanotrophs exist in a symbiotic relationship with submerged sphagnum, the dominant form of vegetation in peat bogs. Methane also is transported to the surface in the tissues of aerenchymatous plants, bypassing these methanotrophs. Aerenchymatous plants are a type of deep-rooted vascular plant. An estimated 30 to 100 percent of the total upward CH_4 flux to the surface is through plant-mediated transport. (Vanselow-Algan *et al*., 2015; Li *et al*., 2016)

Methane is anaerobically produced in peatlands soils by methanogens as the terminal product of the anaerobic decomposition of organic matter, again in saturated, anaerobic environments. Methanogens are facultative bacteria that reduce CO_2 and acetate, intermediate products of anaerobic decomposition, to CH_4. Most CH_4 production results from the breakdown on the products of recent plant photosynthesis. In general, old, recalcitrant peat deposits play a minor role in CH_4 formation. In producing CH_4, methanogens use recently fixed organic carbon released to peatland soils as root exudates and plant litter fall and, through hydrolysis and fermentation, made available as carbohydrate. (Li *et al*., 2016) Methane production is greatest in nutrient-rich peatlands, which upon rewetting emit large amounts of CH_4. (Wilson *et al*., 2018) Rewet, formerly productive pasture is an especially heavy emitter of CH_4. (Hendriks *et al*., 2007) By contrast, nutrient-poor peatlands, like bogs, are low emitters of methane. (Swenson *et al*., 2018) In general, of the principal peatland types, fens are nutrient-rich, while bogs are nutrient-poor.

CH_4 production does not recommence immediately upon peatland rewetting, but may be delayed several years. (Oikawa *et al*., 2013; Urbanova *et al*., 2013) Some vascular plant species like *Eriophorum* *spp.* are an early successional species in bogs. Their presence may act to promote CH_4 emissions from otherwise nutrient-poor bogs through CH_4 xylem transport. (Waddington and Day, 2007)

Water table height is the dominant control on CH_4 production in rewet peatlands. (Wilson *et al*., 2016) Other controls on CH_4 production include: soil temperature, pH, carbon substrate availability and quality, peatland primary productivity, and soil moisture in the layer above the water table. (Abdalla *et al*., 2016; Wilson *et al*., 2016) The presence and extent of vascular plants is the principal control on the transport of CH_4 through the soil column.

CH_4 may be mitigated to a degree through the in-fill of only partially filled drainage ditches and the removal of vascular plants from ditches. (Waddington and Day, 2007) By lowering the water table 10 to 30 centimeters (3.9 to 11.8 inches), some avoidance of CH_4 production may be possible (Hoper *et al*., 2016; Polyda *et al*., 2016), albeit at the expense of elevated peatland CO_2 emissions (see Section IV. Subsection G.a.i).

CH_4 emissions-avoidance from the retirement and restoration of cropped peatland soils or histosols is calculated as the difference between methane emissions from retired, rewet peatlands, and CH_4 emissions from drained cropped peatland soils. Avoided-emissions from the retirement and rewetting of drained, pastured histosols are similarly calculated. CH_4 emissions from drained cropped and pastured peatland soils or muck are discussed in the following subsection (Section IV, Subsection G.c.ii).

To estimate post-retirement emissions from rewet histosols, we reviewed 65 studies with 67 study results, including 52 empirical site studies of CH_4 emissions at rewet, formerly cropped or pastured sites, three meta-analyses of the results of these published empirical studies, and four other derivative statistical analyses of results from roughly the sale pool of studies. Two modeling studies also were reviewed, as were four literature review-type studies or studies that reported results developed on the basis of expert judgment. We used the results the three of the meta-analyses, combined with the results from other four derivative statistical studies, to best represent post-restoration CH_4 emissions.

Using the mean of the results from these seven meta-statistical studies, post-retirement, post restoration CH_4 emissions from peatland soils and muck are estimated to be 170 ± 30.26 kilograms per hectare per year (151.67 ± 27.0 lbs. CH_4 per acre per year). As noted in Section II of this report, in selecting response rates, we give preference to the results of formal meta-analyses, along with those from similar derivative statistical analyses. Meta-analysis, in particular, was designed specifically to address the problem of mean response rate under conditions of wide variability in environmental and other conditions and divergent study designs.

Estimated post-restoration emissions of CH_4 from the all 65 studies were higher than those from the meta-statistical studies, 240 kilograms per hectare per year (214 lbs. CH_4 per acre per year), as were those for empirical site studies (258 kilograms CH_4 per hectare per year) and modeling studies (358 kg CH_4 per hectare per year). Of empirical studies, eddy covariance studies are state-of-the art. Annual per hectare emissions of CH_4 from eddy covariance studies were 383 kilograms, or more than twice that from the meta-statistical studies.

Table 38. Descriptive statistics: Restored peatlands - CH_4

	emissions (kg CH_4/ hectare/yr) [a]	number of study results [b]	ratio, positive to negative results: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses and other derivative statistical analyses or statistical summaries [c]	169.86	9	9/0	30.26	111	229
all studies	240.24	67	66/1	39.43	163	318
empirical site studies	258.39	52	51/1	49.21	162	355
eddy covariance site studies	383.01	12	12/0	84.29	218	548
other site studies	221.00	40	39/1	57.96	107	335
modeling studies	358.19	2	2/0	316.85	(263)	979
literature reviews/expert judgment	103.67	4	4/0	43.58	18	189
annual flux monitoring/modeling	280.96	47	47/0	40.15	202	360
growing season and subgrowing season flux monitoring/modeling	163.02	20	19/1	93.37	(20)	346
1 year of observations or simulations	340.21	19	19/0	115.57	114	567
> 1 year of observations or simulations	219.68	35	34/1	39.90	141	298
1 to 9 year old restored peatlands	216.44	33	32/1	63.34	92	341
10 year old-plus restored peatlands	314.41	22	22/0	70.91	175	453
studies with pre-restoration counterfactual:						
restored peatlands: cropland/pastureland counterfactual	169.50	19	19/0	33.79	103	236
restored peatlands: meta-analyses and other derivative statistical analyses or summaries	157.11	12	12/0	25.09	108	206

[a] negative emissions = removal from atmosphere and destruction in soils

[b] 67 study results, 65 studies (3 meta-analyses, 4 statistical summaries or derivative statistical analyses, 2 modeling studies, 52 empirical site studies, 4 literature reviews)

[c] derivative statistical studies other than meta-analyses

Across all study types, per hectare annual CH_4 emissions ranged from 104 to 383 kg CH_4. Not surprisingly, the mean results from studies with year-long monitoring of fluxes were 70 percent higher than those growing season-only flux monitoring. Emissions of CH_4 from peatland restorations older than 10 years exceeded those from younger restorations, by not quite 50 percent.

The studies were uniform in their judgment that, with peatland rewetting and retirement from agricultural uses, CH_4 emissions will increase dramatically. The evidence supports an emission rate upon peatland restoration of between 150 and 400 kilograms of CH_4 per hectare per year (134 to 357 lbs. of CH_4 per acre per year), with a best estimate of 170 kilograms per hectare per year. There is no evidence to suggest that peatland soils might act in any other way than as large net emitting sources.

Descriptive statistics across all studies of retired, rewet histosols formerly in agricultural uses are given in Table 38. Since most of the science on practice-based greenhouse gas emissions is developed in metric units, these are given in metric units and converted to lbs. per acre per year for inclusion in the summary Table 32.

Lastly, the retirement agricultural uses of histosols and their rewetting will result in an increased CH_4 flux to the atmosphere, which we estimate in Table 32 at 151,000 CO_2-equivalent short tons per year on 100,000 acres (135.48 kilograms of CH_4 per hectare per year). Again, this was calculated as the difference, on 100,000 acres, between CH_4 emissions from retired, rewet peatlands, and CH_4 emissions from drained cropped peatland soils. We identified 17 studies (19 study results) in the literature that presented a similar calculation, with a mean estimate of 169 kilograms per hectare per year. Of these, 12 were results from results from meta-analyses and other derivative statistical assessments, yielding a mean of 157 kilograms per hectare per year, or again quite near our estimate in Table 32.

ii. CH_4 emissions from drained peatland soils in agricultural production

As in rewet peatland soils, CH_4 in drained peatland soils is produced in anoxic zones by facultative methanogenic bacteria. Once formed, CH_4 is transported through diffusion to surface layers, from which it is emitted to the atmosphere. The anoxic zone in drained peatland soils is found at fairly deep levels.

Peat at deep levels is old and partially degraded, limiting CH_4 production deep in the soil column. (Shafer *et al*., 2012) The limited amount of CH_4 that is produced at deeper, anoxic levels is largely oxidized during transport through the oxygen-rich overlying oxic peat layers. (Veber *et al*., 2018) This oxygen-rich layer is populated by methanotrophs, autotrophic bacteria that oxidize methane to gain energy for growth and maintenance. This acts to destroy CH_4 before it can be emitted to the atmosphere. Some small amounts of CH_4 may be produced at anaerobic micro-sites in overlying oxygen-rich layer of peat, but generally conditions in this overlying layer are toxic to CH_4–producing methanogens. (Shafer *et al*., 2012; Urbanova *et al*., 2013)

By introducing oxygen deeply into soils, conventional tillage acts to reinforce the oxic conditions in the overlying unsaturated agricultural peat layers.

In drained peat soils in agricultural use, water tables are lowered through surface drainage or with open ditches. Significant amounts of CH_4 are often formed in these ditches or at their edges, from which CH_4 is subsequently emitted. (Kroon *et al*., 2010)

Drained peatlands in agricultural use are generally small sources of CH_4, and sometimes net sinks. (Abdalla *et al*., 2016) Acting as a sink, dried peatland soils destroy atmospheric CH_4 through the microbial oxidation. Where CH_4 is emitted in small quantities, most of this derives from CH_4 produced in drainage ditches. (Teh *et al*., 2011)

Water table height is the predominant control on CH_4 emissions from drained agricultural peatlands. Water table height controls the size of the oxic, unsaturated zone, which increases as the water table falls. Other controls include: soil temperature, pH, precipitation, and substrate availability at deep peat layers. (Veber *et al*., 2016)

To estimate emissions from drained histosols in agricultural use, we reviewed 52 studies with 67 study results reporting in aggregate 67 study results. Of these, 32 study results were from empirical site studies of CH_4 emissions at drained cropped or pastured sites. Another five were meta-analyses of the results of published empirical studies, and nine were other derivative statistical analyses of results from a similar pool of studies. Eight were literature review-type studies or studies that reported results developed on the basis of expert judgment.

We selected the results from seven statistical analyses as our best estimate of CH_4 emissions from drained, cropped histosols. These included three formal meta-analyses of the results of published empirical studies, and four other derivative statistical analyses of results from roughly the sale pool of studies. For pastured, drained histosols, we used the results from seven meta-statistical analyses, including two meta-analyses and five other derivative statistical analyses. As noted in Section II of this report, in selecting response rates, we give preference to the results of formal meta-analyses, along with those from similar derivative statistical analyses. Using the mean of estimates drawn from published meta-analyses and other derivative statistical analyses, drained cropped peatland soils and muck are estimated to emit, on an annual basis, 34.38 ± 10.01 kilograms of CH_4 per hectare per year (30.67 ± 10.01 lbs. of CH_4 per acre per year).

Annual CH_4 emissions from pastured, drained peaty soils are estimated at 41.78 ± 12.81 kilograms of CH_4 per hectare per year (32.28 ± 11.43 lbs. of CH_4 per acre per year, see Table 39). Since much or most of the science on greenhouse gas emission is developed in metric units, this average rate is, in either case, given in metric tons of carbon and then converted to short CO_2-equivalent tons for use in calculating the values shown for CH_4 emissions-avoidance in the summary Table 32.

Descriptive statistics across all studies of drained histosols in agricultural uses are given in Table 39.

Mean CH_4 emissions across all 52 studies and 67 study results were an estimated 27.71 ± 6.83 kilograms of CH_4 per hectare per year (24.28 ± 6.10 lbs. of CH_4 per acre per year). 51 of these 67 study reported net CH_4 emissions, eleven a CH_4 soil sink. The 32 site studies reported 40 study results, the mean of which was some 27.83 kilograms of CH_4 per hectare per year (24.83 lbs. CH_4 per acre per year). By agricultural use, mean emission levels from empirical studies were, for cropped histosols, 5.30 kilograms of CH_4 per hectare per year, and for pastured drained peaty, mucky soils, 47.27 kilograms of CH_4 per hectare per year.

With the exception of the results from the literature type-studies, none of the confidence intervals, calculated by study type or land-use, overlapped with the zero value (see Table 39). The evidence supports a positive CH_4 emission rate of 10 to 40 kilograms per hectare per year (8.9 to 35.6 lbs. of CH_4 per acre per year).

Table 39. Descriptive statistics: Restored peatlands - CH_4 emission counterfactual [a]

	emissions (kg CH_4/ hectare/yr) [b]	number of study results [c]	ratio, positive to negative results: study numbers [d]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
Peatland drained for agricultural uses						
meta-analyses and other derivative statistical analyses or statistical summaries [e]	38.64	14	13/1	7.91	23	54
cropland	34.38	7	6/1	10.04	15	54
pastureland	41.78	7	7/0	12.81	17	67
all studies	27.71	67	51/16	6.83	14	41
literature reviews/expert judgments	10.72	13	9/4	6.62	(2)	24
site studies [f]	27.83	40	29/11	10.19	8	48
Peatland drained for peat extraction	17.85	21	20/1	4.90	8	27
Peatland drained for all purposes	25.27	93	76/17	5.17	15	35

[a] counterfactual = emissions from drained cropped peatlands

[b] negative emissions = removal from atmosphere and destruction in soils

[c] 67 study results, 52 studies (14 meta-analyses or statistical summaries or derivative statistical analyses, 32 empirical site studies, 6 literature reviews)

[d] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[e] derivative statistical analyses = statistical analyses other than meta-analyses of study results in the publishd literature

H. Retire/rewet cropped mineral wetlands

Through the presence of anaerobic conditions, organic carbon is sequestered in the soils of mineral wetlands. In this, mineral wetland soils act similarly to peatland soils. Strictly anaerobic conditions act to slow the decomposition of organic matter in mineral wetland soils, allowing it to be retained longer in wetlands soils, and leading to the net removal of CO_2 from the atmosphere. When drained for agriculture, this protection against decomposition is removed, resulting in large net emissions of carbon to the atmosphere in the form of emitted CO_2. The soil carbon that, after drainage, is lost from mineral wetlands is old carbon, accumulated over many decades.

The retirement of mineral wetlands from agricultural use and their subsequent rewetting returns wetland soils to pre-drainage conditions. CO_2 emissions cease and, gradually, these soils begin to accumulate organic carbon. As in the case of peatland soils, rewetting acts to increase CH_4 emissions, which offsets a part of greenhouse gas-avoidance that otherwise would have resulted from the hydrological restoration of drained mineral wetlands. N_2O emissions usually decline with wetlands retirement from agricultural use, but generally are less of a factor in the calculations.

Greenhouse gas-avoidance resulting from the retirement of mineral wetlands from agricultural uses and their rewetting is the difference between carbon sequestration in retired, rewet mineral wetlands and CO_2 emissions from drained, cropped mineral wetlands, plus any change in CH_4 and N_2O emissions resulting from wetland rewetting and their retirement from agricultural use. Historically, large numbers of acres of wetlands in Minnesota have been drained for agricultural and other purposes, six million acres or more. (Dahl 1990)

In mineral wetlands drained many decades ago, levels of soil organic carbon (SOC) are likely to have stabilized, resulting in no net CO_2 emissions. Here we focus solely on recently drained mineral wetlands, those drained over the last few decades.

In the process of wetland restoration, water tables are raised and native wetland plants are reintroduced to mineral wetland soils. Soil may be excavated to recreate pre-drainage topography, including surface depressions. During wetland restoration, drainage tiles are removed or drainage ditches are dammed, raising water tables to close to or at the soil surface level.

We calculate greenhouse gas-avoidance as the difference on 100,000 acres between emissions from rewet wetlands that are no longer in agricultural use and emissions from the same wetlands in their pre-rewet, drained, cropped condition. This is shown in Table 40. We estimate that, for each 100,000 acres of mineral wetland soils that are retired from cultivation and rewet, 220,000 CO_2-equivalent short tons of greenhouse gas emissions would are avoided annually. Of this, an estimated 442,000 short tons of CO_2 would be removed from the atmosphere annually as a result of mineral wetland restoration. With rewetting, CH_4 emissions from mineral wetland soils rise dramatically, adding back to emissions totals about 276,000 CO_2-equivalent short tons of emissions. Avoided-emissions of N_2O account for 19,000 CO_2-equivalent short tons of GHG-avoidance annually, while the foregone manufacture of agricultural chemicals and foregone agriculture fuels use account for another 27,000 CO_2-equivalent short tons of emissions-avoidance.

In developing the estimates shown in Table 40, as elsewhere in this report, a 20-year timespan for terrestrial carbon storage was assumed. In our judgment, this is the longest that continuous storage, once initiated, safely can be assumed. Under this assumption, annually avoided-emissions would be an estimated 220,000 CO_2-equivalent short tons. Had a 40-year period of assured storage been assumed, avoided-emissions from peatland retirement and restoration would have totaled 360,000 CO_2-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 775,000 CO_2-equivalent short tons (see Table 40). The approach that we use in converting observed rates of sequestration to avoided-emissions was addressed above in the Methodology section (Section II).

It should be noted, again, that the calculations given in this section pertain to rewet mineral wetlands soils that only recently, within the past few decades, have been drained and converted to cropland. We also do not address less aggressive forms of mineral wetland restoration, for instance, prairie pothole restoration, where restoration might involve only the avoidance of cropping in dry years, without rewetting. Lacking data, we do not address emissions-avoidance from the retirement of drained, pastured mineral wetlands soils.

We do estimate the effect on greenhouse gas emissions of constructed or created mineral wetlands. These are artificially constructed wetlands, usually on upland formerly cropped soils. We assumed an equilibrium condition to have attained in these soil with respect to SOC prior to wetland construction, with no net cultivation-induced change in SOC levels. It is customary to assume that, after a native grassland is converted to cropland, SOC levels stabilize after a number of decades of agricultural use. Under this assumption, the construction of these upland artificial wetlands would act to increase greenhouse gas emissions by 82,000 CO_2-equivalent short tons per year (see Table 40). Much of this results from methane emissions, which are large in constructed wetland but nonexistent in upland soils.

Table 40. Restored mineral wetlands: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils or sediments	(18,970)	crop production
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	not known	crop production
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(7,186)	crop production
CH_4	soils or sediments	276,183	crop production
CO_2 [b,c]	carbon accumulation in wetland sediments and biomass	(441,823)	crop production
CO_2	cultivated soils from lime or urea use	(2,808)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	(6,849)	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(20,184)	crop production
Total		**(221,637)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass			
40 year storage	all sources and sinks	**(360,079)**	crop production
100 year storage	all sources and sinks	**(775,404)**	crop production
Emissions from Constructed Wetlands on Upland Soils [d]			
GHGs	all sources and sinks	**81,744**	crop production

[a] positive = emissions increase, negative = emissions reduction

[b] carbon accumulation in soil and biomass = net removal of CO_2 from the atmosphere = net emission reduction

[c] assumes 20 years of sustained storage of newly sequestered organic carbon in soils and biomass

[d] assumes the excavation of a formerly cropped upland soil in an equilibirum condition with respect to SOC

Small depressional mineral wetlands respond only very slowly to rewetting and retirement from agricultural use. The results given here may not be representative of greenhouse gas emission-avoidance from rewetting this class of mineral wetlands.

Terrestrial carbon sequestration in rewet, formerly cropped mineral wetlands is discussed below, followed by a discussion of post-rewet emissions of N_2O and CH_4 emissions. Small amounts of N_2O emissions from nitrate loading of groundwater and surface water and volatilized and land deposited ammonia contribute to the totals shown in Table 40, as do avoided-emissions from avoided fuel use and from the manufacture of agricultural chemicals foregone. The methods and sources used to estimate avoided-emissions from these sources were discussed above in the Methodology section (Section II, Subsection E) of this report. Counterfactual emissions from drained/cropped mineral wetlands also are addressed. Due to a paucity of information on emissions from drained, cropped mineral wetlands, for our counterfactual, we limit the data that we use to the results from two meta-analyses of published data only.

a. Carbon sequestration in soils and biomass

In a restored condition, freshwater mineral wetlands act to accumulate organic carbon, removing it from the atmosphere and offsetting CO_2 emissions from elsewhere in the economy. Anaerobic conditions in mineral wetland soils inhibit the decomposition of organic matter, causing it to accumulate. (Yu *et al.*, 2017) Once established, wetland plant communities are extremely productive. Wetland plants provide an abundant source of organic carbon, which is introduced to restored wetland soils in the form of plant litter and root senescence and exudation. Sediments washed in from interconnected water bodies provide an additional source of organic carbon, which, with nutrients that also are washed in from interconnected water bodies, act to sustain a high level of mineral wetland productivity.

In a drained state, organic matter in the soils of mineral soils are subject to intense oxidation, which results in the loss of carbon to the atmosphere in the form of CO_2. (Ballantine, *et al*., 2011) Oxidation in drained mineral wetlands is sustained by generally aerobic conditions. These ease with the rewetting of wetlands soils.

In restored mineral wetlands, water tables are allowed to rise to pre-drainage levels through drainage tile removal or the in-fill of drainage ditches. Sometimes, restoration requires that depressions be introduced to the landscape, which results in the removal of most soil organic matter and the compression of subsoils. This can make it difficult for wetland plant communities to be reestablished, slowing the rate of carbon accumulation in these soils. The introduction of top soil and other organic amendments to these otherwise compromised systems has been suggested as a means to circumvent the negative effects of present-day construction practices. (Ballantine *et al*., 2011)

Rates of organic carbon accumulate vary substantially depending on restored wetland type and condition. Restored depressional wetlands with little interconnection with other water bodies accumulate organic carbon more slowly than restored wetlands in the riparian zone, which receive large external inputs of nutrients and organic matter overland and from interconnected water bodies. (Ballantine and Schneider, 2009) Restored wetlands that are continuously inundated accumulate more carbon than those that, with pulsing hydrology, experience seasonal dry downs, like wet soils in flood plains. (Moreno-Mateos *et al*., 2012) During periods when inundation is absent, aerobic conditions are established in wetland soils, leading in these periods to accelerated soil organic matter decomposition. Large restored mineral wetlands recover more quickly after drainage, and accumulate organic carbon at higher rates, than smaller restored mineral wetlands. (Moreno-Mateos *et al*., 2012) Poorly designed restored wetlands with top soils removed often are poor performers, requiring as long as a century to approach pre-disturbance levels of stored organic carbon. (Ballantine *et al*., 2011; Fennessy and Craft, 2008) Within restored mineral wetlands, deep, permanently inundated open water areas with continuously anaerobic soil conditions sequester carbon at faster rates than shallow areas populated with deep-rooted, highly productive macrophytes, but also periodic low water. (Bernal and Mitsch, 2013)

In the most rapidly responding restored mineral wetlands, rapid accumulation of organic carbon does not commence until the beginning of the second decade after restoration. (Bernal and Mitsch, 2013; Vidon *et al*., 2014) In these systems, wetland biogeochemical functions are not fully restored until two decades after restoration. (Moreno-Mateos *et al*., 2012) For slowly accumulating restored systems, like restored depressional mineral wetlands, carbon accumulation in wetland soils does not accelerate beyond low initial levels until 35 years or so after restoration. (Ballantine and Schneider, 2009) Averaging across all restored mineral wetland types, in temperature climates about 80 percent of wetland biogeochemical functions are reestablished by year 30 after restoration. (Moreno-Mateos *et al*., 2012)

Restored prairie potholes are a special class of restored mineral wetlands. During dry years, some prairie potholes are cropped and often are not drained, particularly in the western reaches of the Prairie Pothole Region. For these, restoration involves an absence of cropping in dry years, but no hydrological changes.

Organic carbon may accumulate in restored mineral wetlands from the deposition in the wetland of exogenously produced plant biomass, and from the deposition of sediments and organic particles imported into restored wetlands from surrounding water bodies. However, depending on the fate of the exogenously introduced organic matter in the counterfactual, e.g., in mineral wetlands in a drained cropped condition, the introduction of exogenously produced organic matter from beyond the boundaries of the wetland catchment may or may not represent a net removal of carbon from the atmosphere. For instance, if in absence of the restored wetland, these exogenous imports were to have been deposited deep within flood plain soils, terrestrial burial still would have occurred, and in conditions that would have inhibited decomposition.

Conversely, in the absence of the restored mineral wetland, had this exogenously imported otherwise been decomposed, deposition in the restored wetland would have involved net carbon removal from the atmosphere. As a practical matter, for now it is impossible to distinguish between the two cases.

Constructed or created wetlands are wetlands that are constructed in depressions of upland agricultural soils, mainly for nutrient and sediment control. Depending on hydrology and construction method, constructed wetlands can rapidly sequester organic carbon or only very slowly. (Hosler and Bouchard, 2011; Maynard *et al*., 2011; Mitsch *et al*., 2012; Moore and Hunt, 2012; Cole *et al*., 2001) Due to the paucity of published studies of carbon sequestration in either restored mineral wetland or constructed mineral wetlands separately, it is customary to use the results from studies of both these classes of mineral wetlands to assess the effectiveness of different practices. (Balantine *et al*., 2011; Li *et al*., 2020; Moreno-Mateos *et al*., 2012; Yu *et al*., 2017) We follow this practice.

Finally, controls on organic carbon accumulation in restored mineral wetlands include: water table height, frequency of inundated conditions, wetland net primary productivity, plant community type, nutrient availability and in-flow, and soil type and clay and silt soil content. (Maynard *et al*., 2011; Tangen *et al*., 2015; Yu *et al.*, 2017)

As noted above, large amounts of sediment and woody debris may be washed into riverine or littoral wetlands and flood plains. The resulting additional carbon storage, however, might not represent a net removal of carbon from the atmosphere, but rather a simple translocation of stored organic carbon from one terrestrial pool to another. That type of translocation is most likely to show up as net carbon sequestration in soil sampling-type studies, which measure simple accretion rates.

In total ecosystem carbon studies, whether eddy covariance-based or chamber-based, carbon sequestration is calculated as the difference between, on the one hand, photosynthetic removals of carbon from the atmosphere and its incorporation into plant biomass and ecosystem respiration, on the other hand. Some translocated organic carbon may be respired back to the atmospheres, with the effect that, while in soil sampling sequestration may be overestimated, it may be somewhat underestimated in total ecosystem carbon (TEC) studies by the amount of this additional respired carbon.

So as to not overestimate the sequestration potential of restored or constructed mineral wetlands, we utilize the result from the TEC studies as the best estimate of carbon sequestration in these systems. We reviewed ten total ecosystem studies, nine of which reported net sequestration, one net carbon losses. The mean annual sequestration rate for these ten studies was 2.2 ± 0.55 metric tons of carbon per hectare (0.98 ± 0.25 short tons of carbon per acre per year). This is the estimated rate prior to truncation for an assumed 20-year persistence of newly stored carbon in rewet mineral wetlands.

Overall, we reviewed 47 studies, including 32 empirical site studies, three meta-analyses of the results of published site studies, three additional statistical analyses or summaries of the results from similar pools of study results, two modeling studies, and seven literature reviews or studies that reported results developed on the basis of expert judgment. Of the empirical site studies, 32 were soil sampling-type studies, eight were eddy covariance type TEC studies, and one was a chamber-based TEC study. By study type, mean carbon sequestration rates ranged from 0.68 ± 0.51 metric tons of carbon per hectare, in the case of the two modeling studies, to 2.51 metric tons of carbon per hectare, in the case of the eddy covariance-type empirical site studies.

The mean rate of sequestration across all study types was 2.21 ± 0.38 metric tons of carbon per hectare per year. Of the 47 studies reviewed, two reported net carbon emissions to the atmosphere, two no change in carbon storage, and 43 net sequestration.

The mean rate of sequestration from the three meta-analyses was 2.11 metric tons of carbon per hectare per year, or not too different from the mean rate of the TEC studies. By wetland type, half of the sequestration studies treated sequestration in constructed wetlands, half sequestration in restored wetlands. The mean rate of carbon sequestration in constructed wetlands was about 60 percent higher than that for hydrologically restored, retired mineral wetlands.

The weight of the evidence points to a mean rate of sequestration, prior to truncation for 20-years of assumed storage, in the range of 1 to 2.5 metric tons of carbon per hectare (0.45 to 1.12 short tons of carbon per acre per year), with a best estimate of 2.2 metric tons of carbon per hectare.

The descriptive statistics for the 47 studies that we reviewed are shown in Table 41. Since most of the science on practice-based greenhouse gas emissions is developed in metric units, these are given in metric units and have been converted to lbs. per acre per year for inclusion in the summary Table 40.

Table 41. Descriptive statistics: Constructed and restored wetlands - carbon sequestration in soils and biomass

	biogenic carbon sequestration (Mg C/ha/yr)	number of study results [a]	ratio of sequestration to emission: study numbers [b]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
total ecosystem carbon (NECB/NBP) [c]	2.20	10	9/1	0.55	1.12	3.28
soil organic carbon (SOC) only	1.97	23	20/1/2	0.54	0.91	3.04
eddy covariance empirical site studies (NECB/NBP)	2.51	8	7/1	0.63	1.28	3.75
chamber empirical site studies (NECB/NBP)	1.73	1	1/0	NA	NA	NA
empirical site studies-soil sampling	2.32	23	20/1/2	0.54	1.26	3.38
meta-analyses	3.15	3	3/0	1.26	0.68	5.61
other derivative statistical analyses or statistical summaries [d]	1.11	3	3/0	0.42	0.30	1.93
modeling studies	0.68	2	2/0	0.51	(0.31)	1.67
literature reviews/expert judgment	1.28	7	7/0	0.41	0.47	2.09
constructed wetlands	2.65	20	19/1	0.61	1.46	3.85
restored wetlands	1.67	21	20/1	0.43	0.83	2.52
1 to 9 year old constructed/restored wetlands	3.03	12	10/1/1	0.90	1.27	4.79
10 year old-plus constructed/restored wetlands	2.10	18	16/1/1	0.51	1.10	3.11

[a] 47 study results, 47 studies (3 meta-analyses, 3 statistical summaries or derivative statistical analyses, 2 modeling studies, 32 empirical site studies, 7 literature reviews)

[b] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[c] NECB = Net Ecosystem Carbon Balance; NBP = Net Biome Productivity

[d] derivative statistical studies other than meta-analyses

i. CO_2, N_2O and CH_4 emissions from drained mineral wetland soils in agricultural use

In this study, net carbon sequestration in the mineral wetland soils resulting from their retirement from agricultural use and their rewetting is calculated as the difference between, on the one hand, post-restoration or post-construction sequestration rates and, on the other hand, rates of CO_2 emission from drained mineral wetland soils in agricultural use.

The biogeochemical processes leading to the emission of CO_2 from drained, cropped mineral wetland soils are the same as those involved in organic carbon loss from drained peatland soils in agricultural use. See Section IV, Subsection G.a.ii for that discussion. Published estimates of carbon loss from drained mineral wetlands that are in agricultural use are few in number. The most authoritative derives from an IPCC-developed meta-analysis-like statistical study, the results of which we use as our best estimate of CO_2 emissions from drained, cropped mineral wetland soils. Using this, annual CO_2 emissions from drained mineral soils are an estimated 1.86 metric tons of carbon per hectare (0.83 short tons of carbon per acre per year). This is shown in Table 42.

Also shown in Table 42 are emission estimates for N_2O and CH_4 from drained, cropped mineral wetland soils, along with the sources for each estimate. Our best estimate for drained mineral wetlands of 6.91 kilograms of N_2O per hectare per year (6.16 lbs. per acre per year). For CH_4, our best estimate for emissions is 99.12 kilograms of CH_4 per hectare per year (88.43 lbs. per acre per year).

Table 42. Summary factors: Avoided conversion of mineral wetlands

Wetland Type	**value**	**units**	**source type**	**reference**
Drained mineral wetlands				
CO_2 emissions	1.86	Mg C/ha/yr	[a]	IPCC (2014)
CH_4 emissions	99.12	kg CH_4/ha/yr	meta-analysis	Tan, *et al*. (2019)
N_2O emissions	6.91	kg N_2O/ha/yr	meta-analysis	Tan, *et al.* (2019)
Unmanaged mineral wetlands				
Carbon sequestration in biomass and soils	2.20	Mg C/ha/yr	meta-analyses and other derivative statistical analyses [a]	Bridgeman, *et al.* (2006), Gilmanov, *et al.* (2010), Kolko, *et al.* (2018), Taillardat, *et al.* (2020), Tan, *et al.* (2019), Villa and Bernal (2018)
CH_4 emissions	402.82	kg CH_4/ha/yr	meta-analyses and other derivative statistical analyses [a]	Bridgeman, *et al.* (2006), Knox, *et al.* (2019), Kolko, *et al.* (2018), Taillardat, *et al.* (2020), Tan, *et al.* (2019), Treat, *et al.* (2018), Treat, *et al.* (2019), Trettin, *et al.* (2018)
N_2O emissions	1.88	kg N_2O/ha/yr	meta-analysis	Tan, *et al.* (2019)

[a] statistical analyses other than meta-analyses

Given the small population of studies upon which these best estimates are based, confidence in these estimates, by necessity, is limited. A great deal more work is necessary for these estimates to be better refined and qualified. It seems possible that emission rates will need to be developed for specific wetland types (e.g., depressional, riverine, lascustrine) and by wetland age. Until the scientific literature is better developed, caution is probably best advised in the use of the estimates shown in both Tables 40 and 42.

b. Nitrous oxide

Mineral wetlands located in agricultural regions often are restored with nitrate (NO_3^-) control as the principal intent. Typically, in a completely inundated wetland, N_2O production is inhibited by a limited supply of NO_3^-. In fully inundated conditions, anaerobic conditions prohibit the oxidation (nitrification) of ammonium (NH_4^+) to NO_3^-, limiting its abundance and thus its reduction, during microbial denitrification, to N_2O and dinitrogen (N_2). With an abundant import of nitrate from external sources, in restored mineral wetlands in intense agricultural settings, no such constraint exists to the reduction of NO_3^- to N_2O. (Fennessy and Craft *et al*., 2011; Freeman *et al*., 1997; Sovik et al., 2006; Stadmark and Leonardson, 2005)

N_2O production is particularly intense in restored mineral wetlands with a variable water table and episodic dry-downs, during which, in partially aerobic conditions, in marsh edges, NH_4^+ is nitrified to NO_3^-. This acts to provide additional nitrate for N_2O production in subsequent periods of high water. (Hernandez and Mitsch *et al*., 2006; Kandel *et al*., 2019; Pennock *et al*., 2016) Also, N_2O is produced as a byproduct of nitrification itself. With a central body of deep open water surrounded by shallow marsh edges, the design of restored mineral wetlands also contributes. (Groh *et al*., 2015)

For all of these reasons, N_2O production in and emission from restored mineral wetlands is roughly of the same order of magnitude as that from drained, cropped mineral wetlands. (Kluber *et al*., 2014) In drained mineral wetlands, conditions are largely aerobic with interspersed anaerobic conditions, the result of the consumption of oxygen in soils during intense decomposition of organic matter. N_2O is produced in aerobic soils as a byproduct of nitrification and, under anaerobic conditions, as a terminal product of denitrification.

N_2O production in restored mineral wetlands is highly variable site-to-site. In some restored mineral wetlands with deep open water and complete, permanent inundation, denitrification proceeds through the reduction of NO_3^- to N_2, bypassing N_2O formation. (Berryman *et al*., 2009)

Avoided N_2O emissions are calculated as the difference between emissions from drained mineral wetlands in agricultural use and those from restored and retired mineral wetlands or constructed mineral wetlands. Due to the paucity of published studies of greenhouse gas emissions from either restored mineral wetland or constructed mineral wetlands separately, it is customary to use the results from studies of both these classes of mineral wetlands to assess the effectiveness of different practices. (Li *et al*., 2020) Per hectare rates of emission of N_2O from drained mineral wetlands in agricultural use was discussed above in Section IV, Subsection H.a.

We estimated N_2O emissions from hydrologically restored (rewet) and constructed mineral wetlands using the average of 15 empirical site studies that we identified in the published literature. No meta-analysis of the body of published results was available, nor were modeling studies or studies of another type. Using the mean from these 15 site studies, N_2O emissions from constructed/restored mineral wetlands were estimated to be 5.49 ± 2.06 kilograms of N_2O per hectare per year (4.90 ± 1.84 lbs. of N_2O per acre per year). Five studies gave results for constructed mineral wetlands, while ten of the study results were for hydrologically restored mineral wetlands.

The descriptive statistics for constructed and restored mineral wetlands are shown in Table 43. As elsewhere in this report, these are given in metric units and converted to lbs. per acre per year for inclusion in the summary Table 40. In the relatively few studies of N_2O emissions from constructed wetlands, N_2O emissions were an estimated 8.47 ± 3.32 kilograms per hectare per year (7.56 ± 2.96 lbs. per acre per year), while those from the ten studies of N_2O fluxes from restored mineral wetlands were 3.99 ± 2.59 kilograms per hectare per year (3.56 ± 2.31 lbs. per acre per year), or substantially lower.

Mean estimated emissions from hydrologically restored or constructed wetlands differed little by wetland age or by monitoring period, by 25 percent or less. Differences were larger for wetlands by number of years of observations, with an estimated range of 4.88 to 6.7 kilograms per hectare per year.

Given the relatively few available study results, the error bars shown in Table 43 generally are large and/or indicate a lack of statistical significance. For this reason, caution is advised in uncritically accepting the estimates given in Table 43. It seems possible that, with more study results, the true rate of N_2O emission from these wetland types may prove to be substantially lower or substantially higher than the Table 43 results.

Lastly, we reviewed nine studies that evaluated the change in N_2O emissions resulting from the restoration and retirement from agricultural use of cropped drained mineral wetlands. Averaged across the nine studies, annual N_2O emissions declined with rewetting and retirement an estimated 2.77 kilograms per hectare. Using out best estimates for N_2O emissions from drained mineral wetlands (6.91 kilograms of N_2O per hectare per year) and from restored/constructed mineral wetland soils (5.49

kilograms per hectare per year), we calculate a change in emissions of (-) 1.42 kilograms per hectare per year, or about half that from the nine studies from the literature that provided estimates.

Table 43. Descriptive Statistics: Constructed and restored wetlands - N_2O

	emissions (kg N_2O/ hectare/yr) [a]	number of study results [b]	ratio, positive to negative results: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	5.49	15	15/0	2.06	1.45	9.52
site-empirical studies	5.49	15	15/0	2.06	1.45	9.52
annual flux monitoring/modeling	6.11	7	7/0	2.56	1.10	11.12
growing season and subgrowing season flux	4.94	8	8/0	3.30	(1.53)	11.40
constructed wetlands	8.47	5	5/0	3.32	1.97	14.97
restored wetlands	3.99	10	10/0	2.59	(1.07)	9.06
1 year of observations or simulations	6.70	5	5/0	3.75	(0.66)	14.06
> 1 year of observations or simulations	4.88	10	10/0	2.57	(0.16)	9.92
1 to 9 year old constructed/restored wetlands	7.02	7	7/0	3.65	(0.14)	14.18
10 year old-plus constructed/restored wetlands	6.18	5	5/0	3.48	(0.63)	12.99
studies with counterfactuals	-2.77	9	2/6/1	4.60	(11.79)	6.25

[a] negative emissions = removal from atmosphere and destruction in soils

[b] 15 study results, 15 studies (15 empirical site studies)

[c] derivative statistical studies other than meta-analyses

c. Methane

The same biogeochemical processes that control the production of CH_4 in rewet peatlands soils also operate in the soils of hydrologically-restored mineral wetlands. From the perspective of CH_4 production and emission, roughly the same conditions prevail in rewet mineral wetland soils as prevail in rewet peatland soils. These processes and conditions were discussed in Section IV, Subsection G.c.i.

Avoided CH_4 emissions are calculated as the difference, on 100,000 acres, between emissions from drained mineral wetlands in agricultural use and emissions from restored and retired mineral wetlands or constructed mineral wetlands. Again, due to the paucity of published studies of greenhouse gas emissions from either restored mineral wetland or constructed mineral wetlands separately, it is customary to use the results from studies of both these classes of mineral wetlands to assess the effectiveness of different practices. (Li *et al.*, 2020; Mitsch *et al.,* 2014) Per hectare rates of emission of CH_4 from drained mineral wetlands in agricultural use was discussed above in Section IV, Subsection H.a.

We reviewed 34 studies of CH_4 emissions from restored and constructed mineral wetlands. Due to multiple study results by study type in four studies, 38 study results are included in our database of results. Of the 34 studies, 30 were empirical site studies, one a literature review, one was a formal meta-analysis of the study results that are found in the published literature for CH_4 emissions from rewet/constructed mineral wetlands, and two were related statistical analyses of roughly the same body of published results. We selected the mean emission rate from the one meta-analysis and other two related statistical analyses as the best estimate of CH_4 emissions from retired and rewet mineral wetlands. From this value, rewet mineral wetlands annually emit 347 ± 87 kilograms of CH_4 per hectare per year (309 ± 78 lbs. per acre per year), or almost twice that from rewet peatland soils.

Our database contains 23 study results for constructed mineral wetlands and fifteen results for hydrologically-restored mineral wetlands. Mean estimated CH_4 emissions in the 23 studies from constructed mineral wetlands were 339 ± 64 kilograms per hectare per year (302 ± 57 lbs. per acre per year), and those from rewet mineral wetlands were 347 ± 90 kilograms of CH_4 per hectare per year (309 ± 81 lbs. of CH_4 per acre per year).

By study type, leaving aside the sole literature review, study results clustered in a reasonably tight range of 328 to 458 kilograms of CH_4 per hectare per year. Estimated rates of emission were higher in older constructed and retired/rewet mineral wetlands than younger such wetlands, likely as the result of the gradual return of natural wetland function with age. As might be expected, emissions reported on an annual basis were larger than those reported on a growing season basis.

The descriptive statistics for the 34 studies that were reviewed are shown in Table 44. These are given in metric units and have been converted to lbs. per acre per year for inclusion in the summary Table 40.

Table 44. Descriptive statistics: Constructed and restored wetlands - CH_4

	emissions (kg CH_4/ hectare/yr) [a]	number of study results [b]	ratio, positive to negative results: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses and other derivative statistical analyses or statistical summaries [c]	346.77	4	4/0	86.89	176	517
all studies	341.97	38	38/0	51.83	240	444
empirical site studies	347.11	33	33/0	58.79	232	462
eddy covariance site studies	454.94	5	5/0	155.78	150	760
other site studies	327.85	28	28/0	64.00	202	453
literature reviews/expert judgment	153.00	1	1/0	NA	NA	NA
annual flux monitoring/modeling	403.96	23	23/0	62.92	281	527
growing season and subgrowing season flux monitoring/modeling	289.72	12	12/0	104.26	85	494
constructed wetlands studies	338.60	23	23/0	63.79	214	464
restored wetlands studies	347.13	15	15/0	90.44	170	524
1 year of observations or simulations	375.25	17	17/0	84.82	209	541
> 1 year of observations or simulations	317.14	17	17/0	78.25	164	471
1 to 9 year old constructed/restored wetlands	262.07	15	15/0	72.16	121	403
10 year old-plus constructed/restored wetlands	426.78	14	14/0	83.36	263	590
studies with pre-restoration counterfactual	266.73	7	6/1	154.70	(36)	570

[a] negative emissions = removal from atmosphere and destruction in soils

[b] 38 study results, 34 studies (1 meta-analysis, 2 statistical summaries or derivative statistical analyses, 30 empirical site studies, 1 literature reviews)

[c] derivative statistical studies other than meta-analyses

Finally, we reviewed seven studies that included estimates of the change in CH_4 emissions resulting from the restoration of mineral wetlands. The mean annual change in CH_4 emissions from these seven studies was some 267 kilograms per hectare, albeit with very large error bars. Using the estimates in Tables 42 and 44 for rewet and for drained, cropped mineral wetlands, we estimate annual CH_4-avoidance from rewetting at a very similar 244 kilograms CH_4 per hectare per year.

On the whole, CH_4 emissions from constructed mineral wetlands and hydrologically retired mineral wetlands that have been retired from agricultural use appear to be well understood. We find little evidence that, upon restoration, these wetlands will not be large emitters of CH_4 emissions upon retirement. The weight of the evidence points to an annual emissions in the range of 150 to 400 kilograms of CH_4 per hectare per year.

I. Winter cover crop/Catch crop

Winter cover crops or catch crops are crops, typically cereal rye, perennial rye grass, or winter wheat, that are planted to scavenge excess nitrate from cropland soils, thereby reducing the potential for nitrate leaching into groundwater and, through groundwater flows, to surface waters. Winter cover crops typically are sown after fall harvest of principal cropland cash crops like corn or soybeans, and are chemically or mechanically killed in early spring within a few weeks of the planting of the coming year’s cash crops. Typically, winter cover crops are unharvested; residues from winter cover crops either are incorporated into soil by plowing or are left on the surface to decompose.

Winter cover cropping can use leguminous-type cover crops like hairy vetch or Austrian pea or nonleguminous cereal grains like cereal rye. The residues from leguminous cover crops are rich in organic nitrogen. Leguminous cover crops often are planted as a source of nitrogen to the cash crop that in the spring follows cover crop termination. (Blanco-Canqui *et al*., 2015) With additional nitrogen from a biological source, agricultural producers can limit or wholly eliminate nitrogen-based mineral fertilizer applications to cropland.

Non-leguminous cover crops have deep, extensive rooting systems, which allows for efficient scavenging of excess nitrate from soils. Because of high carbon-to-nitrogen ratios in roots, non-leguminous cover crop residues are somewhat more resistant to decomposition than are leguminous cover crops, and, of the two cover crops types, produce the most biomass per acre planted. (Sainju *et al*., 2018).

By extending the period of active photosynthetic activity into the winter months, cover crops produce large amounts of organic carbon in crop residues that, when added to soils, lead to the accumulation of organic carbon in soils. While both leguminous and nonleguminous cover crops act to build soil carbon, of the two cover crop types, nonleguminous cover crops like cereal rye are more effective in this role. (Kuo *et al*., 1997; Sainju *et al*., 2018) Cereal rye is cold tolerant which, in a cool climate like that of Minnesota, is of importance.

In addition to nitrate scavenging and carbon sequestration, the use of winter cover crops acts to: improve soils structure, reduce water and wind erosion of soils, decrease soil compaction, suppress weeds, and increase biodiversity. (Blanco-Canqui *et al*., 2015; Poeplau *et a*l., 2015) As of 2012, four percent of cropland in the US lake states (Minnesota, Wisconsin and Michigan) that was planted with corn was also cropped with cover crops. (Baranski *et al*., 2018)

In the US Midwest, most cover cropping uses nonleguminous cover crops, particularly cereal rye.

We estimate that, for each 100,000 acres of cropland in winter cover crops, 27,000 CO_2-equivalent short tons of GHGs would be avoided annually. Of this, most would result from biogenic carbon sequestration in cover crop soils. Reduced N_2O emissions from surface water and groundwater resulting from reduced leaching also would be important. Emissions of N_2O from cropped soils generally increase under cover crops, offsetting some of otherwise avoided-emissions through reduced nitrate leaching and soil carbon sequestration. About 95 percent of emissions-avoided would be from in-state sources, and the remainder from the avoided out-of-state manufacture of fertilizer, other agricultural chemicals and fuels. Table 45 shows the estimated net annual greenhouse gas balance from the use of cover crops on 100,000 acres of cropland.

Table 45. Winter cover crops/Catch crops: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	7,511	no cover crop
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	not known	no cover crop
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(7,329)	no cover crop
CH_4 [b]	soils	22	no cover crop
CO_2 [c,d]	carbon accumulation in soils	(26,248)	no cover crop
CO_2	cultivated soils from lime or urea use	-	no cover crop
GHGs-energy	fossil fuel and electricity use in crop production	519	no cover crop
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(1,187)	no cover crop
Total		**(26,712)**	
Emissions with leguminous cover crops-only:			
GHGS	all sources and sinks	**(21,281)**	no cover crop
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass			
40 year storage	all sources and sinks	**(52,960)**	no cover crop
100 year storage	all sources and sinks	**(131,704)**	no cover crop

[a] positive = emissions increase, negative = emissions reduction

[b] a reduction in soil CH_4 oxidation = a relative increase in CH_4 emissions

[c] carbon accumulation in soils = a net removal of CO_2 from the atmosphere = net emission reduction

[d] assumes 20 years of sustained storage of newly sequestered organic carbon in soils and biomass

As elsewhere in this report, in developing the estimates shown in Table 45, it was assumed that 20 years was the longest period of time over which sustained terrestrial carbon storage, once initiated, safely could be assumed. Under this assumption, avoided-emissions are an estimated 27,000 CO_2-equivalent short tons, as noted above. Had a 40-year period of assured storage been assumed, avoided-emissions from the use of cover crops would have totaled 53,000 CO_2-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 132,000 CO_2-equivalent short tons (see Table 45). The approach that we use in converting observed rates of sequestration to avoided-emissions was addressed above in the Methodology section (Section II) of this report.

An additional calculation was done specific to the use of leguminous cover crops, essentially to account for the emissions-avoided effects of less required usage of mineral nitrogen fertilizers. With leguminous winter cover crops, like hairy vetch, an estimated 21,000 CO_2-equivalent short tons of GHGs would be avoided annually on 100,000 acres. The use of leguminous winter cover crops acts to increase direct N_2O emissions from cropland soils, more than offsetting any emission reduction resulting from reduced use and manufacture of synthetic fertilizer.

A number of published studies have estimated net GHG-avoidance under cover cropping. Estimates from these studies of net GHG-avoidance are shown below in Table 46. Taken together, these studies report an average annual rate of avoidance of 0.53 CO_2-equivalent short tons per acre (1.19 CO_2equivalent metric tons per hectare per year).

Terrestrial carbon sequestration resulting from the use of winter cover crops is discussed below, as are avoided direct emissions of N_2O and the effects of winter cover corps on soil CH_4 oxidation. The methods and sources used to estimate avoided indirect N_2O emissions from nitrate leaching and ammonia volatilization, avoided-emissions from fuel use, and avoided-emissions from foregone agricultural chemicals and fuels manufacture were discussed in Section II, Subsection E.

a. Carbon sequestration in soils

Carbon accumulates in soils as a result of reduced decomposition of soil organic matter or, with decomposition rates held constant, increased inputs of organic carbon to soils. Reduced soil erosion and reduced leaching of dissolved organic carbon also can contribute to increasing stocks of soil organic carbon (SOC). Through extensive root systems, cover crops add substantial amounts of soil organic matter to soils. Soil aggregate formation is enhanced by soil organic matter. (Blanco-Canqui *et al*., 2015; Ruis and Blanco-Canqui, 2017) Soil aggregates act to physically protect soil organic matter from bacterial decomposition. In addition, fungi and bacteria associated with cover crop rhizodeposits produce organic acids, like lactate and acetate, and other polymers, which act to bind organic matter to mineral surfaces, adding another, biochemical, layer of protection to soils. (Austin *et al*., 2017; Sainju *et al*., 2003)

By enhancing the physical and biochemical protection of soil organic matter from decomposition, cover crops act to length the residence time of carbon in soils, thereby increasing soil carbon stocks. (Wang *et al*., 2012)

In itself, the extra carbon input to soils from decomposing cover crop residues acts to increase soil organic carbon stocks. At a constant rate of decomposition, any increase in carbon inputs will result in an increase in soil carbon stocks. With cover crops, carbon is added to soils in the form of crop residues, mostly in the form of belowground roots and rhizodeposits. As noted above, of now available cover crops, cereal rye produces the most plant biomass, hence adds the most organic carbon back to soils.

Table 46. Published estimates of greenhouse gas-avoidance from cover crop use [a]

		emissions avoided [a]	
Study	**Type of study**	**CO_2-eq. short tons per acre per year**	**CO_2-eq. short tons per 100,000 acres per year**
Fronning *et al.* (2008) [b]	site study	(0.07)	(7,136)
Gelfand and Robertson (2015)	site study	0.50	49,953
Gong *et al.* (2021)	site study	(0.10)	(10,098)
Lehuger *et al.* (2011)	site study	0.08	8,172
Robertson *et al.* (2000)	site study	0.23	22,747
DeGryze *et al.* (2010)	modeling study	0.60	59,840
DeGryze *et al.* (2011)	modeling study	0.53	53,465
Legato *et al.* (2020)	modeling study	1.56	156,104
Fargione *et al.* (2018)	literature review/expert judgment	0.52	52,298
Graves *et al.* (2020)	literature review/expert judgment	0.52	52,183
Griscom *et al.* (2017)	literature review/expert judgment	0.52	52,298
Kaye and Quemada (2017)	literature review/expert judgment	0.67	67,125
O'Brien *et al.* (2014)	literature review/expert judgment	0.67	66,527
Swan *et al.* (2015) [c]	literature review/expert judgment	0.41	40,778
Abdalla *et al.* (2019)	other derivative statistical analysis [d]	0.92	91,878
Eagle *et al.* (2012)	other derivative statistical analysis [d]	0.86	85,634
This report	literature review	0.27	26,712

[a] results as reported without adjustments

[b] experiment with 100% corn stover removal

[c] partial difference, accounting for direct soils emissions and soil sequestration-only

[d] statistical analyses other than meta-analyses

The sequestration effects of cover crops are limited to the top two to eight inches (5 to 20 centimeters) of cropland soils. (Blanco-Canqui *et al*., 2011; Poeplau and Don, 2015) The potential for sequestration on global soils is an estimated 7.45 short tons of carbon per acre (16.7 metric tons per hectare) realizable over 155 years. (Poeplau and Don, 2015) Of this, about half, or 3.8 short tons per acre (8.5 metric tons per hectare) might be realizable in 23 years, or at an average annual rate of 0.17 short tons per acre (0.37 metric tons per hectare per year). Erosive losses of soil may be reduced by 50 percent by the introduction of cover crops. (Basche *et al*., 2016)

Due to the high spatial variability of soil organic carbon, it is often difficult to detect small changes in soil carbon. Because of this, it is thought that experiments lasting at least ten years may be necessary to determine whether and the degree to which the introduction of cover crops promotes carbon sequestration in cropland soils. (Mbuthia *et al*., 2015; Moore *et al*., 2013) Because of this, it is not uncommon for studies of short duration to be unable to detect cover crop effects on soil organic carbon. (Ruis and Blanco-Canqui, 2017) Meta-analysis and biogeochemical modeling have been suggested as alternative mean to understand long-term soil dynamics. (Poeplau and Don, 2015; Necpalova *et al*., 2018)

The estimates shown in Table 45 for winter cover crops on 100,000 acres were developed using meta-analyses estimates of average annual sequestration rates, discounted to account for an assumed 20-year persistence of newly sequestered organic carbon in soil. We reviewed 112 studies with 175 study results, including five meta-analyses, five other derivative statistical summaries or analyses, 60 empirical site studies (111 study results), 26 modeling studies (34 study results), and 16 literature reviews or studies that report results developed on the basis of expert judgment (17 study results). In certain instances, more than one observation was reported per study to accommodate multiple study results by type of tillage (conventional tillage, reduced tillage and no-till) and cover crop type (nonleguminous and leguminous). To derive maximum soil carbon benefits from cover cropping, cover cropping practice can be combined with less intrusive or no tillage. We track the results of cover cropping for different tillage practices with this consideration in mind.

Using the results from the meta-analyses, the introduction of cover crops to 100,000 acres of cropland would result in 26,000 CO_2-equivalent short tons of annual sequestration. As noted in the Methodology section of this report, formal meta-analysis is a powerful tool for aggregating estimates across study types with differing designs. Using the mean value for the five meta-analyses found in the scientific literature, winter cover crops are estimated to annually sequester 0.42 metric tons of carbon per hectare (0.19 short tons of carbon per acre per year). This is the estimated rate prior to truncation to accommodate a 20-year assumed persistence of carbon in cropland soils.

The descriptive statistics for the 112 studies that were reviewed are shown in Table 47. These are given in metric tons of carbon, but converted to short CO_2-equivalent tons for inclusion in the summary Table 45. The average of all studies reviewed (0.32 metric tons per hectare per year) is nearly identical to what is given in the Poeplau and Don (2015) meta-analysis. By study type, the estimates range from 0.24 to 0.52 metric tons per hectare per year (0.11 to 0.23 short tons of carbon per acre per year). Estimated annual sequestration from the 60 empirical site studies is some 0.32 ± 0.05 metric tons per hectare (0.14 ± 0.02 short tons of carbon per acre per year), or somewhat smaller than the meta-analyses estimate. Excluding the estimates drawn from the modeling studies, the estimates cluster in a range of 0.32 to 0.52 metric tons of carbon per hectare per year.

Overall, in slightly less than nine out of ten study results, cropland soil accumulated organic carbon under cover crops. The rate was slightly lower in empirical site studies, 8.2 out of 10. In a marked difference to the results for many of the practices considered in this report, confidence internals for cover crops across study type were not excessive.

Contrary to conclusions drawn from the scientific literature, sequestration on hectares with nonleguminous cover crops was slightly higher than that for leguminous cover crops or a mix of legumes and nonleguminous cover crops. Sequestration rates for soil depths of 4 to 12 inches (10 to 30 centimeters) were higher than those at depths of 16 inches (40 centimeters) and deeper, but not excessively so. It seems possible that, as more studies are published with sampling depths at or below 40 centimeters, our estimates for sequestration associated with cover crops may contract somewhat. In the scientific literature, sequestration rates often are said to peak in the first decade after the change in practice, declining thereafter. (Necpalova *et al*., 2018) This is borne out by the sequestration rates reported in Table 47.

Table 47. Descriptive statistics: Winter cover crops/Catch crops - carbon sequestration in soils

	biogenic carbon sequestration (Mg C/ha/yr)	number of study results [a,b]	ratio of sequestration to emission: number of study results [c]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	0.42	6	6/0	0.12	0.19	0.65
all studies	0.32	175	151/22/2	0.03	0.25	0.38
other derivative statistical analyses or statistical summaries [d]	0.52	7	7/0	0.15	0.22	0.83
site-empirical studies	0.32	111	90/20/1	0.05	0.23	0.41
modeling studies	0.24	34	32/2	0.05	0.13	0.35
literature reviews/expert judgment	0.32	17	17/0	0.07	0.18	0.46
nonleguminous cover crop	0.37	64	57/7	0.06	0.25	0.49
leguminous cover crop	0.26	49	39/10	0.05	0.16	0.36
mixed leguminous/nonleguminous cover crop or undifferentiated by cover crop type	0.31	57	51/6	0.04	0.22	0.39
conventional tillage	0.26	23	19/4	0.10	0.06	0.46
reduced tillage	0.25	36	29/6/1	0.06	0.13	0.37
no-till tillage	0.36	57	47/10	0.07	0.22	0.50
10 to 30 cm soil sampling/modeling depth [e]	0.36	98	85/12/1	0.04	0.28	0.44
> 40 cm soil sampling/modeling depth [e]	0.27	33	27/6	0.08	0.13	0.42
0 to 9 year annual sequestration rate	0.38	74	59/15	0.06	0.27	0.50
10 year or more annual sequestration rate	0.23	72	64/6/2	0.03	0.17	0.29
cover crops with no-till minus full inversion tillage without cover crops	0.63	27	24/3	0.18	0.27	0.99

[c] 175 study results, 112 studies (5 meta-analysis, 5 other derivative statistical analysis, 26 modeling studies, 60 empirical site studies, 16 expert reviews)

[d] 42 studies report multiple results by cover crop type (leguminous, nonleguminous) and/or tillage (no-till, reduced tillage, conventional tillage)

[e] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[d] statistical summaries or derivative statistical analyses other than meta-analyses

[e] results for lowest reported sampling depth

Differences in sequestration rates by tillage type are evident, which might suggest it might be possible to increase the effectiveness of cover crops in sequestering soil carbon by roughly 20 to 30 percent by simultaneously adopting less intensive tillage practices and cover cropping (see Table 47). An average annual gain in soil organic carbon of about 0.63 metric tons of carbon per hectare is reported in studies that compare a combined cover crop-no till regime to conventional tillage without cover crops (see Table 47).

In total, the weight of the evidence supports a generally positive response rate of soil carbon sequestration under cover crops, with a best estimate, before truncation for 20-years of assumed storage, of 0.42 metric tons of carbon per hectare per year (0.18 short tons of carbon per acre per year).

b. Nitrous oxide

N_2O is produced in cropland by nitrification and denitrification processes. N_2O production is controlled by adequacy of nitrate and ammonium in soils, subject to other limitations imposed by soil temperature, soil wetness, texture, bulk density, and other factors. (Venterea *et al*., 2012) These factors often interact nonlinearly, rendering broad generalizations somewhat problematical.

Having said that, cover crops impact N_2O emissions during the cover crop period by scavenging nitrogen from soils and immobilizing it in plant biomass. This acts to reduce the abundance of nitrogen that is available in soils for nitrification or denitrification. (Baggs *et al*., 2000) Following termination, cover crop residues are usually incorporated in the soils, where rapid decomposition of residues acts to consume soil oxygen, creating anaerobic microsites for denitrification. N_2O is produced in these anaerobic microsites by denitrifying bacteria. (Mitchell *et al*., 2013; Petersen *et al*., 2011; Sardokie-Addio *et al.*, 2003) Large N_2O emissions often follow cover crop termination and residue incorporation.

On an annual basis, these two processes are roughly equal in effect, leading to only small changes in N_2O emissions after the introduction of winter cover crops. (Basche *et al*., 2014; Blanco-Canqui *et al*., 2015; Gillette *et al*., 2018; Guardia *et al*., 2016)

Due to higher nitrogen content of plant tissues, leguminous cover crops may be more emitting on an annual basis than nonleguminous cover crops like cereal rye. (Basche *et al*., 2014; Gomes *et al*., 2009)

In this study, avoided-emissions from the use of cover crops are calculated as the product of the estimated percentage change in emissions resulting from use of cover crops and average Minnesota cropland N_2O emissions. Average Minnesota cropland N_2O emissions are taken from the MPCA Greenhouse Gas Inventory. To estimate the percentage change in N_2O emissions under cover crops we reviewed 46 studies with 73 study results across cover crop type and tillage practice. Of these, 30 studies (46 study results, again across cover crop type and tillage practice) were full-year studies, spanning cover crop and cash crop periods. Of the full-year studies, two were meta-analyses (2 study results), seven were modeling studies (13 study results), 19 were empirical site studies (28 study results), and two were literature reviews or studies that report estimates on the basis of expert judgment (2 study results).

We used the mean estimate from the two meta-analyses as the best estimate of the percentage change in N_2O emission with cover crops. Using the meta-analysis mean estimate, the use of winter cover crops is estimated to increase N_2O emissions by 12 ± 1 percent, a relatively minor change. By study type, the estimate percentage change ranged from +12 to +81 percent. The mean value for all 30 full-year studies that were reviewed was +20 ± 6 percent, slightly lower than that of the 19 empirical site studies that were reviewed.

Of the 30 full-year studies that were reviewed, in terms of study results, one-third reported emission reductions, while two-thirds reported increases. In the empirical site studies, about half of all the studies reported emissions reductions, which is nearer the larger sense of the scientific literature that, once the results are averaged, the percentage change in N_2O emissions will prove muted.

By cover crop type, the increase in full-year N_2O emissions ranged from 9 percent, in the case of nonleguminous cover crops, to 30 percent for leguminous cover crops. In the US Midwest, most current cover cropping involves the use of nonleguminous cover crops, particularly cereal rye. In the studies, N_2O emissions under no-till tillage increased substantially more than did N_2O emissions under conventional or reduced tillage, although on the basis of only a handful of observations for conventional and reduced tillage. The measured increase in N_2O emissions in empirical site studies with one to two years of results was more than double the more subdued rate suggested by the two meta-analyses. The percent increase in emissions in site studies with three years or more of results was less dramatic, but still about 12 percent.

The mean percentage change in the rate of N_2O emissions from all cover crop studies was much larger than for those studies reporting results only on an annual basis, reflecting the large percentage increase in N_2O emissions that often occurs during cover crop residue decomposition.

The descriptive statistics for the studies that were reviewed are shown in Table 48.

The general sense of the analysis presented here, and of the larger scientific literature, is that the effects of cover crops on N_2O soil emissions are likely to be muted. Best available evidence suggests a slight increase in emissions from the introduction of this practice.

c. Methane

The estimated change in methane soil oxidation resulting from the use of winter cover crops on 100,000 acres is miniscule, 22 CO_2-equivalent tons annually. The calculation of net greenhouse gas-avoidance from the use of winter cover crops is largely unaffected by changes in CH_4 emission from or oxidation in soils.

Methane is oxidized in soils by methanotrophic bacteria and is produced in cropland soils in anaerobic microsites by methanogenic bacteria. The balance between the two processes determines whether CH_4 is emitted from soils on a net basis or is consumed and whether a change in CH_4 from cropland, described in terms of CH_4 oxidation, enhances or reduces CH_4 oxidation.

In evaluating the effect of winter cover crops on CH_4 soil oxidation, we reviewed nine studies with 16 discrete observations, including six empirical site studies (nine study results) and three modelling studies (six study results). Using the average value from all nine studies, we estimate that the use of winter cover crops will reduce CH_4 soil oxidation by 1 percent, which applied on 100,00 acres, results in the reported 22 CO_2-equivalent tons of reduction in cropland CH_4 soil oxidation. As noted above, in some cases, more than one observation was reported per study to accommodate results developed for specific important parameters, in the case of cover crops, multiple types of tillage (conventional tillage, reduced tillage and no till practice) and two cover crop types (nonleguminous and leguminous).

Care should be taken with this estimate. Of the nine studies, 45 percent favor an increase in CH_4 soil oxidation with cover cropping, 55 percent a reduction, so the studies as a group are largely inconclusive as to the direction of the change. The 95 percent confidence intervals for this estimate are broad and bracket a set of outcomes ranging from a 26 percent increase in CH_4 soil oxidation to a 29 percent decrease.

Table 48. Descriptive Statistics: Winter Cover Crops/Catch Crops - N_2O

	emissions: % change in emissions per hectare	number of study results	change in emissions, ratio positive-to-negative: numbers of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
full crop studies: [a,b]						
meta-analyses	12%	2	2/0	1%	9%	14%
all studies	20%	46	30/16	6%	7%	33%
empirical site studies	24%	28	15/13	9%	6%	42%
modeling studies	2%	13	10/3	8%	-13%	18%
literature reviews/expert judgment	81%	2	2/0	44%	-6%	168%
nonleguminous cover crop	9%	22	14/8	7%	-4%	22%
leguminous and mixed legiminous/nonleguminous cover crop	30%	21	13/8	10%	10%	50%
no-till tillage	41%	13	11/2	16%	10%	72%
reduced tillage	26%	7	3/4	18%	-9%	61%
conventional tillage	-8%	10	5/5	7%	-22%	7%
1-2 years of observations or simulations	24%	19	11/8	9%	6%	42%
3 years or more of observations or simulations	12%	23	15/8	9%	-6%	30%
partial and full crop-year studies:						
meta-analyses	65%	11	9/2	45%	-22%	153%
all studies	30%	73	51/22	8%	13%	46%

[a] 46 study results, 30 studies (2 meta-analysis, 7 modeling studies, 19 empirical site studies, 2 expert reviews)

[b] 4 studies report multiple results by cover crop type (leguminous, nonleguminous), crop cover treatment (incorporated, nonincorporated, and/or tillage (no-till, reduced tillage, conventional tillage)

The descriptive statistics for the studies that were reviewed are shown in Table 49, including standard errors and 95 percent confidence intervals.

Table 49. Descriptive statistics: Winter cover crops/Catch crops - CH_4

	oxidation: % change in oxidation	number of study results	change in oxidation, ratio positive-to-negative: numbers of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
full crop-year studies: [a,b,c]						
all studies	-1%	16	7/9	14%	-29%	26%
empirical site studies	1%	9	4/5	25%	-49%	50%
modeling studies	-4%	6	3/3	6%	-16%	8%
legume cover crop	31%	6	4/2	20%	-8%	69%
nonleguminous cover crop	-22%	9	3/6	19%	-59%	14%
1 year of observations or simulations	21%	7	4/3	22%	-21%	63%
4 years or more of observations or simulations	-21%	7	3/4	22%	-64%	23%
partial and full crop-year studies:						
all studies	-11%	20	5/15	21%	-52%	30%

[a] 16 study results, 9 studies (3 modeling studies, 6 empirical site studies)

[b] 2 studies report multiple results by cover crop type (leguminous, nonleguminous), crop cover treatment (incorporated, nonincorporated, and/or tillage (no-till, reduced tillage, conventional tillage)

[c] cash crop period plus cover crop period

J. No-till tillage

In conventional tillage, cropland soils are disturbed by mixing and overturning. In its most extreme form, full inversion tillage using a moldboard plow, soil is inverted and mixed down to 8 inches (20 centimeters) or even deeper. By contrast, with no-till, cropland soils go completely untilled, as the name implies. Seeding is done through direct drilling. Weeds are controlled with herbicides. Crop residues are left on the soil surface to decompose.

In Minnesota, relatively little cropland is in no-till cultivation, six percent according to the last available survey. (US Department of Agriculture, 2019). As of 2016, ten percent of all cropland in the US lake states (Minnesota, Wisconsin and Michigan) was in continuous no-till practice and another 13 percent in occasional no-till. (Baranski *et al.*, 2018)

Tillage acts to disrupt soil structure by breaking apart soil aggregates, removing physical and biochemical protections against the microbial decomposition of organic carbon. Physical disruptions to soils are avoided under no-till, allowing soils that under conventional tillage had become carbon-depleted, to reaccumulate carbon. Accumulating soil carbon is carbon that, having been photosynthetically removed from the atmosphere and incorporated into plant biomass, is introduced to soils through root-turnover and rhizodeposits and stabilized there.

No-till may or may not increase soil N_2O emissions. The best available information supports a small increase in emissions, although this is subject to large uncertainties. With fewer field operations, fuel use is reduced under no-till practice, reducing emissions of CO_2 from fossil fuel use in crop production.

In evaluating the emissions-avoidance effects of no-till, we assumed that no-till would be continuously practiced for at least 20 years, without occasionally interspersed years of full inversion tillage. It is possible that governmental policies and programs may be needed to support continuous no-till practice.

A budget of avoided greenhouse gas emissions from no-till cultivation is given in Table 50. We estimate that, for each 100,000 acres of cropland converted from full inversion tillage to no-till practice, 14,000 CO_2-equivalent short tons of emissions that, in absence of a change in tillage practice, would have occurred would be avoided. All of this, plus some, is accounted for by enhanced soil organic carbon (SOC) sequestration in soils. Increased soil emissions of N_2O would offset about 40 percent of the sequestration effects. About 95 percent of emissions-avoidance is from in-state sources, with the remainder from the avoided out-of-state manufacture of fertilizer, other agricultural chemicals and fuels.

In quantifying avoided-emissions, we assumed that carbon stored in soils would remain there for 20 years, followed by microbial decomposition and emission to the atmosphere as CO_2. This is the longest period over which, in our opinion, sustained storage safely can be assumed. Under this assumption, avoided-emissions are an estimated 14,000 CO_2-equivalent short tons. Had a 40-year period of assured storage been assumed, avoided-emissions from the use of no-till practice would have totaled 33,000 CO_2-equivalent short tons. Had 100-years of assured storage been assumed, avoided-emissions would have totaled 88,000 CO_2-equivalent short tons (see Table 50).

The amount of time in storage determines the degree to which, for any particular project, sequestered carbon offsets CO_2 emissions from fossil fuel combustion elsewhere in the economy. This determines the present-day offset value of sequestration. The approach that we use in converting observed rates of sequestration to avoided-emissions was addressed above in the Methodology section (Section II) of this report.

The published literature contains a number of studies of the integrated effect of no-till practice across all greenhouse gases and all emissions sources. The results of these, shown in Table 51, all support a positive emissions effect of conventional tillage to no-till conversions, with reductions per 100,000 acres of conversions ranging 14,000 to 181,000 CO_2-equivalent short tons.

Biogenic carbon sequestration from the use of no-till on cropland soils is discussed below, as are avoided direct emissions of N_2O from soils and the effects of no-till on soil CH_4 oxidation. The methods and sources used to estimate avoided indirect N_2O emissions from nitrate leaching and ammonia volatilization, avoided-emissions from fuel use, and avoided-emissions from foregone agricultural chemicals and fuels manufacture were discussed above in Section II, Subsection E.

Table 50. No-till tillage: Emissions-avoided [a]

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [b]	Counterfactual
N_2O-direct	soils	7,071	conventional tillage
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	553	conventional tillage
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	-	conventional tillage
CH_4 [c]	soils	(283)	conventional tillage
CO_2 [d,e]	carbon accumulation in soils	(18,319)	conventional tillage
CO_2	cultivated soils from lime or urea use	-	conventional tillage
GHGs-energy	fossil fuel and electricity use in crop production	(2,713)	conventional tillage
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(601)	conventional tillage
Total		**(14,291)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils			
40 year storage	all sources and sinks	**(32,610)**	conventional tillage
100 year storage	all sources and sinks	**(87,567)**	conventional tillage

[a] conventional tillage counterfactual

[b] positive = emissions increase, negative = emissions reduction

[c] increase in soil CH_4 oxidation = relative decrease in emissions

[d] carbon accumulation in soil and biomass = net removal of CO_2 from the atmosphere = net emission reduction

[e] assumes 20 years of sustained storage of newly sequestered organic carbon in soils

Table 51. Published studies of the integrated impacts of no-till practice on greenhouse gases from all sources of emissions-avoidance [a]

		emissions avoided [a]	
Study	**Type of study**	**CO_2-eq. short tons per acre per year**	**CO_2-eq. short tons per 100,000 acres per year**
Archer and Halvorson (2010)	site study	0.89	88,711
Cavigelli *et al.* (2009) [b]	site study	0.55	55,216
Dendooven *et al.* (2012) [b]	site study	1.81	180,746
Gelford and Robertson (2015)	site study	0.51	51,291
Gong *et al.* (2021)	site study	0.29	29,234
Grandy *et al.* (2006) [c]	site study	0.40	40,141
Mosier *et al*. (2005)	site study	0.71	71,495
Mosier *et al.* (2006)	site study	1.21	120,958
Robertson *et al*. (2000)	site study	0.45	44,601
Sainju *et al*. (2014) [b]	site study	0.18	17,796
Tellez *et al.* (2017)	site study	0.64	63,811
Tellez *et al.* (2017) [b]	site study	0.59	59,266
Zhang *et al.* (2016)	site study	0.49	49,208
Cui *et al.* (2014) [d]	modeling study	0.26	26,315
Del Grosso *et al.* (2005)	modeling study	0.78	78,052
Grant *et al.* (2004)	modeling study	0.27	27,207
Li *et al.* (2005)	modeling study	0.30	29,883
Eagle *et al*. (2012)	other derivative statistical analysis [e]	0.66	65,563
Six *et al*. (2004)	other derivative statistical analysis [e]	0.31	30,772
Graves *et al.* (2020)	literature review/expert judgment	0.14	14,272
ICF International (2013)	literature review/expert judgment	0.52	51,799
ICF International (2013)	literature review/expert judgment	0.45	45,150
McLeod *et al.* (2010)	literature review/expert judgment	0.07	6,690
Neufeldt *et al.* (2005)	literature review/expert judgment	0.44 to 0.98	44,000 to 98,000
Rajaniemi *et al.* (2011)	literature review/expert judgment	0.14	14,272
Swan *et al*. (2015) [c]	literature review/expert judgment	0.34	34,166
Sainju *et al*. (2016)	meta-analysis	0.69	69,265
This report	literature review	0.14	14,291

[a] results as reported without adjustments

[b] reduced tillage counterfactual

[c] change in soil N_2O and soil organic carbon only

[d] change in soil N_2O and CH_4 and soil organic carbon only

[e] other than formal meta-analysis

a. Carbon sequestration in soils

No-till is a crop production practice in which cropland soils are untilled. This acts to restore to soils some of the physical and chemical protections against the decomposition of soil organic matter that is lost when soil undergoes intensive tillage.

In an undisturbed soil, biogenic carbon is deposited in the soil profile through the growth and decay of plant roots and rhizodeposition in the form of sloughed-off plant cells or root exudates. Some biogenic carbon is also deposited into deep soil layers in the form of leached dissolved organic carbon. In undisturbed soils, organic carbon is physically protected from decomposition by soil bacteria by soil macroaggregates, mostly in soil pores that, due to small size, are inaccessible to bacteria and fungi (or water-soluble enzymes) or too anaerobic for aerobic soil bacteria. (Jones and Donnelly, 2004) Most protected or ‘stabilized’ soil organic carbon (SOC) is found occluded in these sites, bound by polysaccharides produced by fungi during the decomposition of crop residue. (Govaerts *et al*., 2009; Kane, 2015) Soil carbon is also chemically protected by clay and silt particles, which bind to soil organic matter, and, in the very long-term, by various metals and mineral anions and cations which biochemically bind to organic matter to form organomineral complexes. (Balesdent *et al*., 1990; Hassink *et al*., 1997; von Lutzow *et al*., 2006) Once adsorbed on to mineral surfaces, organic matter is highly recalcitrant and remains resident in the soil profile for hundreds to thousands of years.

Intensive tillage acts to disrupt soil structure, breaking up protective soil macroaggregates and exposing soil organic carbon to microbial decomposition. (Six *et al*., 1999; Six *et al*., 2002a) Tillage accelerates soil macroaggregate turnover, shortening macroaggregate lifetime, and limiting the number of microaggregates that, over that shortened lifetime, can form within macroaggregates. (Denef *et al*., 2004; Six *et al*., 2002a) Unprotected organic matter is subject to rapid oxidation in intensively tilled soils, which are more highly aerated than untilled soils, creating the necessary aerobic conditions for rapid microbial decomposition of soil organic matter that, with intensive tillage, is unprotected.

In addition, in intensive tillage crop residues also are incorporated into the plow layer of soils, 6 to 10 inches deep (15 to 25 centimeters), which brings organic matter in residues more fully into contact with decomposing bacteria. (Alvaro-Fuentes *et al*., 2008) Intensively tilled soils are warmer, which additionally promotes microbial decomposition of soil organic matter. Tilled soils are less compacted, allowing for rapid diffusion of trapped CO_2, the principal gaseous product of microbial decomposition, to the atmosphere. Intensively tilled soils also are more prone to soil losses through wind and water erosion. Once removed from cropland, eroded sediments may enter inland surface waters, where some soil carbon may be mineralized and emitted to the atmosphere as CO_2. Inland waters are known be to larger emitters of CO_2. (Butman *et al*., 2016)

No-till practice reverses the processes of soil degradation, slowly building carbon in soils through renewed physical and biochemical protection of soil organic matter. (Balesdent *et al*., 2000) This returns soils to a condition somewhat analogous to that of undisturbed soil. In no-till soils, soil organic carbon is increased by reducing the respiratory loss of carbon from soils, all the while holding constant the input of organic carbon to soils in the form of roots, rhizodeposits and aboveground crop residues. (Ogle *et al*., 2005)

Observationally, no-till soils lose much less CO_2 to the atmosphere in the form of emissions than intensive tillage (21 percent), and have much lower mineralization rates for organic carbon (35 to 45 percent less). (Abdalla *et al*., 2016; Clay *et al*., 2015) Again, observationally speaking, the mean residence time of organic carbon in no-till soils is about 15 percent longer than in intensively tilled soils. (Ogle *et al*., 2012) The conversion from intensive tillage to no-till practice is associated with enhanced aggregate stability. (Jastrow *et al*., 1996) Meta-analyses of data from published site studies are uniform, or nearly so, in their conclusion that, while there is substantial variability in the estimates, no-till stores more organic carbon in soils than do the more intensive forms of tillage. (Aguilera *et al*., 2013; Angers and Eriksen-Hamel, 2008; Bai *et al*., 2018; Chen *et al*., 2020; Congreves *et al*., 2014; Cooper *et al*., 2016; Du *et al*., 2017; Haddaway *et al*., 2017; Li *et al*., 2020; Li *et al*., 2021; Luo *et al*., 2010; Meuer *et al*., 2018; Ogle *et al*., 2005; Ogle *et al*., 2010; Puget and Lal, 2005; Six *et al*., 2002a; Sun *et al*., 2020; Virto *et al*., 2012; West and Post, 2002; Xiao *et al*., 2020; Xu *et al*., 2019)

No-till soils cease to accumulate carbon once the surfaces of clay and silt particles become saturated and the pool of protected soil aggregates is at a maximum, usually within 25 to 30 years of no-till initiation. (Alvarez *et al*., 2005; Marland *et al*., 2004; West and Six, 2007) Carbon sequestration in no-till soils is slow initially and, in the initial decade following conversion to no-till practice from conventional tillage, is difficult to detect. (Al-Kaisi *et al*., 2005) Soil carbon sequestration generally peaks 10 to 20 years after no-till practice is begun, falling off linearly thereafter until long-term equilibrium is reached. (West and Post, 2002)

There are a large number of controls on carbon sequestration in no-till soils, including: crop rotation, climate, soil fertility, nutrient and water management, soil clay and silt fractions, and the degree of SOC depletion and nearness of soils to saturation. Soils that are highly depleted with respect to SOC and are further from saturation are able to store large amounts of soil carbon for extended periods of time. (Stewart *et al*., 2009) Soils high in clay content are more capable of organic carbon storage that soils low in clay content. The amount of crop residue that is returned to soils is controlled by crop rotation, soil fertility, and management practices. Crop rotations and management practices that produce large amounts of crop residue generally have higher levels of SOC under no-till practice than do rotations and practices with minimal crop residue return to soils.

This is especially true of deep-rooted crops like corn, which deliver organic carbon in the form of dead roots and rhizodeposits deep into the subsoil. By rotation, continuous corn under no-till sequesters substantially more carbon that do soybeans or corn and soybeans in rotation. (Cambardella *et al*., 2012)

In general, no-till soils in humid temperate climates tend to sequester more organic carbon than no-till soils in semi-arid temperate climates, mainly due to constraints on crop productivity and residue inputs to soils. (Ogle *et al*., 2005) Soils in humid, cool climates with short growing seasons and fine textured, poorly drained soils tend to respond poorly to no-till, probably due to otherwise slow rates of soil organic matter decomposition and climate-imposed constraints to plant growth and residue return to soils. (Yang and Wander, 1999; Ogle *et al.*, 2012)

Finally, besides increasing total soil organic carbon mass, no-till practice also acts to redistribute SOC throughout the soil column, concentrating it near the surface. (Shi *et al*., 2012) At some sites, this has been accompanied by a decrease in soil organic carbon mass in soil near the bottom of the plow layer, resulting in no net change in SOC from the conversion to no-till. (Anger *et al*., 1995; Yang *et al*., 2008) This is not the general rule; as noted above, most statistical analyses of data from the published literature support an overall positive response rate of SOC to no-till practice.

As discussed in the section on Methodology (see Section II above), the methods used to sample and analyze changes in soil carbon under different management practices, including changed tillage, continue to evolve and improve. In most early studies, soil carbon usually was not measured at the start of the experiments, but rather, in the analysis of management-induced changes in SOC, it was assumed to have been identical across all plots used to measure the response of soils to different practices, including the control plots. This may have affected the reported results, though whether any significant bias might have been involved is not evident. Most soil sampling of no-till soils excludes surface residues, which have been estimated at 1 metric ton of carbon per hectare (1.6 short CO_2-equivalent tons). (Paustian *et al*., 1997) By contrast, crop residue carbon is implicitly included in the measurement of SOC under more intensive forms of tillage, as incorporated residues. This may act to bias low estimates of the response of SOC to no-till. Methods for evaluating changes of soil carbon that measure carbon across a fixed depth may, due to changes in bulk density with changed tillage practice, overestimate the effectiveness of no-till in sequestering carbon. (Du *et al*., 2017) Sampling of carbon deep in the soil column is inherently difficult due to the large variability of soil carbon at these levels. (Kravchenko *et al*., 2011) At this time, no objective analysis has addressed the relative effects of these difficulties or omissions on estimates of sequestration drawn from the literature.

A number of studies have examined the effect on soil organic carbon of an occasional year of full inversion tillage interspersed in a general no-till regimen. Some empirical site studies have found limited or no effect on soil carbon. (Yang *et al*., 2008; Wortman *et a*l., 2010; Dimassi *et al*., 2013) Others have found a substantial negative effect or an inconsistent effect across sites, experimental years and studies. (Baan *et al*., 2009; West *et al*., 2007) In the most recent site study, a ten-year study contrasting no-till with one year of no-till followed by one year of conventional full-inversion tillage, Zhang *et al*. (2018) found a slight soil carbon benefit – 0.05 metric tons per hectare per year – from a rotating no-till/full-inversion till regime. In a modeling study, Conant *et al*. (2007) found substantial negative impacts of periodic tillage on SOC on a 100-year time frame.

In Table 50, we estimate that conversion to no-till from conventional tillage on 100,000 acres would result in 18,000 CO_2-equivalent short tons (4,500 short tons of carbon) of sequestration. The results shown in Table 50 were developed using sequestration estimates for conventional tillage to no-till conversion from 14 meta-analyses, discounted for an assumed 20-year persistence of storage. A simple arithmetic average of the meta-analyses results was employed, resulting in an estimated average annual rate of soil carbon sequestration of 0.29 ±0.04 metric tons of carbon per hectare (0.13 ± 0.02 short tons of carbon per acre). Meta-analysis is a powerful statistical tool for aggregating estimates across studies with different designs. The estimate just given – 0.29 metric tons per hectare – is the estimated annual rate of sequestration prior to truncation to accommodate an assumed 20-year persistence of newly stored organic carbon in soils.

Overall, 211 studies of no-till were reviewed with 221 reported study results. The average annual rate of soil carbon sequestration from the 14 meta-analyses is in fairly good agreement with the estimates developed for other study types.

In addition to the 14 meta-analyses, we reviewed eleven statistical summaries or derivative analyses other than formal meta-analyses, 30 modeling studies, 141 empirical site studies, and 12 literature reviews or studies that report results developed on the basis of expert judgment. Using simple arithmetic averages, sequestration rates resulting from the conversion of conventional tillage to no-till practice are estimated to be, for other derivative statistical analyses or summaries, modeling studies, empirical site studies and literature reviews, 0.24 ±0.04, 0.24 ±0.05, 0.36 ±0.05 and 0.29 ±0.03 metric tons of carbon per hectare per year, respectively.

The descriptive statistics for all the studies that were reviewed are shown in Table 52 by study type, sampling depth, and study duration. Conventional tillage, the counterfactual in these studies is usually full inversion tillage using the moldboard plow or its equivalent, although in some instances no description beyond ‘conventional tillage’ was provided in the studies. Since much or most of the science of terrestrial carbon sequestration is developed in metric units, the values given in Table 52 are in metric tons of carbon per hectare, and have been converted to CO_2-equivalent short tons for use in summary Table 50.

The results from the different study types are generally supportive of the mean estimate drawn from the 14 meta-analyses, although estimates from the empirical site studies might support a higher value. Soil sampling depth does not appear to be a factor. Eighty studies with sampling depths at or below 16 inches (40 centimeters) were reviewed. These yielded average annual sequestration rates, averaged across the 80 studies, of 0.31 metric tons per hectare of carbon (0.14 short tons of carbon per acre), or roughly the same as the mean rate for studies with sampling depths of 4 to 12 inches (10 to 30 centimeters).

Table 52. Descriptive statistics: No-till tillage–carbon sequestration in soils [a]

	biogenic carbon sequestration (Mg C/ha/yr)	number of study results [c,d]	ratio of sequestration to emission: number of study results [d]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	0.29	14	14/0	0.04	0.21	0.38
other derivative statistical analyses or statistical summaries [e]	0.24	12	11/1	0.04	0.15	0.32
empirical site studies	0.36	148	117/30/1	0.05	0.26	0.47
modeling studies	0.24	32	30/2	0.05	0.14	0.35
literature reviews/expert judgment	0.29	12	12/0	0.03	0.23	0.34
40 cm-plus soil sampling/modeling depth [f]	0.31	84	62/21/1	0.07	0.18	0.44
10 to 30 cm soil sampling/modeling depth [f]	0.30	111	100/11	0.05	0.21	0.39
10 to 20 year annual sequestration rate	0.33	109	92/16/1	0.05	0.24	0.42
20 to 30 year annual sequestration rate	0.28	52	45/7	0.05	0.18	0.37
0 to10 year annual sequestration rate	0.41	46	36/10	0.14	0.14	0.68
no-till with cover crop	0.28	19	17/2	0.08	0.12	0.44
no-till on former conventional till/reduced till acres: meta-analyses [g]	0.27	12	0	0.04	0.19	0.35
no-till with cover crops minus full inversion tillage without cover crops	0.63	27	24/3	0.18	0.27	0.99

[a] conventional tillage counterfactual

[b] 221 study results, 211 studies (14 meta-analyses, 11 statistical summaries or other derivative statistical analyses, 30 modeling studies, 3 IPCC-inventory studies, 141 empirical site studies, 12 expert reviews)

[c] 5 studies report multiple results by cover crop treatment

[d] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[e] derivative statistical studies other than meta-analyses

[f] results for lowest reported sampling depth

[g] counterfactual either conventional tillage or undifferentiated between conventional tillage and reduced till

Eighteen studies (19 study results) reported multiple results by cover crop treatment, which we track due to the importance increasingly accorded cover-cropping practice in tillage analysis in the scientific literature. (Dimassi *et al.*, 2014; Mbuthia *et al.*, 2015; Olson *et al.*, 2014) These studies yielded sequestration rates slightly lower than the mean estimate for the 14 meta-analyses, but based on only a handful of studies.

These studies evaluated the change in soil carbon storage between no-till with cover crops and full inversion tillage with cover crops. Studies that have evaluated the change in soil carbon between no-till with cover crops and full inversion tillage without cover crops produced higher estimates of no-till soil carbon benefits, roughly twice the 0.28 metric tons per hectare per year estimate given above for no-till plus cover crops minus conventional tillage plus cover crops (see Table 52).

Consistent with what was noted above about site-to-site variability of results, about 20 percent of the site studies that were reviewed reported SOC losses with no-till. As others have noted, no-till does not always sequester carbon in soils. (Minasny *et al.*, 2017; Ogle *et al.*, 2012) About one-third of these were studies of soils from eastern Canada. This 20 percent also included three Minnesota-based studies, but with the thinness of the sample, with uncertain implications. In a statistical analysis using published data from Minnesota sites, supplemented by data from sites from other Upper Midwest states and eastern Canadian, Anderson *et al*. (2008) and Fissore *et al*. (2010) suggest 0.25 and 0.1 metric tons per hectare per year, respectively, as a likely rate of sequestration for no-till conversion in Minnesota.

Overall, five empirical site studies have been conducted on Minnesota soils, along with one modeling study and two statistical analyses with a mix of Minnesota and other Upper Midwest and Canadian soils.

(Almaras *et al*., 2004; Anderson *et al*., 2008; Clapp *et al.,* 2000; Dolan *et al*., 2006; Fissore *et al*., 2010; Huggins *et al*., 2007; Kwon *et al*., 2013; Venterea *et al*., 2006)

In total, the weight of the evidence points to a positive response rate for sequestration from no-till, before truncation for 20-years of assumed storage, in the range of 0.25 to 0.35 metric tons of carbon per hectare per year (0.11 to 0.16 short tons of carbon per acre per year).

b. Nitrous oxide

Nitrous oxide is produced in cropland soils primarily through microbial activity during nitrification and denitrification. Ammonium (NH_4^+) and nitrate (NO_3^-) abundance is the primary control on the production and emissions of N_2O from cropland, modulated by soil physical and chemical properties, including structure and porosity, soil bulk density, SOC content, soil texture and pH, soil temperature, and water filled pore space, along with weather. Soil management practices also play a role, particularly with respect to the timing of specific management practices like irrigation or crop residue incorporation. Synthetic nitrogen fertilizer is the principal source of NH_4^+ and NO_3^- in soils, along with organic forms of nitrogen like soil organic nitrogen and crop residue nitrogen.

Tillage affects the physical properties of soils, thereby influencing the production of N_2O in soils. No-till soils are often wetter with higher bulk densities and greater concentrations of residues at the soil surface, leading in at least some soils and some experiments, to the formation of anaerobic soil conditions. (Regina and Alukku, 2010; Gregorich *et al*., 2008) The formation of anaerobic conditions acts to stimulate N_2O production through denitrification. Denitrification is the dominant source of N_2O in soils prone to anaerobic conditions through excessive wetness. Measured against water-filled pore space (WFPS), a measure of soil wetness, denitrification is the dominant source of N_2O once WFPS passes 60 to 65 percent. (Liu *et al*., 2007; Metivier *et al*., 2009) Rates of N_2O formation through denitrification generally increase exponentially as soil water filled pore space increases beyond 60 percent. (David *et al*., 2009) Maximum N_2O production in soils typically occurs at water-filled pore space of somewhere between 60 and 85 percent, which also generally coincides with soil wetness at which N_2O production is mostly or entirely through denitrification. (Almaraz *et al*., 2009; Davidson *et al*., 1991; Liu *et al*., 2007)

Multiple effects of no-till on N_2O emissions have been observed, often moving in opposing directions. (Venterea and Stanenas, 2008) For instance, no-till soils are often cooler than tilled soils, due to the presence of surface residues. This acts to depress the rate of microbial activity in the soil, leading to rates of N_2O production lower than they would be otherwise with warmer soils. (Liu *et al*., 2005) With less aeration and reduced soil temperature, mineralization rates in no-till topsoil also are lower than in soils under conventional tillage, reducing the supply of nitrate available for denitrification, and presumably N_2O production. (Bayer *et al*., 2015; Venterea and Stanenas, 2008) In the long-term, no-till practice should act to increase the rate of formation of soil aggregates, leading potentially to enhanced soil porosity, and increased, rather than reduced, soil aeration. (Plaza-Bonilla *et al*., 2014; Six *et al*., 2004)

Much effort has been directed to verifying the long-term effect of no-till practice on N_2O through enhanced soil aggregate formation. All other things equal, with enhanced aggregate formation and enhanced soil aeration, anaerobic conditions are less likely to form in no-till soils, reducing rather than increasing denitrification rates, and presumably N_2O production. (van Kessel *et al*., 2013) Of four statistical analyses of results from the published literature that address this question (three formal meta-analyses, one other derivative statistical analysis), three have found reduced N_2O emissions from soils in no-till practice for longer than ten to twenty years, suggesting that such an effect may be operative, albeit in the out-years of our 20-year window. (Huang *et al*., 2018; Mei *et al*., 2018; Six *et al*., 2004; van Kessel *et al*., 2013)

A reading of the scientific literature indicates that no-till practice on fine-textured soils, like clay, tends to increase N_2O emissions. (Ball *et al*., 2014; Perego *et al*., 2016) On medium and coarse textured soils, like silt loam or sand, the reported effects of no-till are ambiguous, showing increases, decreases or little change. (Mei *et al*., 2018; Rochette *et al*., 2008a; Rochette *et al*., 2008b)

Fluxes of nitrous oxide from cropland are highly variable both spatially and temporally. Due to the large number of controls on N_2O production in soils and its emission, a wide variety of results are possible and often occur at different sites or at the same site under different meteorological conditions. The interactions between the controls on N_2O emissions from tillage change are complex. Simple relationships between, on the one hand, N_2O emissions and, on the other hand, environmental conditions and the specifics of different agricultural practices have yet to be developed or revealed. Regarding the experimental data, it is extremely noisy and, depending on the data considered, can and often does yield contradictory results, whether for tillage or other agricultural practices. Because of this, to extract from the experimental data a firm understanding of the direction of the likely effect of no-till practices on N_2O emissions, and its magnitude, a very large data set is necessary, one now probably beyond our grasp.

The best that now might be done is to develop a sense of the response of N_2O emissions to no-till practice based on best available knowledge, accompanied by a commitment to update that understanding going forward as additional experimental data is developed.

In Table 50, we provided an estimate of emissions-avoided from a change in tillage practice from conventional to no-till on 100,000 acres of some -7,000 CO_2-equivalent short tons (a 7,000 CO_2-equivalent short ton emission increase). This was developed consistent with the approach outlined immediately above, using the mean response rates to this practice change given in twelve published meta-analyses. The mean response rate of N_2O emissions to a change to no-till was positive in nine of these twelve meta-analyses, and negative in the remaining three. The specific emissions-avoidance value given in Table 50 was calculated as the product of the estimated percentage change in emissions resulting from the use of no-till practice in place of conventional tillage and average annual Minnesota cropland N_2O emissions on 100,000 acres. Average annual Minnesota cropland N_2O emissions are from the MPCA Greenhouse Gas Inventory. As noted in the Methodology section (Section II) of this report, meta-analysis is a powerful statistical used to integrate results from experiments of different designs and develop conclusions at broad spatial scales.

Using the meta-analyses mean estimates, the conversion to no-till practice from conventional tillage is estimated to increase N_2O emissions by 11.1 ± 6.5 percent. The effect of a change in tillage from conventional tillage to no-till practice or reduced tillage has been studied in an additional three meta-analyses. Taken together, these reported a mean increase in emissions from tillage change of 4.0 ± 3.8 percent (see Table 53).

Overall, we reviewed 94 studies with 101 study results. Of these, twelve were meta-analyses, four were other derivative statistical summaries or analyses, 15 were modeling studies, 61 were empirical site studies, and two were literature reviews or studies that report estimates on the basis of expert judgment. As discussed in the section on Methodology, in some instances more than one observation was reported per study to accommodate multiple results developed using different study types or, in the case of tillage, comparative results for tillage change combined with and in absence of cover cropping. To derive the maximum soil benefits from tillage change, less intensive or no tillage can be combined with cover cropping practice. We track results for combinations of tillage and cover cropping practice with this in mind.

Emissions increased in 52 of the 101 observations of the larger database, and decreased in 49, suggesting that the median value for percentage change (and probably the mean value), however much the database is expanded, is unlikely to diverge much from a narrow range either side of zero. Of the empirical site studies, 55 percent reported reduced N_2O emissions with tillage change, while 45 percent reported increasing N_2O emissions.

The descriptive statistics for the studies that were reviewed are shown in Table 53. Calculated confidence intervals by study type all overlap the zero value. Thus, a slight nod might be given to a small emission increase under no-till on the basis of the twelve meta-analyses mean results, essentially as currently available information. However, generally, the body of experimental results generally does not support an estimate for a change in emissions in either direction that can be said to be significantly different from zero in a statistical sense. (Gregorich *et al*., 2015; Omonode *et al*., 2011; Venterea *et al*., 2005) The results from the meta-analyses point to a trend or a tendency in the studies in the scientific literature, rather than a firm conclusion.

Finally, we stratified the empirical site studies based on the number of years in each experiment in which soils had been in no-till practice. For soils in no-till practice fewer than 10 years, N_2O emissions were 14.3 percent higher than paired soils in conventional tillage. For soils in no-till practice 10 or more years, N_2O emissions were 0.3 percent higher than paired soils in conventional tillage, based on 27 study results. N_2O emissions generally are much lower in studies with annual monitoring of fluxes, as opposed to flux monitoring limited to growing seasons, but with wide confidence intervals, again overlapping the zero value.

Table 53. Descriptive statistics: No-till tillage - N_2O [a]

	emissions: % change in emissions per hectare or acre	number of study results [b,c]	change in emissions, ratio positive-to-negative: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	11.1%	12	9/3	6.5%	-1.6%	23.8%
other derivative statistical analyses or statistical summaries [d,e]	3.9%	5	3/2	7.5%	-10.8%	18.7%
modeling studies	-0.9%	17	8/9	7.1%	-14.9%	13.0%
empirical site studies	9.4%	64	29/35	8.2%	-6.7%	25.4%
literature reviews/expert judgment	19.8%	3	3/0	11.9%	-3.5%	43.1%
annual flux monitoring/modeling	0.3%	44	19/25	5.8%	-11.1%	11.6%
growing season and subgrowing season flux monitoring/modeling	15.4%	50	29/21	9.6%	-3.3%	34.2%
1 year of observations or simulations	10.9%	25	14/11	9.9%	-8.5%	30.3%
2 to 3 years of observations or simulations	7.9%	37	15/22	12.8%	-17.1%	33.0%
3 years-plus of observations or simulations	1.5%	20	9/11	4.8%	-8.0%	10.9%
< 10 years in no-till	14.3%	49	24/25	10.3%	-5.9%	34.5%
10 years or more in no-till	0.3%	27	11/16	6.0%	-11.4%	12.0%
no-till with cover crop	-4.2%	9	3/6	12.3%	-28.3%	20.0%
no till/reduced tillage on former conventional tillage acres: meta-analyses	4.0%	3	2/1	3.8%	-3.3%	11.4%

[a] conventional tillage counterfactual

[b] 101 study results, 94 studies (12 meta-analyses, 4 statistical summaries or other derivative statistical analyses, 15 modeling studies, 61 empirical site studies, 2 expert reviews)

[c] 5 studies report multiple results by cover crop treatment or multiple geographies

[d] one other derivative statistical analysis, not included above, with conventional tillage and reduced tillage jointly as counterfactual, yielded a 33.6% emission reduction

[e] statistical summaries or derivative statistical analyses other than meta-analyses

c. Methane

Atmospheric methane is oxidized in most uncultivated soils by methanotrophic bacteria. Methanotrophs are sensitive to soil disruption. Tillage, particularly full-inversion tillage, disrupts methanotrophic communities, leading to reduced soil CH_4 oxidation. (LeMer and Roger, 2001) Under no-till practice, disruption to soils is limited, leading generally, although not always, in the published studies to increased soil CH_4 oxidation under no-till. (Regina and Alukukku, 2010; Ussiri *et al*., 2009) No-till soils are often wetter, with increased bulk density. This may promote the formation of anaerobic soil conditions and stimulate CH_4 production by methanogens in surface soils, rather than CH_4 oxidation. (Alluvione *et al*., 2009).

The estimated annual change in soil CH_4 oxidation resulting from the use of no-till practice is small, an increase of 283 CO_2-equivalent short tons (see Table 50). This was calculated using the average percent change in soil CH_4 oxidation in four published meta-analyses with a change in upland soils from conventional tillage to no-till practice. As noted above, formal meta-analysis is a powerful statistical tool useful for aggregating estimates across study types with differing designs. Baseline CH_4 oxidation rates in temperate cropland soils were taken from Aronson and Helliker (2010).

The descriptive statistics from the four meta-analyses are shown in Table 54, along with descriptive statistics for modeling and empirical site studies that were reviewed. Using a simple arithmetic average of the mean results from the four meta-analyses, soil CH_4 oxidation is estimated to increase by 13.7 ± 5.5 percent with a change in tillage from conventional tillage to no-till practice. By contrast, using the results from the modeling and empirical site studies, soil CH_4 uptake and oxidation would be expected to decline 6 and 83 percent, respectively, but based on only a relatively few studies.

The contribution of CH_4 oxidation to overall GHG-avoidance from tillage change is small, with little effect on the larger budget totals developed in Table 50.

Table 54. Descriptive statistics: No-till tillage - CH_4 [a]

	% change in oxidation per hectare or acre	number of study results [b,c]	change in oxidation, ratio positive-to-negative: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	13.7%	4	3/1	5.5%	3%	24%
empirical site studies	-87.8%	22	6/16	34.4%	-155%	-21%
modeling studies	-6.2%	5	2/3	12.2%	-30%	18%

[a] conventional tillage counterfactual

[b] 26 study results, 25 studies (4 meta-analyses, 21 empirical site studies)

[c] 1 study reports multiple results by cover crop treatment

K. Reduced tillage

Instead of no-till, cropland in full inversion tillage can be converted to less intensive, reduced tillage.

Variants of reduced tillage include: chisel till, ridge till, mulch till, sweep till, disk tillage, and subsoiling. As in the case of no-till, reduced tillage reverses the soil processes that, in full inversion conventional tillage, lead to microbial decomposition of soil carbon and soil carbon losses to the atmosphere as CO_2. Under reduced tillage, soils that have suffered large losses of soil organic carbon (SOC), accumulate carbon or, at least, lose less carbon than under full inversion tillage. Soils under full inversion tillage are less physically- and biochemically-protected against microbial degradation of organic matter, leading to rapid loss of organic carbon from these soils.

As of the last available state-level survey, 44 percent of Minnesota cropland was in one form or another of reduced tillage. (US Department of Agriculture, 2019) As of 2016, 38 percent of all cropland in the US lake states (Minnesota, Wisconsin, and Michigan) was in continuous reduced tillage and another 28 percent in occasional reduced tillage (Baranski *et al*., 2018)

Table 55 shows the estimated emissions-avoidance effects of the conversion of 100,000 acres of cropland from full inversion tillage to reduced tillage. We estimate that, for each 100,000 acres of cropland converted from full inversion tillage to reduced tillage, 7,000 CO_2-equivalent short tons of GHGs would be avoided or offset, nearly all of it from in-state carbon sequestration in soils.

As discussed in the Introduction of this report, the amount of time in storage determines the degree to which, for any particular project, sequestered carbon offsets CO_2 emissions from fossil fuel combustion elsewhere in the economy. This determines the present-day offset value of sequestration. In calculating the emissions-avoidance effects of reduced tillage, we assumed a 20-year timespan of assured storage of carbon in soils, resulting in annual emissions-avoidance on 100,000 acres of cropland of 7,000 CO_2-equivalent tons. Had we instead assumed a 40-year period of assured storage of carbon in soils, GHG-avoidance from the use of reduced tillage in place of full inversion tillage on 100,000 acres of cropland would have totaled 13,000 CO_2-equivalent short tons. Had we assumed a 100-year timespan for sustained storage, estimated avoidance would have totaled 29,000 CO_2-equivalent short tons (see Table 55). The approach that we use in converting observed rates of sequestration to avoided-emissions was addressed above in the Methodology section (Section II) of this report.

As noted often in this report, sequestered soil carbon is carbon that, having been photosynthetically removed from the atmosphere in the form of CO_2, is incorporated into plant biomass and, eventually, soils.

A number of estimates have been published of the greenhouse gas-avoidance resulting from a change in tillage from conventional or full inversion tillage to reduced tillage. These include estimates by Eagle *et al*. (2012) and Swan *et al*. (2015), which report emissions-avoidance from a change to reduced tillage of 0.31 and 0.22 CO_2-equivalent short tons per acre per year, respectively. On 100,000 acres, these per acre estimates translate to reductions of 31,000 and 22,000 CO_2-equivalent short tons per year, or reductions higher than the estimates given in this report.

Biogenic carbon sequestration from the use of reduced tillage on cropland soils is discussed below, as are avoided direct emissions of N_2O from soils and the effects of reduced tillage on soil CH_4 oxidation. The methods and sources used to estimate avoided indirect N_2O emissions from nitrate leaching and ammonia volatilization, avoided-emissions from fuel use, and avoided-emissions from foregone agricultural chemicals and fuels manufacture are discussed in the Methodology section of this report, Section II, Subsection E.

Table 55. Reduced tillage: Emissions-avoided [a]

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres pear year) [b]	Counterfactual
N_2O-direct	soils	21	conventional tillage
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	553	conventional tillage
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	-	conventional tillage
CH_4 [c]	soils	52	conventional tillage
CO_2 [d,e]	carbon accumulation in soils	(5,619)	conventional tillage
CO_2	cultivated soils from lime or urea use	-	conventional tillage
GHGs-energy	fossil fuel and electricity use in crop production	(1,658)	conventional tillage
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(367)	conventional tillage
Total		**(7,019)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils			
40 year storage	all sources and sinks	**(12,638)**	conventional tillage
100 year storage	all sources and sinks	**(29,494)**	conventional tillage

[a] conventional tillage counterfactual

[b] positive = emissions increase, negative = emissions reduction

[b] decrease in soil CH_4 oxidation = relative increase in emissions

[d] carbon accumulation in soil and biomass = net removal of CO_2 from the atmosphere = net emission reduction

[e] assumes 20 years of sustained storage of newly sequestered organic carbon in soils

a. Carbon sequestration in soils

The physical and biochemical processes through which organic carbon is sequestered in soils are discussed in the no-till section of this report (see Section IV, Subsection J.a). That discussion will not be repeated. Suffice it to say that the same processes that are in play during no-till are in play in reduced tillage, albeit to a lesser degree. In general, reduced tillage is considered to be of reduced effectiveness relative to no-till, storing more organic carbon than conventional tillage but less than no-till practice. (Chambers *et al*., 2016; Eagle *et al*., 2012; Eve *et al*., 2002; Swan *et al*., 2015)

In Table 55, reduced tillage on 100,000 acres is estimated to result in 6,000 CO_2-equivalent short tons of sequestration. This is an annual estimate and is the difference in soil carbon storage between conventional full inversion tillage and various forms of reduced tillage like chisel till or disk till. The results shown in Table 55 were developed using five meta-analyses sequestration estimates for conventional tillage to reduced tillage conversion, discounted for an assumed 20-year persistence of storage. A simple arithmetic average of the meta-analyses results was employed, resulting in an estimated average annual rate of soil carbon sequestration of 0.09 ±0.11 metric tons of carbon per hectare (0.04 ± 0.05 short tons of carbon per acre).

In developing this estimate, 124 studies of reduced tillage were reviewed with 129 study results, including 93 empirical site studies, 16 modeling studies, seven literature reviews or studies that report results developed on the basis of expert judgment, three statistical summaries or statistical analyses other than formal meta-analyses, and the five formal meta-analyses. The results from the meta-analyses were selected in deference to the place meta-analyses increasingly has assumed in the scientific literature in determinations of response rates for ecological processes. Sequestration rates for the 124 studies reviewed range from 0.09 to 0.21 metric tons of carbon per hectare per year (0.04 to 0.09 short ton of carbon per acre per year).

The descriptive statistics for the studies that were reviewed are shown in Table 56 by study type, soil sampling depth and experiment duration. Following the practice followed in much or most of the science of terrestrial sequestration, these are given in metric units, and then converted to CO_2equivalent short tons for use in summary Table 55. The estimates provided in Table 56 are estimates of annual sequestration prior to truncation to accommodate the assumed 20-year persistence of newly stored organic carbon in soils.

In general, there are many fewer analyses directed toward reduced tillage than no-till practice. Despite far fewer observations, the standard errors and confidence intervals reported in Table 56 are roughly similar in width to those reported in Table 52 for no-till. Of study types, the results from the modeling studies and the derivative statistical analyses and summaries are in good agreement with the average developed from the results from the meta-analyses, the results from the empirical studies and literature reviews less so, though still indicating net sequestration in cropland soils.

The fraction of empirical site studies that report net losses of SOC during conversion from conventional tillage to reduced tillage is about 30 percent, up from about 20 percent under no-till. At the 40 centimeter and below soil sampling depth, about one-third of studies show a negative SOC response to reduced tillage, and two-thirds a positive response. The mean rate of sequestration at these depths is 55 percent of the rate reported for the 10 to 30 centimeter soil layer, raising the possibility that, to some degree, the magnitude of the response rate developed from the meta-analyses results might be an artefact of inappropriately shallow soil sampling.

For this reason, caution is advised in how much certainty we ascribe to the sequestration rates shown in Table 56. More research may be needed to understand how the mass of soil organic carbon across the entire soil column changes under reduced tillage. Generally, the weight of the evidence supports a positive response rate for reduced tillage.

Table 56. Descriptive statistics: Reduced tillage – carbon sequestration in soils [a]

	biogenic carbon sequestration (Mg C/ha/yr)	number of study results [b,c]	ratio of sequestration to emission: number of study results [d]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	0.09	5	4/1	0.11	(0.13)	0.31
other derivative statistical analyses or statistical summaries [e]	0.11	3	3/0	0.01	0.09	0.12
empirical site studies	0.21	98	67/29/2	0.05	0.10	0.32
modeling studies	0.11	16	15/1	0.04	0.04	0.18
expert judgment/literature reviews	0.20	7	7/0	0.07	0.07	0.33
40 cm-plus soil sampling/modeling depth [f]	0.13	51	31/18/2	0.08	(0.03)	0.28
10 to 30 cm soil sampling/modeling depth [f]	0.24	67	55/12	0.05	0.14	0.34
10 to 20 year annual sequestration rate	0.23	64	51/13	0.05	0.12	0.33
20 to 30 year annual sequestration rate	0.03	27	20/7	0.05	(0.08)	0.13
0 to 10 year annual sequestration rate	0.36	29	17/11/1	0.13	0.09	0.62

[a] conventional tillage counterfactual

[b] 129 study results, 124 studies (5 meta-analyses, 3 statistical summaries or other derivative statistical analyses, 16 modeling studies, 93 empirical site studies, 7 expert reviews)

[c] 5 studies report multiple results by cover crop treatment

[d] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[e] derivative statistical studies other than meta-analyses

[f] results for lowest reported sampling depth

b. Nitrous oxide

Avoided-emissions from the conversion from conventional tillage to reduced tillage are calculated as the product of the estimated percentage change in emissions resulting from use of reduced tillage in place of conventional tillage on 100,000 acres, and average Minnesota cropland N_2O emissions, again on 100,000 acres. As discussed in the Methodology section of this report, average Minnesota cropland N_2O emissions are from the MPCA Greenhouse Gas Inventory. To estimate the percentage change in N_2O

emissions under reduced-till on cropland formerly in conventional tillage, we reviewed 48 studies with 49 study results. These include six meta-analyses, one other derivative statistical analysis, eleven modeling studies and 30 empirical site studies.

We used the mean estimate from the six meta-analyses as the best estimate of the percentage change in N_2O emission with reduced tillage practice on croplands formerly under conventional tillage practice. Of the six meta-analyses, four reported N_2O emission increases with reduced tillage in place of conventional tillage, while two reported reductions. Using the mean estimate for the six meta-analyses, the use of reduced tillage practice on cropland formerly under conventional tillage practice is estimated to increase N_2O emissions by 0.03 ± 4.03 percent. As in the case of no-till on cropland formerly under conventional tillage, the estimated percentage N_2O change selected for the calculation of avoided-emissions should be seen as what is now best available information, but probably without larger statistical significance. As in the case of no-till, it is intended for use in developing tentative results, with full understanding that the underlying database for analysis is inadequate and that much yet needs to be done for a sound understanding of N_2O response to tillage change to be developed.

Descriptive statistics are shown in Table 57 for all the studies that have been reviewed. Calculated confidence intervals by study type are wide, and with the exception of those for the modeling studies, all overlap the zero value. Taken as a whole, the body of results taken from the published literature generally does not support an estimate for a change in emissions in either direction that can be said to be significantly different from zero in a statistical sense.

There is no evident pattern in the results by number of study years. The mean of the results of empirical site studies that, in reporting N_2O fluxes, do so on an annual basis is negative, but again the confidence intervals are wide.

Of the 31 empirical site results, N_2O emissions increased in 15 and decreased in 16, suggesting that the median result for the percentage change (and probably the mean value), however much the database is expanded, is unlikely to diverge much from a narrow range either side of zero.

Finally, in absence of an estimate for changed N_2O emissions, net greenhouse gas effects of reduced tillage in place of conventional tillage would remain almost unchanged from those shown in Table 55, about 7,000 CO_2-equivalent tons.

Table 57. Descriptive Statistics: Reduced Tillage - N_2O [a]

	emissions: % change in emissions per hectare	number of study results [b,c]	change in emissions, ratio positive-to-negative: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	0.03%	6	4/2	4.0%	-7.9%	7.9%
other derivative statistical analyses or statistical summaries [d]	-15.3%	1	0/1	NA	NA	NA
modeling studies	-12.4%	11	2/9	5.3%	-22.8%	-1.9%
empirical site studies	7.9%	31	15/16	8.8%	-9.2%	25.0%
annual flux monitoring/modeling	-4.8%	32	12/19/1	3.9%	-12.4%	2.8%
growing season and subgrowing season flux monitoring/modeling	16.0%	17	9/8	14.6%	-12.5%	44.6%
1 year of observations or simulations	16.8%	12	5/7	19.7%	-21.8%	55.3%
2 to 3 years of observations or simulations	-3.0%	26	10/16	5.9%	-14.6%	8.6%
3 yrs-plus of observations or simulations	2.0%	3	2/1	3.4%	-4.6%	8.5%

[a] conventional tillage counterfactual

[b] 49 study results, 48 studies (6 meta-analyses, 1 statistical summary or other derivative statistical analysis, 11 modeling studies, 30 empirical site studies)

[c] 1 study reports multiple results by cover crop treatment

[d] derivative statistical studies other than meta-analyses

c. Methane

Tillage acts to disrupt methanotrophic communities that oxidize CH_4 to CO_2. With no-till, some recovery in rates of soil oxidation is evident, but with conversion from conventional tillage to reduced tillage, less so. It is thought that CH_4 oxidation in cropland soils is about one-third of that of undisturbed grassland soils. (Aronson and Helliker, 2010; Aronson *et al*., 2013) It is also thought that recovery of soil CH_4 oxidizing capacity might take up to several hundred years after disruptions cease. (Allen *et al*., 2009)

The estimated annual change in soil CH_4 oxidation resulting from the use of reduced tillage practice is small, a 52 CO_2-equivalent short ton decrease in oxidation (see Table 55). This was calculated using the average percent change in soil CH_4 oxidation from a single available meta-analysis with a change in upland soils from conventional tillage to reduced tillage. Baseline CH_4 oxidation rates in temperate cropland soils were taken from Aronson and Helliker (2010).

Using the single meta-analysis estimate, developed by Feng *et al*. (2018) using a global database, the use of reduced tillage practice on cropland formerly under conventional tillage is estimated to reduce CH_4 oxidation slightly, by 2.5 percent (see Table 58). In perusing the scientific literature, we also reviewed ten empirical site studies. Using the results from the empirical site studies, soil CH_4 uptake and oxidation might be expected to increase by 42 percent, but based on a very few number of studies showing widely scattered results (+408 to -50 percent change in soil CH_4 oxidation).

Table 58. Descriptive statistics: Reduced tillage - CH_4 [a]

	% change in oxidation per hectare	number of study results [b]	change in emissions, ratio positive-to-negative: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	-2.5%	1	0/1	NA	NA	NA
empirical site studies	41.7%	11	6/4/1	41195%	-14%	97%

[a] conventional tillage counterfactual

[b] 12 study results, 11 studies (1 meta-analysis, 10 empirical site studies)

L. No till: Reduced tillage counterfactual

No-till practice can be introduced to cropland already in reduced tillage. As noted above in Section IV, Subsection J, the use of no-till results in less disruption to cropland soil structure, restoring to soils some of the physical and biochemical protection against microbial decomposition of organic matter that is found in undisturbed native grassland. This is true in the case of conversion to no-till from either full inversion tillage or reduced tillage, only to a lesser extent in the case of reduced tillage. Soil organic carbon (SOC) stocks in undisturbed or less disturbed soils tend to be higher than soils that are intensively disrupted by tillage.

The physical and biochemical processes involved in the accumulation of or sequestration of carbon in soils are discussed above in the No-till sections of this report (Section IV, Subsection J.a). That discussion will not be repeated. The same is true for changes in N_2O emissions from tillage change. No estimate is available for CH_4 oxidation in reduced tillage soils converted to no-till practice.

As of the last available tillage survey, six percent of Minnesota cropland was in no-till practice and 44 percent in some form of reduced tillage. (US Department of Agriculture, 2019) In 2016, an estimated 10 percent of cropland in the US lake States (Minnesota, Wisconsin, and Michigan) was in continuous no-till and 38 percent in continuous reduced tillage. (Baranski *et al*., 2018)

The estimated GHG emission-avoidance resulting from the conversion of cropland tillage from reduced tillage to no-till is shown in Table 59. From Table 59, an estimated 20,000 CO_2-equivalent short tons of emissions would be avoided from the conversion of 100,000 acres from reduced tillage to less impacting no-till. Of this, two-thirds is from enhanced carbon storage in no-till soils. Of the remainder, most of this is due to reduced direct N_2O soil emissions.

In quantifying avoided-emissions, we assumed that carbon stored in soils would remain there for 20 years, followed by microbial decomposition and emission to the atmosphere as CO_2. This is the longest period over which, in our opinion, sustained storage safely can be assumed. Under this assumption, avoided-emissions are an estimated 20,000 CO_2-equivalent short tons (see Table 59). Had a 40-year period of assured storage been assumed, avoided-emissions from the use of no-till practice in place of reduced tillage would have totaled 33,000 CO_2-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 72,000 CO_2-equivalent short tons (again see Table 59).

Table 59. No-till tillage: Emissions-avoided [a]

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [b]	Counterfactual
N_2O-direct	soils	(6,597)	reduced tillage
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	553	reduced tillage
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	-	reduced tillage
CH_4	soils	not known	reduced tillage
CO_2 [c,d]	carbon accumulation in soils	(12,927)	reduced tillage
CO_2	cultivated soils from lime or urea use	-	reduced tillage
GHGs-energy	fossil fuel and electricity use in crop production	(1,054)	reduced tillage
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(234)	reduced tillage
Total		**(20,259)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils			
40 year storage	all sources and sinks	**(33,187)**	reduced tillage
100 year storage	all sources and sinks	**(71,969)**	reduced tillage

[a] reduced tillage counterfactual

[b] positive = emissions increase, negative = emissions reduction

[c] carbon accumulation in soil and biomass = net removal of CO_2 from the atmosphere = net emission reduction

[d] assumes 20 years of sustained storage of newly sequestered organic carbon in soils

The amount of time in storage determines the degree to which, for any particular project, sequestered carbon offsets CO_2 emissions from fossil fuel combustion elsewhere in the economy. This determines the present-day offset value of sequestration. The approach that we use in converting observed rates of sequestration to avoided-emissions was addressed above in the Methodology section (Section II) of this report.

a. Carbon sequestration in soils

In Table 59, an estimate for annual carbon sequestration in cropland formerly under reduced tillage and converted to no-till of 13,000 short tons of CO_2 or 3,528 tons of carbon was given, covering 100,000 acres. As discussed immediately above, this was developed using an average rate of sequestration per acre, discounted to account for an assumed 20-year persistence of storage of newly sequestered carbon in soils. In cropland under no-till, CO_2 is removed from the atmosphere and incorporated into the roots and aboveground live crop biomass and, eventually, into cropland litter and soils. This offsets emissions of CO_2 from elsewhere in the economy.

In estimating the average annual sequestration rate in no-till soils converted from reduced tillage practice, we reviewed 172 studies with 187 study results. These included 149 empirical site studies, 13 modeling studies, and four statistical summaries or derivative statistical analyses. Of the 172 studies, ten studies reported multiple results, adding cover crop practice as a secondary factor influencing soil carbon. To derive maximum soil carbon benefits from tillage change, less intrusive or no-till practice is often combined with cover cropping practice. We track the results for combinations of tillage and cover cropping practice with this in mind.

An average value for all of the studies reviewed was selected to best represent annual sequestration rates in no-till soils converted from reduced tillage practice. No formal meta-analysis was available for sequestration rates in no-till soils converted from reduced tillage practice. No other study attribute clearly pointed to one study type over the rest as clearly superior or as uniquely indicative of the 'true' value of carbon sequestration in no-till soils converted from reduced tillage practice. Using the average value for the studies that were reviewed, no-till practice on former reduced tillage cropland is estimated to sequester on an annual basis 0.21 ± 0.05 metric tons of carbon per hectare (0.09 ± 0.02 short tons of carbon per acre per year). This is an estimate of average sequestration prior to truncation to accommodate the assumed 20-year persistence of newly stored carbon in soils.

In developing the sequestration estimates, the calculations were done initially in metric units and then converted to English or common units. By study type, annual sequestration rates for no-till soils converted from reduced tillage practice range from 0.12 to 0.27 metric tons of carbon per hectare (0.05 to 0.12 short tons of carbon per acre). The sum of the mean estimates plus standard error never straddles zero for any of the study types, although with several, the number of observations is small. Soil organic carbon declined in about 20 percent of all the studies reviewed, increasing in about 80 percent, which is consistent with site-to site variability reported across all tillage studies.

The descriptive statistics for the various studies that were reviewed are shown in Table 60. Roughly the same amount of soil organic carbon is sequestered in reduced tillage studies in which soils are sampled to a depth of 4 to 12 inches (10 to 30 centimeters) as is sequestered in those in which soils are sampled to a depth of 16 inches (40 centimeters). At the 95 percent confidence level, the possibility that sequestration might be negative cannot be completely excluded for sampling depth at or below the 16-inch (40 centimeter) sampling depth. By duration of experiment, estimated rates of sequestration differ little between studies with experiment duration of 10 to 20 years and those lasting 20 to30 years. The mean sequestration rate for studies of 0 to 10 years in duration are higher, but more than one-third of these studies report declining SOC levels with no-till (in comparison to reduced tillage).

The study results by soil sampling depth and experiment duration suggest that some caution be exercised with the numbers. But, having said that, generally the weight of the evidence now supports a positive response rate for no tillage on soils formerly in reduced tillage.

Table 60. Descriptive statistics: No-till tillage - carbon sequestration in soils [a]

	biogenic carbon sequestration (Mg C/ha/yr)	number of study results [b,c]	ratio of sequestration to emission: number of study results [d]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	0.21	187	144/42/1	0.05	0.12	0.29
empirical site studies	0.22	164	122/41/1	0.06	0.11	0.32
modeling studies	0.12	16	14/2	0.03	0.06	0.17
derivative statistical analyses or statistical summaries	0.27	4	4/0	0.08	0.12	0.43
40 cm-plus soil sampling/modeling depth [e]	0.19	64	44/19/1	0.08	0.02	0.35
10 to 30 cm soil sampling/modeling depth [e]	0.20	109	85/24	0.06	0.08	0.31
10 to 20 year annual sequestration rate	0.16	83	69/14	0.06	0.04	0.28
20 to 30 year annual sequestration rate	0.17	37	27/9/1	0.06	0.06	0.29
0 to 10 year annual sequestration rate	0.27	64	43/21	0.10	0.07	0.46

[a] reduced tillage counterfactual

[b] 187 study results, 172 studies (4 statistical summaries or derivative statistical analyses, 13 modeling studies, 149 empirical site studies)

[c] 10 studies report multiple results by cover crop treatment

[d] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[e] results for lowest reported sampling depth

b. Nitrous oxide

Avoided-emissions from the displacement of reduced tillage with no-till practice are calculated as the product of the estimated percentage change in emissions resulting from use of no-till in place of reduced tillage and average Minnesota cropland N_2O emissions. Average Minnesota cropland N_2O emissions are from the MPCA Greenhouse Gas Inventory. To estimate the percentage change in N_2O emissions under no-till on cropland formerly in reduced tillage, we reviewed 60 studies with 62 study results. These included: one meta-analysis, six modeling studies and 53 empirical site studies.

We used the estimate from the single meta-analysis as the best estimate of the percentage change in N_2O emission with no-till practice on croplands formerly under reduced tillage practice. Using this estimate, the use of no-till practice on cropland formerly under reduced tillage practice is estimated to reduce N_2O emissions by 10.3 percent. By study type, the estimate percentage change ranges from (-) 8.8 to (-) 33.1 percent.

Of the 62 study results reviewed, 16 showed increased N_2O emissions with no-till on former reduced tillage cropland, 45 reported reductions, and one reported no change. The descriptive statistics for the reviewed studies are shown in Table 61, with standard errors and upper and lower 95 percent confidence intervals. The confidence interval for the percentage change for all studies is fairly broad and straddles the zero value, suggesting a lack of statistical significance in the estimates. The change in mean N_2O fluxes from studies that report emissions on an annual, as opposed to growing season, basis is substantially larger than the mean change in growing season-only fluxes. There is no evident pattern in the results by number of study years.

M. Cropland to hayland conversion

Cropland planted to alfalfa or perennial grasses for harvest is substantially less emitting than is cropland planted to row crops or small grains. A good stand of alfalfa lasts about five years before it is plowed under and replanted. Alfalfa usually is fertilized only at planting. Other perennial grasses also are fertilized, albeit at low rates. Because of the generally low rates of fertilization with either synthetic fertilizer or manure, soils in perennial grasses and alfalfa for hay harvest emit less N_2O to the atmosphere. Fewer upstream emissions from the out-of-state manufacture of synthetic fertilizer also result.

Table 61. Descriptive statistics: No-till tillage - N_2O [a]

	emissions: % change in emissions per hectare	number of study results [b,c]	change in emissions, ratio positive-to-negative: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	-10.3%	1	0/1	NA	NA	NA
all studies	-8.8%	62	16/45/1	6.3%	-21.2%	3.6%
modeling studies	-33.1%	6	0/6	7.4%	-47.7%	-18.6%
empirical site studies	-6.1%	55	15/39/1	7.0%	-19.9%	7.6%
annual flux monitoring/modeling	-13.4%	31	8/22/1	6.1%	-25.5%	-1.4%
growing season and subgrowing season flux monitoring/modeling	-0.6%	27	8/19	12.6%	-25.3%	24.1%
1 year of observations or simulations	-29.7%	17	2/15	5.6%	-40.7%	-18.7%
2 to 3 years of observations or simulations	7.4%	34	13/20/1	10.4%	-12.9%	27.8%
3 yrs-plus of observations or simulations	-28.8%	9	0/9	5.5%	-39.7%	-18.0%

[a] reduced tillage counterfactual

[b] 62 study results, 60 studies (1 meta-analysis, 6 modeling studies, 53 empirical site studies)

[c] 1 study reports multiple results by cover crop treatment

Besides avoided direct N_2O soil emissions and avoided-emissions at fertilizer manufacture, cropland planted to perennial grasses and alfalfa also accumulates substantial amounts of soil organic carbon (SOC). Perennial grasses and alfalfa are untilled, excepting tillage at crop establishment. The organic carbon in untilled soils is physically and biochemically protected against microbial decomposition, which allows these soils to accumulate organic carbon. Large inputs of carbon belowground through root turnover and rhizodeposits also contribute to accumulating soil organic carbon.

Avoided-emissions from the conversion of cropland to hayland are an estimated 121,000 CO_2-equivalent short tons of GHGs. Table 62 gives the breakdown of avoided-emissions by gas and source. One-third of avoided-emissions result from biogenic carbon sequestration in former cropland soils planted to perennial grasses and alfalfa for harvest. Another 45 percent results from reduced direct N_2O emission from hayland soils. About 10 percent of avoided-emissions result from the avoided manufacture of synthetic fertilizer and other agricultural chemicals not applied to converted haylands. Organic carbon that is stored in soils is carbon that, having been photosynthetically fixed in plant biomass and later deposited in soils in the form of roots and crop residues, was removed from the atmosphere.

In developing these estimates, we assumed that 20 years was the longest period of time over which sustained carbon storage, once initiated, safely could be assumed. The sequestration estimates given in Table 62 were calculated under that assumption. If instead a 40-year timespan had been assumed, annual GHG-avoidance from the conversion of 100,000 acres of cropland to hayland would have been higher, totaling 164,000 CO_2-equivalent short tons, rather than 121,000 CO_2-equivalent short tons, the total calculated under the 20-year assumption. Had we assumed a 100-year timespan of assured storage, estimated avoided-emissions would have totaled 291,000 CO_2-equivalent tons (see Table 62). The approach that we use in converting observed rates of sequestration to avoided-emissions was addressed above in the Methodology section (Section II) of this report.

Table 62. Cropland to hayland: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(52,012)	crop production
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	(2,107)	crop production
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(11,703)	crop production
CH_4	soils	not known	crop production
CO_2 [b,c]	carbon accumulation in soils and biomass	(42,625)	crop production
CO_2	cultivated soils from lime or urea use	(2,786)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	3,706	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(13,371)	crop production
Total		**(120,897)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass			
40 year storage	all sources and sinks	**(163,523)**	crop production
100 year storage	all sources and sinks	**(291,399)**	crop production

[a] positive = emissions increase, negative = emissions reduction

[b] carbon accumulation in soils = a net removal of CO_2 from the atmosphere = net emission reduction

[c] assumes 20 years of sustained storage of newly sequestered organic carbon in soils and biomass

A number of estimates have been developed of the net change in greenhouse gas emissions resulting from the conversion of cropland to hayland. These are shown below in Table 63 in CO_2-equivalent short tons per 100,000 acres. They support a range of emissions reductions of 37,000 to 298,000 short CO_2equivalent tons for each 100,000 acres of conversions.

Biogenic carbon sequestration in soils from the conversion of cropland to hayland is discussed below, as are avoided direct emissions of N_2O from soils. Little is known about the effects of cropland to hayland conversion on CH_4 oxidation rates, although these effects are likely to be minor. The methods and sources used to estimate avoided indirect N_2O emissions from nitrate leaching and ammonia volatilization, avoided-emissions from fuel use, and avoided-emissions from foregone agricultural chemicals and fuels manufacture were discussed above in Section II, Subsection E of this report.

Table 63. Change in total greenhouse gases from conversion of cropland to hayland rotation [a]

		emissions avoided [a]	
Study	**Type of study**	**CO_2-eq. short tons per acre per year**	**CO_2-eq. short tons per 100,000 acres per year**
Barsottti *et al*. (2012)	site study	2.04	203,960
Gelford and Robertson (2015)	site study	0.37	36,796
Meyer-Aurich *et al.* (2006)	site study	1.20	120,021
Robertson *et al*. (2000)	site study	0.37	37,465
Sulaiman *et al.* (2017) [b]	site study	2.98	298,381
Shafer and Thompson (2015)	modeling study	1.38	138,263
Eagle *et al*. (2012)	other derivative statistical analysis [c]	0.64	63,779
Swan *et al*. (2015) [b]	literature review/expert judgment	0.41	40,778
Sainju *et al*. (2016)	meta-analysis	0.66	66,411
This report	literature review	1.21	120,897

[a] results as reported without adjustments

[b] change in soil N_2O and soil organic carbon only

[c] other than formal meta-analysis

a. Carbon sequestration in soils

The biological and biochemical processes involved in the sequestration of carbon on former cropland in hay for harvest are the same as in soils of cropland converted to unmanaged grassland. That discussion can be found in Section IV, Subsection A.a, and will not be repeated.

In Table 62, an estimate of 43,000 CO_2-equivalent short tons was given for annual carbon sequestration on 100,000 acres of cropland converted to hayland. As discussed above, this was developed using an average rate of sequestration per acre, discounted to account for an assumed 20-year persistence time of newly stored carbon in soils and biomass. Since most of the science of terrestrial carbon sequestration is developed in metric units, this average annual rate is given first in metric tons of carbon per hectare (see Table 64 below) and converted to CO_2-equivalent short tons for inclusion in summary Table 62.

In developing this estimate, 57 studies were reviewed with 59 study results, including seven modeling studies, 39 empirical site studies, four statistical summaries or derivative statistical analyses, and seven literature reviews or studies in which average sequestration rates were derived from an exercise in expert judgment. In developing the estimate for sequestration given in Table 62 for 100,000 acres of hayland, we used a simple average of the results from all 57 studies, or 0.68 ± 0.15 metric tons of carbon per hectare per year (0.3 ± 0.07 short tons of carbon per acre per year). These are estimated rates prior to truncation to accommodate an assumed 20-year persistence of stored carbon in soils. One study reported multiple results produced with different study types.

The descriptive statistics for these 57 studies are shown in Table 64. Of the 59 results that were reported in these 57 studies, six indicated soil carbon losses with cropland conversion to hayland and 53 net carbon sequestration. Average sequestration rates are shown in Table 64 by study type. Across study types, annual sequestration rates range from 0.45 to 1.8 metric tons of carbon per hectare (0.2 to 0.8 short tons of carbon per acre per year). The available total ecosystem carbon studies give an average change in total ecosystem carbon of 1.37 metric tons per hectare per year (1.51 short tons of carbon per acre per year) over six studies. No meta-analysis of the results of published studies was available to support the calculation. The weight of the evidence points to a positive response rate for sequestration for cropland-to-hayland conversions, before truncation for 20-years of assumed storage, in the range of 0.5 to 1.5 metric tons of carbon per hectare per year (0.22 to 0.67 short tons of carbon per acre per year).

By forage type, annual sequestration in alfalfa soils in the reviewed studies was an estimated 0.74 metric tons of carbon per hectare, or not substantially different from the 0.61 metric tons per hectare for nonalfalfa perennial grasses and 0.85 metric tons per hectare for a mix of alfalfa and nonalfalfa grasses. Twenty-nine studies gave results for nonalfalfa perennial grasses, 22 for alfalfa and six for a mix of alfalfa and nonalfalfa grasses. Net sequestration in studies that sampled soils below 12 inches (30 centimeters) of depth was about 20 percent lower than those sampling 12 inches (30 centimeters) or less, but based on only a handful of studies. Net sequestration rates were substantially lower in short duration studies of less than 10 years. Sequestration rates in studies that measured carbon stocks over periods of 10 to 20 years generally exceeded the mean sequestration rate for all 35 studies.

Table 64. Descriptive statistics: Cropland to hayland - carbon sequestration in soils

	biogenic carbon sequestration (Mg C/ha/yr)	number of study results [a,b,c]	ratio of sequestration to emission: number of study results [d]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	0.68	59	53/6	0.15	0.38	0.97
derivative statistical analyses or statistical summaries [e]	1.80	4	4/0	1.32	(0.80)	4.39
empirical site studies	0.65	40	35/5	0.18	0.28	1.02
modeling studies	0.45	8	8/0	0.11	0.23	0.67
literature reviews/expert judgment	0.47	7	7/0	0.08	0.31	0.63
alfalfa	0.74	22	19/3	0.36	0.02	1.45
nonalfalfa perennial grasses	0.61	29	28/1	0.13	0.35	0.87
mix of alfalfa and nonalfalfa perennial grasses or unidentified	0.85	6	6/0	0.18	0.49	1.20
5 to 30 cm soil sampling/modeling depth [f]	0.62	24	21/3	0.16	0.30	0.94
>30 cm soil sampling/modeling depth [e]	0.79	13	12/1	0.37	0.06	1.53
1 to 10 year annual sequestration rate	0.52	21	17/4	0.22	0.08	0.95
10 to 20 year annual sequestration rate	0.92	11	10/1	0.36	0.21	1.62
20 to 30 yr annual sequestration rate	0.58	16	16/0	0.10	0.39	0.77

[a] 59 study results, 57 studies (4 statistical summaries or derivative statistical analyses, 7 modeling studies, 39 empirical site studies, 7 expert reviews

[b] 2 studies report multiple results by study type

[c] includes 10 study results for studies without cropland counterfactuals (e.g., counterfactuals with annual rotations), with an average sequestration rate of 1.07 Mg C/ha/yr

[d] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[e] statistical summaries or derivative statistical analysis other than meta-analyses

[f] results for lowest reported sampling depth

b. Nitrous oxide

N_2O is produced in cropland during nitrification and denitrification by soil bacteria that oxidize ammonia or reduce nitrate to gain energy. The processes and environmental controls on N_2O production in grassland soils were discussed in the section on restored grassland (see Section IV, Subsection A.b). They are the same as occur in cropland planted to perennial grasses and alfalfa for harvest.

N_2O emissions from the conversion of cropland to hayland are calculated as the difference between average annual cropland emissions, as developed using data from the MPCA greenhouse gas emission inventory, and emissions estimated for cropland soils converted to perennial grasses and alfalfa for harvest. Mean cropland N_2O emissions in Minnesota are, on an annual basis, an estimated 4.81 kilograms per hectare (4.29 lbs. N_2O per acre). From a 2017 meta-analysis, we estimate annual N_2O emissions of 1.89 kilograms per hectare (1.69 lbs. per acre) from soils in alfalfa or perennial grass (see Table 65).

In developing these estimates, we reviewed 32 studies with 36 study results, including 22 empirical site studies (23 study results), six modeling studies (eight study results), one meta-analysis and three statistical summaries or derivative statistical analyses (4 study results). Four of these studies reported multiple results across forage types, which we tracked. Across all 32 studies, annual N_2O emissions from hayland averaged 2.1 kilograms per hectare (1.87 lbs. N_2O per acre), or reasonably close to the meta-analysis estimate (see Table 65). The results of the meta-analysis were selected as the best estimate of hayland emissions due to the general statistical power of the meta-analysis technique.

Table 65. Descriptive statistics: Cropland to hayland - N_2O

	emissions (kg N_2O/ hectare/yr) a	number of study results [b,c]	ratio, positive to negative results: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	1.89	1	1/0	NA	NA	NA
all studies	2.10	36	36/0	0.38	1.14	2.63
derivative statistical analyses or statistical summaries [d]	1.70	4	4/0	0.35	1.42	2.79
empirical site studies	1.43	23	23/0	0.33	1.06	2.34
modeling studies	3.56	8	8/0	1.36	(1.24)	4.11
alfalfa studies	1.74	18	18/0	0.27	3.02	4.10
other hay and grasses studies	2.60	11	11/0	1.08	1.01	5.26
fertilized grassland	3.14	10	10/0	1.12	(0.47)	3.94
annual flux monitoring/modeling	2.24	25	25/0	0.51	1.61	3.60
growing season flux monitoring/modeling	1.58	8	8/0	0.65	1.86	4.41
1 to 2 years of observations or simulations	2.66	14	14/0	0.90	0.47	4.01
3 years and greater of observations or simulations	1.83	15	15/0	0.34	0.92	2.24

[a] negative emissions = removal from atmosphere and destruction in soils

[b] 36 study results, 32 studies (1 meta-analysis, 3 statistical summaries or derivative statistical aanlyses, 6 modeling studies, 22 empirical site studies)

[c] 4 studies report multiple results by forage type

[d] statistical summaries or derivative statistical analyses other than meta-analyses

By study type, in Table 65 N_2O emissions from hayland range from 1.70 to 3.56 kilograms per hectare per year, for a two-fold difference in mean estimates by study type. Because of this, some care should be taken in accepting without reservations the results of a single meta-analysis. More studies of an empirical nature, spanning a wider array of environmental conditions, may be needed to reduce uncertainties.

By monitoring period, the studies that report emissions from hayland on an annual basis and also on a long-term basis (three-years or longer) yield results similar to, if slightly larger than, the meta-analysis results, which provides some measure of comfort.

N. Perennial grass added to annual crop rotation

The conversion of annual crops to perennial grasses or alfalfa can be implemented on a rotational basis by the introducting of one or more years of a perennial grass or alfalfa into an annual rotation. The conversion of cropland in annual crops to perennial grasses or alfalfa results in increased organic carbon in soils (see discussion in Section IV, Subsection M.a above). Organic carbon in soil is photosynthetically derived through root and crop residue inputs to soil during crop growth and after harvest. Additional carbon storage in soils results in CO_2 removal from the atmosphere.

Additionally, the conversion of cropland to perennial grasses or alfalfa, even on a rotational basis, results in reduced synthetic nitrogen applications to cropland, hence reduced soil emissions of N_2O, as well as reduced downstream N_2O emissions from surface waters from nitrate leached from cropped soils. Reduced greenhouse gas emissions from the avoided manufacture of nitrogen fertilizer, other agricultural chemicals and fuels used in crop production also result.

With several years of perennial grasses or alfalfa added to annual rotations, soil carbon increases and N_2O emissions, during cultivation, as well as upstream and downstream of cultivation, decline, albeit to a lesser degree than in the complete conversion of cropland to hayland without interspersed years of annual crops.

Table 66 shows the estimated net change in greenhouse gas emissions resulting from the lengthening of annual crop rotation by adding to annual rotations two or more years of perennial grasses or alfalfa. Greenhouse gas-avoidance on 100,000 acres with extended rotations with perennial grasses or alfalfa is an estimated 41,000 CO_2equivalent tons annually. Of this, about two-thirds percent derives from carbon sequestration in soils. The rest results from reduced direct emissions of N_2O from cropland soil and reduced indirect nitrate leaching-related emissions from surface waters. Reduced out-of-state emissions from the avoided manufacture of fertilizer and other agricultural chemicals also are important, accounting for about one-quarter of total avoided-emissions.

In this calculation, we assumed that biogenic carbon stored in cropland soils will persist in storage for 20 years, after which it will be reemitted to the atmosphere as CO_2. As noted elsewhere in this report, twenty years is the longest period that, in our judgment, sustained terrestrial storage safely can be assumed for purposes of its present-day valuation. If instead of 20 years, we had assumed a 40- year timespan, the greenhouse gas-avoidance on 100,000 acres would have totaled 67,000 CO_2-equivalent tons per annum, up from 41,000 tons, the total calculated under the 20-year assumption. Had we assumed a 100-year timespan of assured storage, estimated annually avoided-emissions would have totaled 143,000 CO_2-equivalent tons.

We developed these estimates using estimates from studies employing a wide variety of annual rotations and perennial grasses and forages. Many of the studies included corn in monoculture or in two-year rotation with soybeans, often with two to three years of alfalfa added. Other perennial grasses that were included rotationally in the studies were non-alfalfa hay, timothy and other pasture grasses. Besides corn-based annual rotations, other base rotations treated in the studies included mostly small grains in various rotations with legumes, row crops like corn or other small grains.

In calculating emissions-avoided from avoided agricultural chemical use, for the base rotation, we used a two-year corn-soybean rotation, averaged with the results from corn in monoculture. For the extended rotation, we used two four-year rotations comprised of corn-corn-alfalfa-alfalfa and corn-soybeans-alfalfa-alfalfa.

Table 66. Add a perennial grass to crop rotation: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(1,599)	crop production
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	(1,053)	crop production
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(6,826)	crop production
CH_4	soils	not known	crop production
CO_2 [b,c]	carbon accumulation in soils and biomass	(25,518)	crop production
CO_2	cultivated soils from lime or urea use	(1,393)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	6,886	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(11,888)	crop production
Total		**(41,392)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass			
40 year storage	all sources and sinks	**(66,910)**	crop production
100 year storage	all sources and sinks	**(143,465)**	crop production

[a] positive = emissions increase, negative = emissions reduction

[b] carbon accumulation in soils = net removal of CO_2 from the atmosphere = net emission reduction

[c] assumes 20 years of sustained storage of newly sequestered organic carbon in soils and biomass

a. Carbon sequestration in soils

In converting years three and four of either a corn-soybean-corn-soybean rotation or a continuous corn rotation (corn-corn-corn-corn) to alfalfa or a perennial grass, organic carbon is sequestered in soils. The biological and biochemical processes that are involved are the same as were discussed for the conversion of cropland to hayland and restored grassland (see Section IV, Subsection A.a and Section IV, Subsection M.a).

In Table 66, an estimate of 26,000 CO_2-equivalent tons was given for annual carbon sequestration on 100,000 acres of cropland converted from corn monoculture or corn-soybean rotation to a four-year rotation that includes alfalfa or a nonleguminous perennial grass in rotational years three and four. As discussed above, this estimate was developed using an average rate of sequestration per acre, discounted to account for an assumed 20-year persistence of newly stored carbon in soils and biomass. Since most of the science of terrestrial carbon sequestration is developed in metric units, this average annual sequestration rate is given first in metric tons of carbon per hectare (see Table 67 below) and converted to CO_2-equivalent short tons for inclusion in summary Table 66.

In developing these estimates, 45 studies were reviewed, including eight modeling studies, 28 empirical site studies, five statistical summaries or derivative statistical analyses, and four literature reviews or studies in which average sequestration rates were derived from an exercise in expert judgment. In calculating the estimate for sequestration given in Table 66 for extended rotations with alfalfa or perennial grasses, we used a simple average of the results from these 45 studies, or 0.41 ± 0.11 metric tons of carbon per hectare per year (0.18 ± 0.05 short tons of carbon per acre per year). These are estimated rates prior to truncation to accommodate an assumed 20-year persistence of stored carbon in soils and biomass. No meta-analysis of published studies was available to support a calculation.

The descriptive statistics for these 45 studies are shown in Table 67. Of these, 38 studies reported net carbon sequestration, while six reported losses of carbon. The calculated confidence interval for the set of all studies that were reviewed was fairly broad, suggesting that, while the direction of the change in soil carbon in well understood, more may need to be done to narrow the range of possible average annual sequestration rates. Across study types, annual sequestration rates range from 0.32 to 0.46 metric tons of carbon per hectare (0.14 to 0.21 short tons of carbon per acre per year).

Table 67. Descriptive statistics: Add a perennial grass or alfalfa to crop rotation – carbon sequestration in soils

	biogenic carbon sequestration (Mg C/ha/yr)	number of study results [a]	ratio of sequestration to emission: number of study results [b]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	0.41	45	38/6/1	0.11	0.18	0.63
derivative statistical analyses or statistical summaries [c]	0.37	5	5/0	0.17	0.05	0.70
empirical site studies	0.46	28	21/6/1	0.18	0.10	0.82
modeling studies	0.28	8	8/0	0.06	0.17	0.40
literature reviews/expert judgment	0.32	4	4/0	0.10	0.13	0.51
alfalfa added to rotation	0.44	15	10/4/1	0.21	0.03	0.84
generic perennial added to rotation	0.36	9	8/1	0.10	0.17	0.56
other hay, unidentified hay or grass leys added to rotation	0.23	18	16/2	0.03	0.16	0.30
5 to 30 cm soil sampling/modeling depth [d]	0.33	24	21/3	0.10	0.13	0.52
>30 cm soil sampling/modeling depth [d]	0.31	11	7/3/1	0.20	(0.08)	0.69
1 to 10 year annual sequestration rate	1.19	5	4/0/1	0.81	(0.58)	2.96
10 to 30 year annual sequestration rate	0.37	21	17/4	0.14	0.09	0.65
>30 year sequestration rate	0.19	12	11/1	0.04	0.12	0.27

[a] 45 study results, 45 studies (5 statistical summaries or derivative statistical analyses, 8 modeling studies, 28 empirical site studies, 4 expert reviews)

[b] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[c] statistical summaries or derivative statistical analyses other than meta-analyses

[d] results for lowest reported sampling depth

By type of hay or perennial grass, there was relatively little difference in estimated rates of annual carbon sequestration. Sequestration in studies that sampled soil carbon below 16 inches (40 centimeters) is identical to estimated average sequestration in studies with more shallow sampling depths. By length of study, sequestration was extremely rapid in studies of ten years or less, but based only a few studies. Sequestration rates for studies that measured the change in carbon stocks over periods of 10 to 30 years were generally similar to the mean sequestration rate for all 45 studies that were reviewed.

b. Nitrous oxide

Table 68. Descriptive Statistics: Add a perennial grass or alfalfa to crop rotation - N_2O

	emissions: % change in emissions per hectare	number of study results [a]	change in emissions, ratio positive-to-negative: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	-3%	18	3/15	8%	-19%	14%
derivative statistical analyses or statistical summaries [b]	-3%	1	0/1	NA	NA	NA
empirical site studies	-2%	12	2/10	12%	-25%	21%
modeling studies	-4%	4	1/3	15%	-33%	25%
literature reviews/expert judgment	-2%	1	0/1	NA	NA	NA
alfalfa	-4%	14	2/12	10%	-24%	16%
other hay or generic perennial	2%	4	1/3	12%	-22%	27%
annual flux monitoring/modeling	7%	10	2/8	14%	-20%	34%
growing season flux monitoring/modeling	-14%	7	0/7	6%	-25%	-3%

[a] 18 study resulls, 18 studies (1 statistical summary or derivative statistical analysis, 4 modeling studies, 12 empirical site studies, 1 expert review)

[b] statistical summaries or derivative statistical analyses other than meta-analyses

O. Corn-soybean rotation in place of continuous corn

Generally, the conversion of cropland from monoculture to crops in rotation results in increased soil organic carbon (SOC) sequestration and reduced greenhouse gas emissions. (Eagle *et al*., 2012; Varvel, 1994; West and Post, 2002) In Minnesota, about 13.5 million acres of cropland are planted in either corn or soybeans in two-year rotation with corn. (Bierman *et al*., 2012) Of this, about 10 percent or about 1.3 million acres are planted in corn in monoculture, also known as continuous corn. A corn-soybean rotation is favored by farmers due to generally higher corn yields, and generally higher per acre profitability. (Al-Kaisi *et al*., 2015)

Table 69 shows the estimated net annual greenhouse gas balance from converting cropland from continuous corn to a two-year corn-soybean rotation. We estimate that, for each 100,000 acres of cropland converted from continuous corn to corn and soybeans, an additional 35,000 CO_2-equivalent short tons of greenhouse gases would be emitted annually, or 0.35 short CO_2-equivalent tons per acre. About 54,000 CO_2-equivalent short tons would be emitted from soils in the form of CO_2. A part of this emission would be offset by reductions in the direct emission of N_2O from soils, an estimated 1,000 CO_2-equivalent short tons. A further 17,000 would be offset by avoided upstream emissions resulting from the manufacture of nitrogen fertilizer that would be avoided under a two-year corn-soybean rotation. [14]

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[14] This assumes nitrogen fertilization rates, under continuous corn, of 162 lbs per acre, and 110 lbs per acre for corn and 0 lbs per acre for soybeans under a two–year corn-soybean rotation.

Table 69. Corn-soybean rotation replacing continuous corn: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(958)	crop production
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	not known	crop production
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	not known	crop production
CH_4	soils	not known	crop production
CO_2 [b]	soils	54,046	crop production
CO_2	cultivated soils from lime or urea use	-	crop production
GHGs-energy	fossil fuel and electricity use in crop production	(909)	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(17,296)	crop production
Total		**34,883**	

[a] positive = emissions increase, negative = emissions reduction

[b] net soil carbon loss = net CO_2 emission to the atmosphere

Under soybean production, substantially less biogenic carbon in the form of crop residues is returned annually to soils than would be the case under corn production. With reduced carbon inputs, but unchanged respiration-related losses, soil carbon declines, implying a net emission of CO_2 to the atmosphere. Direct emissions of N_2O decline in a corn-soybean rotation due to zero or near-zero synthetic nitrogen requirements of soybeans and reduced synthetic nitrogen applications to corn.

Out-of-state emissions from fertilizer manufacture decline as nitrogen fertilizer needs contract. Regarding CH_4 emissions and N_2O emissions downstream after nitrate leaching or ammonium volatilization, not enough is known to support an analysis of how emissions from these sources might change.

A number of estimates have been developed of the net change in greenhouse gas emissions resulting from use of a two-year corn-soybean rotation *in lieu* of corn following corn. These are shown below in Table 70 in CO_2-equivalent short tons per 100,000 acres. With one notable exception, they support a range of emissions increase of 21,000 to 78,000 short CO_2-equivalent tons for each 100,000 of conversions.

Table 70. Change in total greenhouse gases from conversion from continuous corn to corn-soybean rotation [a]

		emissions increase [a]	
Study	**Type of study**	**CO_2-eq. short tons per acre per year**	**CO_2-eq. short tons per 100,000 acres per year**
Adviento-Borbe *et al*. (2007)	empirical site study	0.78	78,461
Archer and Halvorson (2010)	empirical site study	0.34	34,483
Doberman *et al*. (2007)	empirical site study	0.21	21,412
Mosier *et al*. (2005)	empirical site study	0.29	29,040
Mosier *et al.* (2006)	empirical site study	0.42	42,141
Robertson *et al*. (2011)	modeling study	(0.54)	(53,942)
Walters *et al*. (2007)	modeling study	0.47	47,208
Sainju *et al*. (2016)	meta-analysis	0.22	22,483
This report	literature review	0.35	34,883

[a] results as reported without adjustments

CO_2 emissions from cropland soils are discussed below, as are avoided direct emissions of N_2O from reduced mineral fertilizer needs under a two-year corn-soybean rotation. As noted just above, insufficient information is available to support an assessment of how soil CH_4 oxidation under continuous corn might change under a two-year corn-soybean rotation.

a. Carbon sequestration in soils

Crop residues contain substantial amounts of organic carbon in the form of biomass. After grain harvest, these are returned to the soil either as surface residues or, after incorporation, as buried crop residues. In soil in which the mass of soil organic carbon (SOC) is stable, returned crop residues act to offset respiration losses of carbon. With reduced residue inputs to soils, a part of respiration losses are not offset, leading to a net loss of carbon from soils in the form of CO_2 emission to the atmosphere.

Soybeans produce substantially less crop residue than does corn, 60 to 70 percent less. Because of this, averaged over two years, a corn-soybean rotation produces and returns to soil 20 to 30 percent less biomass carbon than does continuous corn. (Gal *et al*., 2007; Pikul *et al*., 2008) As a result, soils under a two-year corn-soybean rotation lose soil organic carbon relative to soils under continuous corn, typically 0.1 to 0.3 short tons of carbon per acre per year. (West and Post, 2002; Pikul *et al*., 2008; Adviento-Borbe *et al*., 2007) Of this loss, most or all is incurred during the soybean year of the rotation, based on eddy covariance studies of net ecosystem carbon change under a corn-soybean rotation. (Baker and Griffis, 2005; Verma *et al*., 2005)

Generally, all other things being equal, soil organic carbon is positively correlated with residue returns to the soil, increasing linearly with residue return. (Clapp *et al*., 2000; Havlin *et al*., 1990; Huggins *et al*., 2007; Larson *et al*., 1972) Other factors that might play a role in the observed difference in soil organic carbon under continuous corn and the two–year corn-soybean rotation include possible decreased soil aggregation under the two-year rotation and accelerated residue decomposition with high nitrogen soybean residues. (Coulter *et al*., 2009) With decreased soil aggregation, organic carbon in soils is less protected against microbial decomposition, leading to soil carbon loss. Soil aggregation is known to decline with decreased inputs of organic matter to soils. As discussed above in the cover crop section of this report (see Section IV, Subsection I.a), soil macroaggregates are bound together by organic acids and polymers derived from decomposing soil organic matter.

Soybean residues are rich in nitrogen, which, it is thought, promotes the rapid decomposition of organic matter relative to decomposition of corn-derived residues that are relatively nitrogen poor. (Jagadamma *et al*., 2007)

By converting from corn monoculture to a two-year corn-soybean rotation, an estimated 0.54 short tons of CO_2 per acre would be emitted to the atmosphere annually (0.15 short tons of carbon per acre). This estimate was developed from a simple arithmetic average of the results of 34 studies that were reviewed. These included: one derivative statistical study of literature estimates, three modeling studies, 29 empirical site studies and one literature review. No meta-analysis was available to support the calculation. In developing the emission rate estimates, the calculations were done initially in metric units and then converted to English or common units. On 100,000 acres, an estimated 54,000 short tons of CO_2 would be emitted annually.

The descriptive statistics for the studies that were reviewed are shown in Table 71. Of the three modeling studies, one showed a net gain and two a net loss of soil organic carbon under corn-soybean rotation on cropland formerly in corn monoculture. In 26 of the 29 empirical site studies, SOC storage in cropland under corn-soybean rotation declined after conversion from continuous corn, increasing in three. Using the average value for all 34 studies that were reviewed, cropland soils formerly under corn monoculture but converted to a two-year corn-soybean rotation are estimated to lose 0.33 ± 0.09 metric tons of carbon per hectare (0.15 short tons of carbon per acre) annually. Excluding the odd modeling result, the estimated SOC loss in the reviewed studies ranges from 0.19 to 0.37 metric tons of carbon per hectare per year (0.08 to 0.17 short tons of carbon per acre per year). The one available derivative statistical analysis of estimates from the published literature gives a slightly lower value (0.19 metric tons of carbon per hectare per year) than the mean value from the 34 studies, but is based on a set of somewhat older studies dating from the 1980s and 1990s.

By soil depth, per hectare emissions are somewhat larger with soil sampling at or below 12 inches (30 centimeters), but based on a relatively few study results. Emission rates in studies that average SOC change over periods longer than 20 years are substantially less, suggesting that, beyond 20 years, soils may begin to approach a new equilibrium beyond which emissions cease.

Table 71. Descriptive statistics: Corn-soybean rotation replacing continuous corn - carbon sequestration in soils

	biogenic carbon sequestration (Mg C/ha/yr)	number of study results [a]	ratio of sequestration to emission: study numbers [b]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	(0.33)	34	4/30	0.09	(0.51)	(0.15)
derivative statistical analyses or statistical summaries [c]	(0.19)	1	0/1	NA	NA	NA
empirical site studies	(0.37)	29	3/26	0.11	(0.58)	(0.16)
modeling studies	(0.03)	3	1/2	0.19	(0.40)	0.34
5 to 30 cm soil sampling/modeling depth [d]	(0.33)	23	1/22	0.08	(0.48)	(0.18)
> 30 cm soil sampling/modeling depth [d]	(0.39)	9	1/8	0.29	(0.96)	0.18
1 to 10 year annual sequestration rate	(0.56)	10	0/10	0.14	(0.84)	(0.27)
10 to 20 year annual sequestration rate	(0.38)	14	2/12	0.17	(0.70)	(0.06)
20 to 30 year annual sequestration rate	(0.05)	11	2/9	0.11	(0.26)	0.17

[a] 34 study resulls, 34 studies (1 statistical summary or derivative statistical analysis, 3 modeling studies, 29 empirical site studies)

[b] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[c] statistical summaries or derivative statistical analyses other than meta-analyses

[d] results for lowest reported sampling depth

b. Nitrous oxide

N_2O emissions generally decline in cropland converted from continuous corn to a corn-soybean rotation.

In the US, soybeans are unfertilized with nitrogen or are fertilized at low levels of nitrogen fertilizer. Two-year nitrogen fertilizer totals for the corn-soybean rotation are often half of those for continuous corn. The rate of application of synthetic nitrogen to cropland is one of the dominant controls on N_2O emission. Using the standard method, one percent of each unit of nitrogen applied as fertilizer to crops is converted to N_2O in soils and emitted to the atmosphere. (IPCC, 2006) Based on the US national greenhouse gas inventory, emissions of N_2O from fertilizer use on cropland account for about one-third of total cropland N_2O emissions. (USEPA, 2017)

Reviewing the literature, N_2O emission reductions under corn-soybean rotations are usually attributed to reduced synthetic nitrogen applications, generally during the soybean phase of the rotation. (Behnke *et al.*, 2008; Drury *et al*., 2008; Gregorich *et al*., 2015; Osterholz *et al.,* 2014) A contributing factor could be the high amounts of incorporated crop residue that, in continuous corn, promote the formation of anaerobic conditions in the plow layer and promote N_2O production and emission through enhanced rates of denitrification. (Venterea and Coulter, 2015) Where N_2O emissions do not decline with a change to a corn-soybean rotation, this is sometimes attributed to the effect of confounding influences. (Decock, 2014) Where soil fertilization is a dominant control on N_2O emissions, this control is substantially modulated by the influence of soil qualities like soil texture, clay content, water-holding capacity, aeration and SOC content, as well as weather and weather events, particularly in relation to fertilization events. At any one site in any one year, these influences can overwhelm the influence of nitrogen fertilizer on observed N_2O emissions.

From Table 69, it is estimated that the conversion of 100,000 acres of cropland formerly in corn monoculture to a corn-soybean rotation would reduce N_2O emissions by 1,000 CO_2-equivalent tons. This estimate was developed using the results from the single meta-analysis found in the scientific literature. The results of this meta-analysis were selected as the best estimate of the change in N_2O emissions due to the general statistical power of the meta-analysis technique. Emission reductions are calculated as the product of the estimated average percentage change in emissions resulting from converting cropland formerly in corn monoculture to a corn-soybean rotation and average Minnesota cropland N_2O emissions. As discussed in the section on methods, average Minnesota cropland N_2O emissions are from the MPCA Greenhouse Gas Inventory. Using the estimated percentage change in N_2O emissions from the single meta-analysis, and average Minnesota cropland N_2O emissions, the conversion of cropland formerly in corn monoculture to a two-year corn-soybean rotation is estimated to reduce N_2O emissions by 1.5 percent.

The studies that were reviewed included: 15 empirical site studies, three modeling studies and the one meta-analysis. Of the 19 studies reviewed, 15 reported reduced N_2O emissions with corn-soybean rotation on cropland formerly in corn monoculture and 4 reported increases. Of the 15 empirical studies, twelve reported reductions in N_2O emissions, three increases, while the results from the modeling studies were mixed, one study showing increased emissions, two showing declining N_2O emissions with a change in cropping practice from continuous corn to a corn-soybean rotation. The one available meta-analysis reported a reduction in emissions.

The descriptive statistics for the reviewed studies are shown in Table 72, with standard errors and confidence intervals. The confidence interval for the percentage change for all studies is broad, though exclusively in negative territory. The width of the confidence interval provides adequate reason for caution. Clearly, a wide range of estimates are possible, though the weight of the evidence broadly supports a negative value.

Table 72. Descriptive statistics: Corn-soybean rotation replacing continuous corn - N_2O

	emissions: % change in emissions per hectare	number of study results [a]	change in emissions, ratio positive-to-negative: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	-1.5%	1	0/1	NA	NA	NA
all studies	-17.7%	19	4/15	7.4%	-32.2%	-3.3%
empirical site studies	-20.7%	15	3/12	9.0%	-38.4%	-2.9%
modeling studies	-8.4%	3	1/2	11.6%	-31.0%	14.3%
annual flux monitoring/modeling	7.0%	8	4/4	11.6%	-15.7%	29.7%
growing season flux monitoring/modeling	-40.6%	10	0/10	5.0%	-50.4%	-30.9%
1 to 2 years of observations or simulations	-9.8%	8	2/6	13.8%	-36.9%	17.3%
3 years-plus of observations or simulations	-22.3%	9	2/7	8.8%	-39.6%	-5.0%

[a] 19 study resulls, 19 studies (1 meta-analysis, 3 modeling studies, 15 empirical site studies)

Also troubling is the mean percent change estimated for studies that give results on an annual basis, rather than growing season basis. The number of studies is quite small, and if we limit the population of studies to empirical site studies, is but four studies. While this is far too few studies to conclude anything, particularly with respect to notoriously variable N_2O emissions estimates, the anomalous increase in N_2O emissions in these studies argues for caution. Clearly a good many more empirical studies of this question are required for a more certain quantitative estimate of response of N_2O emissions to rotation change.

P. Crop residue retention

Crop residues sometimes are baled and removed from the field for use as animal bedding, forage and, in future applications, biofuels feedstock. In Minnesota, about 450,000 acres of aboveground residues are removed from the corn fields for forage for livestock, in addition to some unknown amount of other crop residues removed for bedding. Crop residue retention acts similarly to cover crops to build soil carbon stocks, as well as to increase soil N_2O production. By contrast, residue removal, if substantial, acts to lessen soil organic carbon stocks.

Here we evaluate crop residue return as a best practice against an assumed crop residue removal counterfactual. Table 73 shows the results for 100,000 acres of crop residue retention. We estimate that, for each 100,000 acres of full aboveground residue retention, 17,000 CO_2-equivalent short tons of greenhouse gas emissions would be avoided, again, against a crop residue removal counterfactual. Of this 17,000 CO_2-equivalent short tons, all plus a little would result from soil organic carbon sequestration, at a rate of about 0.06 short tons of carbon per acre per year. Increased N_2O emissions would offset about 30 percent of this avoidance, and reduced field fuel use an additional 10 percent.

Table 73. Crop residue retention: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	6,249	residue removal
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	586	residue removal
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(1,725)	residue removal
CH_4 [b]	soils	332	residue removal
CO_2 [c,d]	carbon accumulation in soils	(20,208)	residue removal
CO_2	cultivated soils from lime or urea use	-	residue removal
GHGs-energy	fossil fuel and electricity use in crop production	(1,969)	residue removal
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(436)	residue removal
Total		**(17,171)**	residue removal
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass			
40 year storage	all sources and sinks	**(37,378)**	residue removal
100 year storage	all sources and sinks	**(98,002)**	residue removal

[a] positive = emissions increase, negative = emissions reduction

[b] reduction in soil CH_4 oxidation = relative increase in emissions

[c] carbon accumulation in soils = net removal of CO_2 from the atmosphere = net emission reduction

[d] assumes 20 years of sustained storage of newly sequestered organic carbon in soils and biomass

As elsewhere in this report, in developing these estimates, we assumed 20 years to be the longest period of time over which sustained carbon storage, once initiated, safely could be assumed. If instead a 40-year timespan had been assumed, annual greenhouse gas-avoidance for 100,000 acres of full crop residue retention would have totaled 37,000 CO_2-equivalent short tons. Had we assumed a 100-year timespan of assured storage, estimated annual avoided-emissions would have totaled 98,000 CO_2-equivalent short tons per acre. The methodology section (Section II) of this report includes a description of the approach we use in converting observed rates of sequestration to avoided-emissions.

Due to the complexities involved, in developing this analysis, we do not treat the emissions-avoidance effects of reduced downstream residue use. It is possible that, with crop residue used as a biofuels feedstock, downstream greenhouse gas-avoidance could be substantial. Given the absence in the literature of relevant response rates, we also do not consider the effects of reduced synthetic nitrogen applications, if any result, from crop residue return practices.

Soil organic carbon sequestration from crop residue retention on cropland is discussed below, as are emissions of N_2O and the effects of residue retention on CH_4 oxidation. Section III, Subsection E contains a discussion of the methods used to estimate indirect emissions (or emissions-avoidance) from nitrate leaching and ammonia volatilization and land deposition, as well as a discussion of avoided-emissions from fuel use and its production.

a. Carbon sequestration in soils and biomass

During soil carbon sequestration, CO_2 is removed photosynthetically from the atmosphere and incorporated into plant biomass and, through root senescence and exudation, into soils. Soil carbon sequestration can be accomplished by decreasing soil respiratory losses, which result from microbial decomposition of organic matter in soils. It also can result from practices that increase organic carbon input into soils. Carbon is removed from the atmosphere and stored in soils when the photosynthetic fixation of carbon in plant biomass and, indirectly, in soils, exceeds ecosystem respiratory losses.

Of the practices considered in this report, the retirement from agricultural uses of upland grasslands and drained peatland and mineral wetlands, acts to inhibit organic matter losses to the atmosphere, as does tillage change to less intensive forms of tillage. Avoided upland grassland conversion to agricultural use, along with avoided conversion of undisturbed peatlands and mineral wetlands to cropland and pastureland, acts similarly. By contrast, in soils under cover crops, carbon is stored principally as a result of enhanced photosynthetic fixation of atmospheric CO_2 in plant biomass (and indirectly, through root senescence and exudation, into soils). The same is true in the case of the perennialization of annual crop rotations and cropland afforestation, whether in uplands or in the riparian zone.

During crop residue retention, organic carbon is sequestered in soils principally as a result of reduced respiratory losses, in the case of residue removal, offsite losses resulting from residue use as bedding and fodder or as a bioenergy feedstock. Left in the field, 12 to 15 percent of the organic carbon in crop residues is converted to soil organic carbon (SOC), usually within several years. (Han et *al*., 2018; Liu *et al*., 2014; Wang *et al*., 2017) Its retention in soils reduces respiratory losses by this same 12 to 16 percent, leading to a net removal of CO_2 from the atmosphere.

Alternatively, focusing solely on the soil, by minimizing removals, crop residue retention adds organic carbon to soils, causing SOC to increase by this 12 to 16 percent retention in soils.

As a result of decades of study, it has long been understood that SOC increases linearly with the amount of crop residue retained in the field after harvest. (Han *et al.,* 2018; Wang *et al*., 2017) Typical average annual rates of sequestration range from 0.1 to 0.5 metric tons of carbon per hectare (0.04 to 0.22 short tons per acre per year). (Han *et al*., 2018; Jones *et al*., 2017; Poeplau *et al*., 2017; Wang *et al*., 2017) In the most recent meta-analyses of the data, measured against complete residue removal, crop residue retention has been observed to increase the mass of SOC in soils by between 9 and 12 percent, at least over a soil depth of 30 centimeters (11.8 inches). (Liu *et al*., 2014; Poeplau *et al*., 2017)

By contrast, crop residue removal acts to decrease organic carbon in soils, 0.06 to 0.09 metric tons of carbon per hectare per each one percent of crop residue removed. (Anderson-Teixeira *et al*., 2009) For full crop residue removal, SOC declines on the order of eight to twelve percent and may be half that from 60 percent removal. (Anderson-Teixeira *et al*., 2009; Jones *et al*., 2018; Raffa *et al*., 2013; Xu *et al.*, 2019)

The amount of crop residue retention needed to maintain SOC levels at present levels has been variously estimated to be 2.5 to 8.5 metric tons per hectare per year (1.16 to 3.70 short tons per acre per year), depending on climate, tillage practice, soil sampling depth, and other factors. (Huang *et al*., 2018; Jin *et al*., 2017; Johnson *et al.*, 2014; Karlen and Higgins, 2014) For Minnesota corn-soybean rotations under no-till tillage, Datzell *et al.* (2013) estimate this value at 3.65 metric tons of crop residues per hectare per year (1.63 short tons per acre per year). In Minnesota, per acre crop residue production from corn is about 7.51 metric tons per year (4.35 short tons per year). [15]

Crop residue retention acts to minimize off-site respiratory losses of organic carbon. Crop residues may also act to enhance the protection afforded soil macroaggregates from microbial attack through binding agents, produced in soils from residues, and through residue-derived particulate organic matter that acts to bind soil microaggregates to soil macroaggregates. (Liu *et al*., 2014)

Several years of crop residue retention are typically required before enhanced sequestration in soils is observed. Enhanced sequestration is generally limited to 15 to 25 years after the initiation of residue

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[15] dry ton-basis, calculated from Minnesota corn grain yields and the conversion factor from grain yield to crop residue amounts given US Department of Energy (2016)

retention, after which SOC levels stabilize. (Buysee *et al*., 2013; Liu *et al*., 2014; Poeplau *et al*., 2017) Crop residue incorporation may or may not result in greater soil carbon sequestration than surface placement. (Liu *et al*., 2014; Mitchell *et al*., 2016)

In the US, 70 to 77 percent of crop residue is in the form of corn stover, while wheat straw accounts for 20 to 25 percent of US crop residue production. (Karlen and Higgins, 2014)

Controls on soil carbon sequestration from crop residue retention include: soil temperature, soil type and texture, soil nitrogen, the mass of crop residue carbon retained in soils, SOC levels prior to the start of enhanced crop residue retention, crop residue contact with soils, and tillage. (Allmaras *et al*., 2004; Wang *et al*., 2017) Soil temperature controls the rate of microbial activity in soils. Soil carbon sequestration through crop residue return is promoted through the presence of fine textured soils with high clay content, which acts to chemically adsorb organic matter, inhibiting decomposition. (Adler *et al*., 2015) High rates of carbon sequestration are associated with low initial levels soil organic carbon. (Liu *et al*., 2014) Full inversion tillage acts to inhibit soil carbon sequestration. (Jin *et al*., 2017)

Finally, other benefits of crop residue return include: lower soil temperatures, greater soil water-holding capacity, improved soil nutrient status, and reduced wind and water erosion. (Villamil and Nafzinger, 2015) Through slow spring warm-up, crop residue return can act to delay spring planting. Excess levels of crop residues also may act to inhibit seed germination, promote weed infestations and fungal disease, and, through nitrogen immobilization in an organic form, to impair nutrient cycling. (Golany *et al*., 2010; Villamil and Nafzinger, 2015)

In Table 73, an estimate for annual carbon sequestration resulting from crop residue return of 20,208 short tons of CO_2 or 5,515 tons of carbon was given, covering 100,000 acres of restorations. As discussed above, this was developed using an average rate of sequestration per acre, discounted to account for an assumed 20-year persistence of storage. When crop residues are returned to soils, a part of crop residue carbon is retained in soils. This acts to minimize upward fluxes of CO_2 from soils to the atmosphere arising from ecosystem respiration, resulting in the net accumulation of ecosystem organic carbon, particularly in soils.

The sequestration estimate given in Table 73 was developed from five meta-analyses of published side-by-side site studies of changes in soil carbon with crop residue retention (calculated against a crop residue removal counterfactual), plus another four derivative statistical analyses of side-by-side studies from a similar pool of studies. As noted in the methodology section of this report (Section II), meta-analysis is a powerful statistical tool used to integrate results of experiments of different designs and draw conclusions at broad spatial scales.

Using the estimates from the five meta-analyses and the four other derived statistical analyses, crop residue return is estimated annually to sequester 0.32 ± 0.09 metric tons of carbon per hectare (0.52 short tons of CO_2), implying that, on a per acre basis, carbon storage in cropland soils in which crop residues are retained acts annually to offset 0.3 tons of CO_2 emitted elsewhere in the economy. This is the estimated rate prior to truncation to accommodate an assumed 20-year persistence of newly stored organic carbon in croplands.

Overall, 89 studies were reviewed. By study type, nine meta-analyses and other derivative statistical summaries or analyses were reviewed, as were the 50 soil sampling-type site studies, one eddy-covariance study, 18 modeling studies, and six literature and expert reviews.

In the reviewed studies, by study type, estimated rates of carbon sequestration ranged from 0.32 to 0.44 metric tons of carbon per hectare (0.14 to 0.20 short tons of carbon per acre). Only a handful of the 89 studies that were reviewed reported reductions in carbon storage from crop residue return; slightly less than 90 percent reported increased carbon storage.

The descriptive statistics for the studies by study type, by soil sampling depth, and by age of grassland restoration are shown in Table 74. Results are given in metric tons of carbon, but converted to short CO_2-equivalent tons for inclusion in the summary Table 73. Estimated annual sequestration from the 51 empirical site studies is some 0.44 ± 0.08 metric tons of carbon per hectare (0.2 ± 0.04 short tons of carbon per acre), or somewhat larger than the meta-analyses estimate. In the modeling studies estimated annual sequestration is an estimated 0.33 ± 0.09 metric tons of carbon per hectare, while in the literature and expert reviews, it is an estimated 0.4 ± 0.12 metric tons of carbon per hectare.

In a marked difference to the results for many of the practices considered in this report, confidence internals for crop residue return across study type were not excessive.

From Table 74, mean soil carbon sequestration by soil depth at 10 to 30 centimeters of depth (4 to 12 inches) is some 0.31 metric tons of carbon per hectare, or virtually the same as the overall meta-analyses estimate, and 0.62 metric tons of carbon per hectare at depth of 40 centimeters or below. By percentage of residue return, soil carbon sequestration is an estimated 0.46 metric tons per hectare for 0 to 35 percent crop residue retention, 0.09 metric tons per hectare for 40 to 60 percent retention, and 0.29 metric tons per hectare for 75 percent retention. The fall-off in sequestration at 40 to 60 percent crop retention is unexplained.

Table 74. Descriptive statistics: Crop residue retention - carbon sequestration in soils

	biogenic carbon sequestration (Mg C/ha/yr)	number of study results [a]	ratio of sequestration to emission: number of studies [b]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses and other derivative statistical studies or statistical summaries [c]	0.32	9	9/0	0.09	0.14	0.51
modelling studies	0.33	18	18/0	0.09	0.15	0.51
literature reviews/expert judgment	0.40	6	6/0	0.12	0.17	0.63
site studies	0.44	65	54/11	0.08	0.28	0.60
full crop retention (100% retained)						
0 to 35% residue retention counterfactual (CF)	0.46	74	64/10	0.07	0.32	0.60
40 to 60% residue retention CF	0.09	21	15/6	0.10	(0.10)	0.28
75% residue retention CF	0.29	2	2/0	0.02	0.26	0.31
10 to 30 cm sampling/modeling depth [d]	0.31	58	49/9	0.06	0.18	0.43
>40 cm sampling/modeling depth	0.62	23	20/2/1	0.13	0.36	0.88
3 to 10 year of observations or simulations	0.55	30	26/3/1	0.10	0.35	0.76
11 to 20 years of observations or simulations	0.37	37	33/4	0.09	0.19	0.55
>20 years of observations or simulations	0.17	20	18/2	0.05	0.08	0.27
crop residue removal						
all studies	(0.39)	86	11/74/1	0	(1)	(0)

[a] 98 study results, 89 studies (5 meta-analyses, 4 statistical summaries or derivative statistical analyses, 18 modeling studies, 51 empirical site studies, 6 literature reviews)

[b] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[c] statistical summaries or derivative statistical analyses other than meta-analyses

[d] results for lowest reported sampling depth

The overwhelming weight of evidence supports a positive response rate for carbon sequestration from crop residue return, before truncation for 20 years of assumed storage, generally in a range of 0.3 to 0.4 metric tons of carbon per hectare per year (0.13 to 0.18 short tons per acre), with a best estimate near 0.32 metric tons per hectare per year.

CO_2 emissions to the atmosphere from crop residue removal, the obverse of crop residue retention, are an estimated 0.39 metric tons of carbon per hectare per year (0.64 short tons of CO_2 per acre per year).

b. Nitrous oxide

The microbial processes in which N_2O is produced in soils with retained crop residues were discussed in Section IV, Subsection I.b, “Winter cover crops/Catch crops.” That discussion will not be repeated.

In this study, avoided-emissions from crop residue retention are calculated as the product of the estimated percentage change in emissions resulting from crop residue retention and average Minnesota cropland N_2O emissions. Average Minnesota cropland N_2O emissions are taken from the MPCA Greenhouse Gas Inventory. To estimate the percentage change in N_2O emissions resulting from crop residue retention, we reviewed 30 studies with 37 study results. Of these, eight studies were meta-analyses of the results of published controlled site studies, six were modeling studies, and 16 were empirical site studies, mostly side-by-side site studies (see Table 75).

By study type, the estimated percentage increase in N_2O emissions associated with crop residue retention ranged from 10 to 35 percent. N_2O emissions increased in 28 of the 37 study results in our database. We used the mean estimate from the eight meta-analyses as the best estimate of the percentage change in N_2O emission with crop residue retention. Using the mean estimate from these eight studies, crop residue retention is estimated to increase N_2O soil emissions by 10 ± 8 percent. Of the eight meta-analyses, six reported increased N_2O emissions with crop residue retention, two a decrease.

We stratified the studies by tillage type (no till, reduced tillage and conventional full inversion tillage), percent residue removal (25 to 50 percent, 100 percent), and, in the site studies, the number of years of N_2O flux observations. N_2O emissions increased across this subgrouping of studies, although with results that, in a formal statistical sense, could not be said always to differ significantly from zero. There is a suggestion in the data that, with no till, N_2O emissions will increase, but at rates substantially less than under other more aggressive forms of tillage, but based on a relatively few studies (seven).

Table 75. Descriptive statistics: Crop residue retention - N_2O

	emissions: % change in emissions per hectare	number of study results [a]	ratio, positive to negative results: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	10%	8	6/2	8%	-6%	26%
modelling studies	35%	6	5/1	16%	4%	66%
site studies	30%	23	17/6	15%	2%	59%
no-till	4%	7	4/3	11%	-17%	25%
reduced tillage	34%	7	6/1	15%	5%	63%
conventional tillage	30%	9	6/3	19%	-7%	66%
25 to 50% residue removal	41%	9	7/2	19%	4%	79%
100% residue removal	29%	24	18/6	14%	2%	56%
1 year of observations or simulations	14%	9	4/5	20%	-25%	54%
2 years and greater of observations or simulations	43%	16	15/1	18%	9%	77%
crop residue removal						
meta-analyses	-4%	2	1/1	7%	-18%	11%

[a] 37 study results, 30 studies (8 meta-analysis, 6 modeling studies, 16 empirical site studies)

The weight of the evidence generally favors an increase in N_2O emissions with crop residue retention of 10 percent or greater. This is consistent with the results reported for cover crops, a practice in which crop residues in the form of plowed-under rye, other small grains or vetch act to elevate N_2O emissions (see Section IV, Subsection I above).

Finally, based on the mean of the results from two meta-analyses, crop residue removal, the obverse of crop residue retention, acts to reduce N_2O emissions to the atmosphere, by 4 percent (see Table 75).

c. Methane

Methane is oxidized in soils by methanotrophic bacteria and is produced in cropland soils in anaerobic microsites by methanogenic bacteria. The balance between the two processes determines whether CH_4 is emitted from soils on a net basis or is consumed.

The estimated annual change in soil CH_4 oxidation resulting from crop residue retention is small, a 332 CO_2-equivalent short ton reduction in oxidation (see Table 73). This was calculated using the mean percent change in soil CH_4 oxidation from two meta-analyses of data from side-by-side site studies. Baseline CH_4 oxidation rates in temperate cropland soils were taken from Aronson and Helliker (2010).

Using the two meta-analyses estimates, developed for Chinese upland crop production, crop residue retention is estimated to reduce CH_4 oxidation by 16 percent (see Table 76).

In general, relatively few studies have been directed toward changes in CH_4 soil oxidation resulting from crop residue retention. Besides the two meta-analyses, we identified three empirical site studies and two modeling studies. Using the results from the empirical site studies, soil CH_4 uptake and oxidation might be expected to decline by 57 percent. The change in CH_4 soil oxidation has little effect on overall avoidance totals.

Table 76. Descriptive statistics: Crop residue retention - CH_4

	emissions: % change in soil oxidation per hectare	number of study results [a]	ratio, positive to negative results: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	-16%	2	0/2	6%	-28%	-4%
all studies	-18%	9	1/8	30%	-76%	40%
modelling studies	75%	2	1/1	75%	-73%	222%
site studies	-57%	5	0/5	37%	-128%	15%

[a] 9 study resulls, 7 studies (2 meta-analysis, 2 modeling studies, 3 empirical site studies)

Q. Short rotation woody crops

Short rotation woody crops (SWRCs) are fast growing trees, typically poplar or willow, grown in rotations, after a year of establishment, of 3 to 10 years and harvested for bioenergy purposes, fiber or as feedstock for chemical uses. Over even short rotations, SRWCs like hybrid poplar accumulate large amounts of organic carbon in belowground biomass and soils. This is particularly true over successive rotations. Removed from the atmosphere and photosynthetically-fixed in biomass, and then, through root senescence and exudation, removed to soils, this organic carbon persists belowground for the lifetime of the crop, typically 20 years, the lifetime of most SRWC plantations.

Aboveground carbon accumulation can be substantial. Harvested on a 3 to 10 year cycle, it may be used for bioenergy purposes or fiber. As noted elsewhere in this report, we do not treat the downstream aspects of emissions-avoidance, which for bioenergy can be substantial. [16]

In Minnesota, at present about 1,800 acres of land are cultivated annually in SRWCs, slightly down from about 1,900 in 2012.

Table 77 shows greenhouse gas emissions-avoidance for SRWCs, which on 100,000 acres of land converted to short rotation woody crops, is an estimated 157,000 CO_2-equivalent short tons annually, or 1.57 CO_2-equivalent short tons per acre per year. Of this, about half results from enhanced sequestration of carbon in soils and belowground biomass, and about 30 percent from lessened emissions of N_2O to the atmosphere. The avoided out-of-state manufacture of agricultural chemicals and fuels accounts for about 10 percent of emissions-avoidance.

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[16] With the displacement of electricity generated with wind turbines or solar photovoltaics, the downstream effects might be negative, adding emissions to rather than subtracting emissions from practice totals.

Table 77. Short rotation woody crops: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(48,446)	crop production
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	(2,148)	crop production
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(14,020)	crop production
CH_4 [b]	soils	not known	crop production
CO_2 [c,d]	carbon accumulation in soils	(85,839)	crop production
CO_2	cultivated soils from lime or urea use	not known	crop production
GHGs-energy	fossil fuel and electricity use in crop production	1,635	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(8,628)	crop production
Total		**(157,447)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass			
40 year storage	all sources and sinks	**(243,285)**	crop production
100 year storage	all sources and sinks	**(500,801)**	crop production

[a] positive = emissions increase, negative = emissions reduction

[b] reduction in soil CH_4 oxidation = relative increase in emissions

[c] carbon accumulation in soil and biomass = net removal of CO_2 from the atmosphere = net emission reduction

[d] assumes 20 years of sustained storage of newly sequestered organic carbon in soils and biomass

In estimating greenhouse gas-avoidance from the establishment of hybrid poplar and willow plantations and their harvest, it is assumed that land in SWRCs previously had been cropped in like corn, soybeans, wheat or similar commodity crops. It is also assumed that carbon stored belowground in soils and biomass remains there for 20 years, followed by microbial decomposition and emission to the atmosphere as CO_2. This is the longest period of time over which, in our opinion, sustained storage safely can be assumed. Under this assumption, annual emissions-avoidance on 100,000 acres is an estimated 157,000 CO_2-equivalent short tons. Had a 40-year period of assumed storage been assumed, annually avoided emissions from SRWCs would have totaled 243,000 CO_2-equivalent short tons per 100,000 acres. With 100-years of assumed assured storage, annual greenhouse gas avoidance, again on 100,000 acres, would be some 501,000 CO_2-equivalent short tons.

Relatively few empirical result exist for the response of N_2O soil emissions to cropland conversion to SRWCs. The same is true for emissions-avoidance from indirect sources of N_2O from NO_3^- leaching and NH_3 volatilization and its subsequent deposition on land. For these sources, we use the response rates for cropland retired to trees (see Section IV, Subsection B above), which may somewhat overstate the avoidance potential of SRWCs. SRWCs are often fertilized in the initial year of each harvest rotation, or once each three to ten years. By contrast, in the analysis presented in Section IV, Subsection B (cropland afforestation), no nitrogen inputs to forest growth were assumed.

For this reason, caution should be exercised by the reader with respect to the estimates shown in Table 77, which depending on harvest rotation length, might be smaller than shown by a few thousand to twenty thousand CO_2-equivalent short tons.

a. Carbon sequestration in soils and biomass

The biophysical and biochemical processes that underlie carbon sequestration in afforesting upland acres are discussed in Section IV, Subsections B.a and C.a above. That discussion will not be repeated.

In Minnesota, hybrid poplar is the preferred SRWC species. Others include: willow, yellow poplar, alder, aspen, eastern cottonwood, loblolly pine, and sweet gum.

During terrestrial carbon sequestration, CO_2 is removed photosynthetically from the atmosphere and incorporated into plant biomass and, through root senescence and exudation, into soils. This acts to offset a part of CO_2 emitted to the atmosphere from elsewhere in the economy. From Table 77, with 100,000 acres of short rotation woody crops, roughly 86,000 CO_2-equivalent short tons of emissions would be offset annually through the terrestrial storage of carbon, or 0.86 CO_2-equivalent short tons per acre. This was developed using an average rate of sequestration per acre in belowground biomass and soils, discounted to account for an assumed 20-year persistence of storage. Because aboveground biomass is removed from SRWC acres after periods as short as three or four years, organic carbon accumulation in aboveground biomass is not counted in sequestration totals. Twenty years is the longest period of time that, in our estimation, safely can be assumed in calculating the offset value of present-day sequestration.

For the rate of SWRC sequestration, we used the mean rate of carbon sequestration in belowground biomass and soils from 15 studies that were identified in the published scientific literature. These included: eleven site studies, two modeling studies and two literature or expert reviews. Using an average of the results from these 15 studies, the cultivation of SWRCs is estimated to result annually in 2.23 ± 0.43 metric tons per hectare of carbon sequestration (0.99 ± 0.19 short tons of carbon per acre per year) (see Table 78). This is the estimated rate prior to truncation to accommodate an assumed 20-year persistence of newly stored carbon in SRWCs.

In developing this sequestration estimate for belowground biomass and soils, 43 studies were reviewed, including three meta-analyses of the results from SWRC empirical site studies , one other derivative statistical analysis using a similar pool of empirical site studies, two modeling studies, 35 empirical site studies, and two literature reviews.

Table 78. Descriptive statistics: Short rotation woody crops - carbon sequestration in soils and biomass

	biogenic carbon sequestration (Mg C/ha/yr)	number of study results [a]	ratio of sequestration to emission: number of studies [b]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
SOC plus below ground biomass						
all studies [c]	2.23	15	15/0	0.43	1.38	3.08
site studies	2.72	11	11/0	0.52	1.71	3.74
modeling studies	1.00	2	2/0	0.22	0.57	1.43
literature reviews/expert judgment	0.75	2	2/0	0.17	0.43	1.08
by parts: site studies	2.11	see below	see below	see below	see below	see below
SOC	0.79	24	17/6/1	0.51	(0.21)	1.79
belowground biomass	1.33	16	16/0	0.25	0.83	1.82
by parts: meta-analysis (SOC); site studies (belowground biomass)	1.94	see below	see below	see below	see below	see below
SOC (meta-analyses and other derivative statistical analyses [c])	0.61	4	4/0	0.14	0.34	0.89
belowground biomass (site studies)	1.33	16	16/0	0.25	0.83	1.82
SOC (all studies)	0.87	34	27/6/1	0.32	0.24	1.49
belowground biomass (site studies)	1.33	16	16/0	0.25	0.83	1.82
Against cropland counterfactual-only:						
SOC plus belowground biomass	1.50	see below	see below	see below	see below	see below
SOC-only (meta-analyses and other derivative statistical analyses [c])	0.62	3	3/0	0.20	0.23	1.01
belowground biomass	0.88	2	2/0	0.11	0.66	1.10

[a] SOC plus belowground biomass: 75 study results, 43 studies (4 meta-analyses or statistical summaries or derivative statistical analyses, 2 modeling studies, 35 empirical site studies, 2 literature reviews)

[b] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[c] studies reporting change in both SOC and belowground biomass; excludes totals under category below 'studies by parts'

[d] statistical summaries or derivative statistical analyses other than meta-analyses

In addition to the sequestration estimate described immediately above, we developed two additional estimates, mixing and matching estimates for belowground sequestration in biomass, drawn from 16 site studies, with the estimated mean rate of soil carbon sequestration drawn either from empirical site studies (24 studies) or meta-analyses. In these two additional estimates, sequestration of organic carbon in belowground biomass and soils came to 1.94 and 2.11 metric tons of carbon per hectare per year (see Table 78).

Of the 43 studies that were reviewed, none reported net losses of carbon from SRWC production. While somewhat expansive, the calculated confidence intervals were, with one exception, positive.

Three studies reported results for sequestration in SRWC soils against a cropland counterfactual. An additional two studies reported results for sequestration in SRWC belowground biomass. Using the mean estimates drawn from these studies, total sequestration in SRWC soils and belowground biomass came to some 1.5 metric tons of carbon per hectare per year (0.67 short tons of carbon per acre).

In general, the evidence supports a positive annual sequestration rate for SRWC cultivation, prior to truncation for 20-years of assumed storage, in the range of approximately 1.5 to 2. 5 metric tons of carbon per hectare (0.67 to 1.11 short tons per acre), with a best estimate a conservative 2.23 metric tons per hectare.

R. Biochar soil amendments

Biochar is a pyrolyzed soil amendment akin to charcoal. Due to its aromatic structure, and its high proportion of aromatic carbon, biochar is highly resistant to microbial degradation. Biochar is produced industrially in oxygen-depleted conditions through pyrolysis using crop residues, waste wood, biomass from energy crops, livestock manure and other biomass as a feedstock. For use in agricultural settings, biochar is optimally produced at temperatures of roughly 350 to 600 degrees Celsius during slow, rather than fast, pyrolysis. Once incorporated into soils as pellets, biochar has an estimated mean residence time in soils of hundreds to thousands of years, during which constituent organic carbon is retained in the biochar. Left in the form of crop residues or biomass from energy crops, 90 percent of this biomass otherwise would have been returned to the atmosphere within one year, resulting, in comparison with biochar, in net emissions of CO_2. (Poeplau, *et al*. 2021)

A mean residence time of 556 years has been suggested from the most recent met-analysis of study results for biochar mean residence time that are found in the scientific literature. (Wang *et al*., 2016)

During pyrolysis, biochar is co-produced with bio-oil and biogas, which may be refined for commercial use or retained for process heat for the pyrolysis process.

In this study, we estimate greenhouse gas-avoidance of biochar produced from crop residue feedstock, accounting for 100-year integrated retention of organic carbon in soils in the form of biochar in evaluating its offset value. As discussed in Section II above, sequestered carbon can be expressed as a CO_2 offset - as the number of tons of emitted CO_2 from fossil fuel combustion that, over a 100-yer period, it offsets. We use the biochar offsets value as our estimate of biochar carbon sequestration, consistent with our treatment of sequestration throughout this report. We also evaluate any soil organic carbon lost on cropland acres harvested for crop residue feedstock, plus any changes in N_2O emissions resulting from biochar application to agricultural soils. Emissions from energy use in crop residue production and transport are also considered. Little is known about the change in CH_4 flux from or to soils resulting from biochar application.

The 100-year integrated total of retained biochar-derived organic carbon is estimated using the formalism for biochar carbon decay given in Fargione *et al.* (2018). Roughly speaking, by year 100, about 80 percent of initially sequestered organic carbon will remain after 100- years. (Wang *et al*., 2016) No dependence on future changes in agricultural or land-use practice is involved in the calculation of this 100-year integrated total.

We assessed biochar at an application rate of 15 metric tons of biochar per hectare (6.68 short tons per acre), about the median estimate from the studies of biochar found in the scientific literature. Overall, rates of application in the published studies range from a few metric tons per hectare to about 40 metric tons per hectare. Slow pyrolysis was assumed, as was a range of pyrolysis temperature of 350 to 600 degrees Celsius.

Greenhouse gas-avoidance from biochar is shown in Table 79 for applications on 100,000 acres. For a pulse input of 15 metric tons of biochar per hectare (6.68 short tons per acre), 2.5 million CO_2-equivalent short tons of greenhouse gas-avoidance might be expected. Of this, most is associated with organic carbon sequestration in soils, and most of this would be felt by the atmosphere within the first year after biochar production and its incorporation into soils. On 100,000 acres, at 15 metric tons per hectare of biochar application, 2.7 million tons of CO_2 emissions would be offset through soil sequestration, of which about ten percent would be offset by upstream biochar production emissions, mostly in the form of soil organic carbon lost from cropland committed to crop residue production. Complete removal of aboveground crop residue is assumed.

Besides one-time sequestration (or biochar production emissions), biochar application also would result in a continuing stream of N_2O emissions-avoidance, of about 16,000 CO_2-equivalent short tons per year on 100,000 acres, plus a small continuing loss of soil CH_4 oxidation capacity (862 CO_2-equivalent short tons per year). Total first year greenhouse gas-avoidance on 100,000 acres would total some 2.7 million CO_2-equivalent short tons per acre, while second year through year 20 emissions would total 20,000 CO_2-equivalent short tons per year.

Twenty-year cumulative emissions-avoidance would come to 2.85 million CO_2-equivalent short tons per 100,000 acres. To render these estimates comparable to those for practices where a change in practice, made in some discrete year, results in a 20-year stream of greenhouse gas-avoidance, annualized avoidance totals are given for biochar in Table 80 for a 20-year annualization period. Using 20-years to annualize the results from Table 79, biochar soil applications, including upstream feedstock production and manufacturing emissions, results in annual emissions-avoidance on 100,000 acres of 128,000 CO_2-equivalent short tons. Of this, all plus a little more results from enhanced soil carbon sequestration. N_2O emissions-avoidance adds an additional 16,000 CO_2-equivalent short tons to this, while increased greenhouse gas emissions from feedstock production and biochar manufacture and transport offset about 27,000 CO_2-equivalent short tons.

Table 79. Biochar soil amendments: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
Sources with continuing effects			
N_2O-direct	soils	(16,279)	no biochar supplement
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	76	no biochar supplement
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(4,455)	no biochar supplement
CH_4 [b]	soils	not known	no biochar supplement
CO_2	cultivated soils from lime or urea use	not known	no biochar supplement
total		**(20,658)**	
Sources with one-time effects, year of application			
CO_2 [b]	carbon accumulation in soils	(2,731,796)	no biochar supplement
GHGs-energy	fossil fuel and electricity use in crop production	13,224	no biochar supplement
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	2,929	no biochar supplement
In-State Upstream GHGs	upstream crop residue collection, processing, transport	270,262	no biochar supplement
Total		**(2,445,381)**	

[a] positive = emissions increase, negative = emissions reduction

[b] reduction in soil CH_4 oxidation = relative increase in emissions

[c] carbon accumulation in soils = net removal of CO_2 from the atmosphere = net emission reduction

Annualizing for 20 years, per acre greenhouse gas-avoidance would be 1.27 CO_2-equivalent short tons per acre per year.

Biogenic carbon sequestration resulting from biochar soil amendments is discussed below, as are avoided direct emissions of N_2O from biochar-amended soils and the effects of biochar soil amendment on soil CH_4 uptake and oxidation. The Methodology section (Section II, Subsection E) of this report contains a discussion of the methods and sources used to estimate avoided indirect N_2O emissions from nitrate leaching and ammonia volatilization, as well as a discussion of avoided-emissions from fuel use, and a discussion avoided-emissions from foregone agricultural chemicals and fuels manufacture.

Table 80. Biochar soil amendments: Emissions-Avoided Annualized [a]

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [b]	Counterfactual
N_2O-direct	soils	(16,279)	no biochar supplement
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	76	no biochar supplement
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(4,455)	no biochar supplement
CH_4 [c]	soils	not known	no biochar supplement
CO_2 [d]	carbon accumulation in soils	(136,590)	no biochar supplement
CO_2	cultivated soils from lime or urea use	not known	no biochar supplement
GHGs-energy	fossil fuel and electricity use in crop production	13,224	no biochar supplement
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	2,929	no biochar supplement
In-State Upstream GHGs	upstream crop residue collection, procecessing, transport	13,513	no biochar supplement
Total		**(127,582)**	

[a] while most emissions-avoidance from biochar soil amendments occurs during the year of application, here they are annualized using 20 year annualization to make them comparable to other practices where a change, made in a single year, yields a 20-year stream of future emissions-avoidance

[b] positive = emissions increase, negative = emissions reduction

[c] reduction in soil CH_4 oxidation = relative increase in emissions

[d] carbon accumulation in soils = net removal of CO_2 from the atmosphere = net emission reduction

a. Carbon sequestration in soils and biomass

Biochar is the residual solid co-produced, with biogas and bio-oil, during the pyrolysis of biomass. Pyrolysis is the thermochemical decomposition organic materials under conditions of high heat in oxygen-deprived environments. Biochar, a byproduct of pyrolysis, is a solid material with an aromatic structure with randomly organized aromatic rings. (Leng *et al*., 2019) Biochar is formed from different biomass feedstocks, including waste wood, agricultural crop residues, other agricultural wastes, biomass from bioenergy crops, manure and wastewater sludges. During its formation, feedstock cellulose, lignin and pectin are completely destroyed and, with dehydrogenation, deploymerization and progressive aromaticization, are replaced with a condensed polyaromatic structure that is intrinsically resistant to microbial and abiotic degradation. (Zimmerman and Gao, 2013)

In soils, biochar is highly resistant to microbial attack, with the result that it persists in soils for hundreds to thousands of years after placement. Its long persistence in soils may be traced to its intrinsic chemical recalcitrance. (Marschner *et al*., 2008)

By lengthening the residence time of organic carbon in terrestrial pools, like agricultural soils, biochar inhibits respiratory losses of organic carbon to the atmosphere, leading to lower rates of atmospheric CO_2 accumulation than would have occurred in absence of biochar formation. This acts to offset emissions of CO_2 elsewhere in the economy.

Biochar is comprised mostly of a pool of highly recalcitrant aromatic carbon. However, depending on the conditions under which biochar is formed, after pyrolysis is complete between 3 and 20 percent of biochar carbon may remain in a labile form that is vulnerable to microbial decomposition. (Roberts *et al*., 2010; Wang *et al*., 2015) Once biochar is applied to soils, this labile part is rapidly mineralized, and lost to the atmosphere in the form of CO_2. Averaged across study results found in the scientific literature, these losses appear small, about three percent of biochar carbon. (Wang *et al*., 2015)

Biochar persistence in soils is measured by its mean residence time (MRT) in soils, which the most recent meta-analysis of the results of published studies is put at 556 years. (Wang *et al*., 2015) Estimated MRTs found in studies in the scientific literature generally range from a few hundred years to about 5,000 years, although several studies have reported MRTS of three to five decades.(de la Rosa *et al*., 2018; Singh *et al*., 2015) In our review of 56 studies, the estimated MRT is 977 years (see the discussion below).

Biochar persistence is closely related to the conditions under which, during pyrolysis, it is formed. In general, mean residence time of biochar increases with increased pyrolysis temperature. At 350 degrees Celsius pyrolysis temperature, MRT is an estimated 69 to 693 years, while at 500 to 650 years, MRT is estimated to be greater than 693 years. (Spokas *et al*., 2010) Recalcitrance generally follows the degree of biochar aromaticity, which increases with pyrolysis temperature. (Wang *et al*., 2015; Zimmerman and Gao, 2013) The IPCC (2019) expresses persistence in terms of the amount of biochar carbon remaining 100 years after its formation and soil application. In the IPCC assessment, by pyrolysis temperature, 65, 80 and 89 percent of initial biochar carbon remains after biochar formation and its application to soils at 350-450, 450 to 600 and greater than 600 degrees Celsius pyrolysis temperature, respectively. (IPCC, 2019)

Biochar yield is higher at lower pyrolysis temperatures. At 350 to 500 degrees Celsius pyrolysis temperatures, yields are an estimated 30 to 60 percent of total retain carbon in pyrolysis-derived biochar, biogas and bio-oil. (Stewart *et al*., 2013) Generally, lower pyrolysis temperatures are favored for biochar production for agricultural purposes. At 400 degrees Celsius pyrolysis temperature, biochar MRTs are an estimated 200 to 4,400 years. (Schmidt *et al*., 2019)

Biochar persistence is also related to biochar feedstock, with wood-derived biochar generally considered the most chemically recalcitrant, manure and wastewater sludges the least recalcitrant. (IPCC, 2019)

Biochar carbon accumulation in soils increases linearly with application rate. (Liu *et al*., 2016) In the published studies, biochar in variously applied as a large single pulse or sequentially as a series of smaller pulses over a number of years. The response of soils to application rates as high as 45 metric tons per hectare (20.1 short tons per acre) has been studied. (Lu *et al*., 2021)

Soil microorganisms preferentially decompose the biochar labile carbon. As a result, application of biochar acts to marginally reduce the mineralization of native soil organic carbon (SOC), leading to a small decline in CO_2 fluxes to the atmosphere from native SOC. (Ding *et al*., 2017) In the work of some researchers, mineralization of biochar labile carbon acts to stimulate microbial activity generally, resulting in enhanced mineralization of native SOC and enhanced CO_2 fluxes from native SOC to the atmosphere. (Maestrini *et al*., 2015) Published meta-analyses of the body of study results suggest that, on average, biochar acts to reduce the mineralization of native soil organic carbon. (Wang *et al*., 2015) This is particularly so with respect to crop residue-derived biochar, wet and carbon rich soils, and soils with high clay content. (Ding *et al*., 2017; Wang *et al*., 2015) Physical occlusion of biochar carbon in macroaggregates and the formation of organic-mineral complexes have been suggested to explain increased carbon storage in native SOC. (Lehman *et al*., 2009; Wang *et al*., 2015)

Biochar in dry soils or sandy soils with low SOC acts to stimulate microbial activity in native SOC, leading enhanced mineralization of native SOC and enhanced CO_2 losses. (Ding *et al*., 2017) It seems possible that, with more study, the effects of biochar on native SOC may prove to enhance the mineralization of native SOC generally, with enhanced CO_2 fluxes from native SOC to the atmosphere.

Finally, with respect to biochar production, biochar is optimally produced at pyrolysis temperatures of 350 to 550 degrees Celsius during slow pyrolysis. High parasitic energy losses generally prohibit the use of fast pyrolysis, with biomass retention times of seconds, from use in producing biochar. (Schmidt *et* *al.,* 2019) Higher pyrolysis temperatures during slow pyrolysis favor the production of bio-oil and biogas, but also higher biochar stability. Biochar nutrient availability is higher in biochars that are formed at lower pyrolysis temperatures. (Crombie *et al*., 2015) An optimal pyrolysis temperature, considering all of these factors, has yet to be determined.

The mean residence time (MRT) of biochar carbon in soils has been estimated mostly from laboratory incubations, but also from field observations. We use published estimates of biochar mean residence time to calculate the offset to CO_2 emitted to the atmosphere elsewhere in the economy afforded by the use of biochar as a soil amendment.

In the calculation of biochar soil carbon sequestration, we assume a biochar application rate of 15 metric tons per hectare (6.69 short tons per acre). Biochar is assumed to be produced from crop residue. The carbon content of biochar produced from slow pyrolysis from crop residues is roughly 65 percent. Retention is calculated using the equation for exponential decay given in Fargione *et al.* (2018), while integrated 100-year retention in tons-years is from the integral of this formalism. The CO_2 offset resulting from biochar application equals the integrated 100-year retention of biochar carbon, in ton-years, divided by 52 tons-years, the integrated 100-year retention in the atmosphere of a pulse emission of CO_2. To offset one ton of emitted CO_2 from fossil fuel combustion, a ton of sequestered CO_2 (as carbon) would need to remain in storage for 52 years.

In the scientific literature, the mean residence time is estimated to range from 30 to about 5,000 years (Kuzyakov *et al*., 2014; de la Rosa *et al*., 2018), although most estimates fall into a range of about 200 to 1500 years. From the literature that we reviewed, we calculated a mean estimate for biochar MRT of 977 years.

A part of carbon sequestered in biochar is offset by SOC losses from soils used to produce crop residue feedstock for biochar. During crop residue removal, soil organic carbon is depleted from agricultural soils. From the 52 studies that we reviewed with complete residue removal, complete residue removal results in an annual 0.46 metric tons per hectare loss of soil carbon (see Database bibliography, “Crop residue retention/residue removal”). Corn stover, which accounts for between 70 and 77 percent of US crop residue production, is the assumed source of crop residue. In calculating the loss of SOC resulting from the production of feedstock for biochar for use on 100,000 acres, we assumed: complete above ground crop residue removal; a biochar yield of 39 percent; and per acre corn stover yield of 4.35 tons per acre per year (dry basis), based on 2015-2019 Minnesota corn grain yields and the factor the given in US Department of Energy (2016) to convert grain yield to corn stover production.

Based on the results presented in the Wang et al. (2015) meta-analysis, no positive priming effect was assumed.

In developing our estimate of biochar MRT, we reviewed 56 studies that included 81 study results. Of these 56 studies, 39 were studies based on laboratory incubations or empirical site studies, one was a meta-analysis of the published data from laboratory incubations or empirical site studies, one was a related statistical analysis of the same class of results, seven were literature reviews, and eight were studies without an identifiable method. Averaged across these 56 studies, the mean study MRT is some 977 years, and the associated sequestration rate resulting from biochar soil application, again at a rate of 15 metric tons of biochar per hectare in a single application, and expressed as a carbon dioxide offset, is an estimated 13.07 metric tons of carbon per hectare (5.83 short tons per acre).

In developing an estimate for carbon sequestration from biochar soil application, we stratified the results by biochar feedstock. We selected the mean rate MRT of biochar produced from crop residues as our best estimate of carbon sequestration from biochar application. This was from 23 study results. Based on these 23 study results, 15 metric tons of biochar applied in a single pulse would result in an offset of emitted CO_2 equal to 16.71 ± 2.34 metric tons of carbon per hectare (7.45 ± 1.04 short tons per acre). Comparable values for biochar produced from a wood and bioenergy grasses like switchgrass would be 10.14 and 14.58 metric tons of carbon per hectare, respectively (4.53 and 6.50 short tons per acre respectively).

Table 81 gives the descriptive statistics for carbon sequestered in biochar calculated from the MRTs found in the studies that we reviewed. Again, sequestration is shown as a CO_2-offset and resulting from a pulse placement of 15 metric tons of biochar per hectare. By study type, the results cluster in a range of 11.97 to 15.48 metric tons of carbon per hectare (5.34 to 6.91 short tons per acre). By study type, MRTs range from 534 to 3,100 years. Sequestration rates calculated from results from the two meta-statistical studies are an estimated 13.95 metric tons of carbon per hectare.

By pyrolysis temperature, results range from a relatively small 7.88 metric tons of carbon per hectare sequestration rate for biochar pyrolysis temperature of 300 to 400 degrees Celsius to 15.13 metric tons of carbon per hectare for biochar pyrolysis temperature of greater than 550 degrees. From the discussion in the literature, the preferred pyrolysis temperature for biochar manufacture is in the range of 400 to 550 degrees Celsius.

More research may be needed to narrow the preferred rate of per acre biochar application, as well to define an economically optimal rate of temperature of biochar pyrolysis. The calculated confidence intervals depend substantially on how uncertain our guesses are for preferred application rates and optimal pyrolysis temperatures. Provisionally, the research demonstrates biochar to be a very effective mitigation measure on cropland and pastureland, as well as on other landscapes.

Table 81. Descriptive statistics: Biochar soil amendments- carbon sequestration in soils (biochar carbon mean residence Time (MRT)-derived estimates

	biogenic carbon sequestration (Mg C/ha/yr) [a,b]	number of study results [c]	ratio of sequestration to emission: study numbers [d]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval	MRT (years)
MRT-based estimates by biochar feedstock:							
crop residue-derived biochar	16.71	23	23/0	2.34	12.12	21.31	746
wood-derived biochar	10.14	39	39/0	0.56	9.03	11.25	1,100
grassland bioenergy-derived biochar	14.58	1	17/0	1.06	12.62	16.54	1,051
MRT-based estimates by study type:							
meta-analyses	13.95	2	2/0	3.06	7.95	19.95	556
survey-based studies	14.82	2	2/0	3.17	8.62	21.03	1,250
literature reviews/expert judgment	15.48	9	9/0	1.14	13.25	17.72	722
2 pool exponential model-based studies	12.41	55	55/0	0.62	11.20	13.62	688
logarthmic degradation model-based studies	17.67	3	3/0	2.50	12.76	22.58	534
oxygen:carbon biochar ratio-type studies	11.97	1	1/0	NA	NA	NA	1,443
other method [e]	14.26	9	9/0	1.49	11.34	17.18	3,101
all studies	13.07	81	81/0	0.49	12.11	14.04	977
MRT-based estimates by pyrolysis temperature:							
300 to less than 400 C	7.88	5	5/0	2.20	3.57	12.18	133
400 to 450 C	12.86	26	26/0	0.87	11.16	14.56	678
450 to 550 C	13.94	17	17/0	0.76	12.44	15.43	958
greater than 550 C	15.13	9	9/0	0.96	13.26	17.01	1,356

[a] soil carbon sequestration limited to added biochar component of soil

[b] biochar carbon mean residence time-derived value

[c] 81 study results, 56 studies (1 meta-analysis, 1 survey-type study, 37 2-pool exponential modeling studies, 1 logarithmic decay modeling study, 1 oxygen:carbon study, 7 literature reviews, 8 studies without identified method or using other approaches than above)

[d] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[e] studies that do not specify methods plus MRT estitmates based on soil sampling, carbon budget approaches, and laboratory uncubations with one-pool exponential models

b. Nitrous oxide

Nitrous oxide emissions generally decline in the presence of biochar in soils. This is an empirical result, based on large set of observations, but one not well understood. It is hypothesized that soil N_2O emissions may decline in the presence of biochar due to: improved soil aeration, increased soil pH, biochar-induced nitrogen immobilization, and/or toxicity effects of biochar on microbial nitrifier and denitrifier soil populations. (He *et al*., 2017) It is known that soil acidity acts to promote the reduction during denitrification of nitrate to dinitrogen (N_2), bypassing N2O formation. (Borchard *et al*., 2019) It is likely that a good deal more research will be necessary until the biochemical processes involved in the response of N_2O to biochar soil applications are understood.

In this analysis, we rely upon the body of published empirical results that have been built up over the last twenty years.

We calculate avoided N_2O emissions from the use of biochar as a soil amendment as the product of the estimated percentage change in N_2O emissions resulting from addition of biochar to soils and average Minnesota cropland N_2O emissions. Average Minnesota cropland N_2O emissions are taken from the MPCA Greenhouse Gas Inventory. To estimate the percentage change in N_2O emissions from the use of biochar as a soil amendment, we reviewed 56 studies with 57 study results. Of these, fifteen studies were meta-analyses of the results of published controlled site studies of the response of N_2O soils emissions to biochar application. Using the mean estimate from these 15 studies, the use of biochar is estimated to reduce N_2O emissions by 25 ± 3 percent.

As noted in the methodology section of this report (Section II), meta-analysis is a powerful statistical tool used to integrate results of experiments of different designs and draw conclusions at broad spatial scales.

By study type, we reviewed 38 empirical controlled site studies of the response of N_2O soils emissions to biochar application and three literature reviews, as well as the fifteen meta-analyses. These 56 studies gave an overall response rate of N_2O from biochar application of (-) 26 percent. Of these 56 studies, three reported increasing N_2O emissions with biochar application, 53 declining emissions. By study type, the response of emissions clustered into a tight range of (-) 28 to (-) 33 percent. By feedstock type, the response rate ranged from (-) 29 percent to (-) 40 percent for crop residue-derived biochar and wood-derives biochar, respectively.

The descriptive statistics for biochar use are given in Table 82. As elsewhere in this report, the estimates given in Table 82 are reported in metric units, and then converted to English units for use in Tables 79 and 80.

Response rates of N_2O to biochar use increased with increasing amounts of applied biochar, from (-) 17 percent at application rates of less than 10 metric tons per hectare (4.46 short tons per acre) to (-) 35 percent at application rates of greater than 20 metric tons per hectare. At the 10 to 20 metric tons, the mean response rate was (-) 25 percent. In our calculations, we assumed a pulse 15 metric ton biochar application.

By emissions monitoring period, the 38 studies, the N_2O emissions-avoidance declined slightly as the monitoring period was lengthened beyond the growing season to an annual, but at (-) 22 percent remains close to the (-) 25 percent response rate taken from the fifteen meta-analyses.

Finally, the fifteen meta-analyses developed estimates of N_2O-avoidance by biochar feedstock type, by pyrolysis temperature used in the manufacture of biochar, and by biochar application rate (see Table 82). In these formal meta-analyses, N_2O emissions declined by 45, 37, 39, and 42 percent from the application of wood-derived biochar, crop residue-derived biochar, biochar produced at temperatures of 350-500 degrees Celsius and biochar produced at temperatures of greater than 500 degrees Celsius, respectively. The mean rate of N_2O avoidance at biochar application rates of 10 to 20 metric tons per hectare was 13 percent in the eight met-analyses that reported reductions in N_2O emissions on the basis of application rate, or about half of the mean response rate adopted for use in this study.

In general, the empirical work, built up over two decades, supports a robust estimate of reduced N_2O emissions with biochar soil application. Much more work is obviously needed on the underlying biogeochemical process that are in play in these reduction.

Table 82. Descriptive statistics: Biochar soil amendments - N_2O

	emissions: % change in emissions per hectare	number of study results [a]	change in emissions, ratio positive-to-negative: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	-25%	15	0/15	0.03	(0.31)	(0.20)
empirical site studies	-26%	37	3/34	0.05	(0.35)	(0.17)
literature reviews/expert judgment	-33%	3	0/3	0.08	(0.50)	(0.17)
wood-based biochar	-40%	18	1/17	0.06	(0.52)	(0.27)
crop residue-based biochar	-26%	24	1/23	0.03	(0.33)	(0.20)
<10 Mg biochar/ha application rate	-17%	13	2/11	0.09	(0.34)	0.01
10 to 20 Mg biochar/ha application rate	-23%	23	2/21	0.05	(0.32)	(0.13)
>20 Mg biochar/ha application rate	-33%	28	3/25	0.05	(0.42)	(0.24)
annual flux monitoring/modeling	-22%	27	2/25	0.04	(0.31)	(0.14)
growing season and subgrowing season flux monitoring/modeling	-31%	23	2/21	0.05	(0.42)	(0.20)
meta-analyses:						
wood-based biochar	-45%	8	0/8	0.04	(0.52)	(0.37)
crop residue-based biochar	-37%	8	0/8	0.06	(0.48)	(0.26)
pyrolysis temperature 350-500C	-39%	5	0/5	0.04	(0.47)	(0.30)
pyrolysis temperature >500C	-42%	5	0/5	0.05	(0.52)	(0.31)
10 to 40 Mg/ha biochar application rate	-23%	1	0/1	NA	NA	NA
10 to 20 Mg/ha biochar application rate	-13%	6	0/6	0.06	(0.25)	(0.01)
>20 Mg/ha biochar application rate	-30%	2	0/2	0.19	(0.66)	0.06

[a] 57 study results, 56 studies (15 meta-analyses, 38 empirical site studies, 3 literature reviews)

S. Nitrification inhibitors

Nitrification inhibitors are synthetic additives to nitrogen-based chemical fertilizer that act to delay well into the growing season the microbial transformation of nitrogen from an ammonium form to nitrate. In a nitrate form, nitrogen is readily available to the plant. If present in a nitrate form early in the growing season, before peak plant nutritional needs, a good part of applied nitrogen can be lost to the environment through nitrate leaching and air emissions in the form of nitrous oxide, nitrogen oxides (NO, NO_2), and dinitrogen (N_2). The production in soil of N_2O, and its subsequent emission to the atmosphere, results in part from the accumulation of excess nitrate in soils.[17] With nitrification inhibitors, early season accumulation of excess nitrate is limited, leading to lower early season N_2O emissions.

A wide variety of nitrification inhibitors are commercially available. Some of the inhibitors now in use include: DCD (dicyandiamide), DMPP (3,4-dimethylpyrazole phosphate), DMPSA (3,4 dimethylpyrazole succinic acid), PIADIN (3-methylpyrazole), pronitridine and nitrapyrin. These are marketed under various

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[17] N_2O production in and emissions from cultivated soils result from the presence in soils of excess nitrogen in the form of nitrate (NO_3^-), which heterotrophic facultative bacteria reduce to N_2O, and ammonium (NH_4^+), from which autotrophic nitrifying bacteria gain energy through the nitrification of ammonium. More generally, N_2O is produced microbially in soils during nitrification, denitrification, nitrifier denitrification and codenitrification, using excess soil NO_3^- and NH_4^+, and modulated at particular locations by soil type and soil organic content, soil water content, pH, bulk density, and other factors.

trade names including Guardian, ENTEC, N-Serve, Instinct, and Centuro. Neem is a natural nitrification inhibitor.

With the exception of data for nitrapyrin use, reliable statistics for nitrification inhibitor use in Minnesota are not available. The MPCA (2020) reports that crops on about 1 million acres of cropland are treated with nitrapyrin.

A detailed budget of greenhouse gas emissions-avoidance from the use of nitrification inhibitors is given in Table 83. We estimate GHG-avoidance on 100,000 acres of fertilized cropland treated with nitrification inhibitors of about 30,000 CO_2-equivalent short tons annually. Of this, most results from reduction of direct N_2O emissions from soils. Thus far, no impacts on soil carbon sequestration from the use of nitrification inhibitors have been noted in the scientific literature.

The efficiency of nitrogen use by the plant increases with the use of nitrification inhibitors. (Abalos *et al*., 2014; Qiao *et al*., 2015; Xia et *al*. 2016) This may suggest that, with the nitrification inhibitors, per acre synthetic nitrogen applications will decline. However, as noted above in the section on methods (Section II), in absence of sure empirical evidence on producer response to increased nitrogen use efficiency in the form of reduced per acre nitrogen applications, we do not address potential emissions-avoidance arising from this source. Crop yields generally increase with the use of nitrification inhibitors. (Feng *et al*., 2016; Thapa *et al*., 2016; Yang *et al*., 2016) It seems possible that, in pursuit of higher yields, producers using inhibitors may maintain or even increase per acre nitrogen applications.

Table 83. Nitrification inhibitors: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(25,908)	no inhibitors
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	448	no inhibitors
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(4,389)	no inhibitors
CH_4 [b]	soils	(248)	no inhibitors
CO_2 [b,c]	carbon accumulation in soils	-	no inhibitors
CO_2	cultivated soils from lime or urea use	-	no inhibitors
GHGs-energy	fossil fuel and electricity use in crop production	-	no inhibitors
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	-	no inhibitors
Total		**(30,097)**	
Emissions with nitrification inhibitors plus urease inhibitors:			
GHGs	all sources and sinks	**(24,459)**	no inhibitors

[a] positive = emissions increase, negative = emissions reduction

[b] increase in soil CH_4 oxidation = relative decrease in emissions

[c] carbon accumulation in soils = net removal of CO_2 from the atmosphere = net emission reduction

Annual per acre avoidance with the use of nitrification inhibitors is roughly 0.30 CO_2-equivalent short tons. In some inhibitor formulations, nitrifications inhibitors are paired with urease inhibitors. Per acre avoidance for combined nitrification/urease inhibitor formulations are slightly less than for nitrification inhibitors alone, about 0.24 CO_2-equivalent short tons per acre per year.

Avoided direct N_2O emissions from soils are treated below, as are the effects of nitrification inhibitors on CH_4 soil oxidation. For reasons just noted, the effects of inhibitor use on soil carbon are not treated. The methods used to estimate indirect emissions (or emissions-avoidance) from nitrate leaching and ammonia volatilization and land deposition, were discussed above in Section III, Subsection E.

a. Nitrous oxide

Most synthetic fertilizers in use are in the form of ammonia or ammonia-producing compounds like urea. Anhydrous ammonia is an example of a nitrogen fertilizer in an ammonia form. Once applied to soils, ammonium in ammonium-based fertilizers is nitrified, a process in which ammonium (NH_4^+) is converted to nitrate (NO_3^-). In the case of urea-based fertilizers, an additional step is required, the prior hydrolysis of urea to ammonium. Nitrification inhibitors (NI) act to inhibit the first stage of nitrification in soil, in which ammonium is oxidized to hydroxylamine. (Riser and Schulz, 2015) In soils, nitrification proceeds step-wise, first through the oxidation of NH_4^+ to hydroxylamine, its further oxidation to nitrite (NO_2^-) and to nitrate (NO_3^-). In the first stage of nitrification, NH_4^+ is oxidized to hydroxylamine (NH_2OH) by the monooxygenase enzyme, which is bound in the membranes of certain soil bacteria.

Nitrification inhibitors deactivate the monooxygenase enzyme, inhibiting the conversion of ammonium to nitrate and retaining mineral nitrogen in soils in an ammonium form. N_2O is produced during nitrification. By inhibiting microbial nitrification, nitrification inhibitors suppress the rate of N_2O formation in soils.

Nitrous oxide is formed during both nitrification and as a terminal product of denitrification. During denitrification, nitrate is reduced in anaerobic soils conditions to N_2O and dinitrogen (N_2). N_2O formation during denitrification depends on the presence of a pool of NO_3^- in excess of plant nutritional needs. By inhibiting the conversion of NH_4^+ to nitrate, nitrification inhibitors also act to limit the pool of nitrate available for microbial reduction to N_2O, inhibiting N_2O formation during denitrification.

Nitrification inhibitors degrade in soils, with the result that any inhibitory effect of nitrification inhibitors on N_2O formation is temporary. Depending on soil temperature and other soil conditions, the inhibitory effect of nitrification inhibitors is four to ten weeks, after which the rate of emission of N_2O returns to pre-suppression levels. (Zaman *et al*., 2009; Selbie *et al.*, 2014; Omonode and Vyn 2013) The half-life of dicyandiamide (DCD), one of the most popular NIs, is about 20 days at 20 degrees Celsius (68 degrees Fahrenheit). (Shi *et al.*, 2014)

Nitrification inhibitors degrade rapidly with temperatures in excess of 20 degrees Celsius. (Li *et al*., 2014) They also are susceptible to leaching from soils to groundwater. (Vallejo *et al*., 2005) The longevity of nitrification inhibitors in soils depends upon, among other things, air and soil temperature, precipitation, drainage, and soil type and texture.

Nitrification inhibitors are most effectively applied in spring. During summer, high air temperatures shorten their half-life, limiting their inhibitory effect to a few weeks. (Cardenas *et al.*, 2016). While it is hard to generalize, nitrogen inhibitors appear to be most effective in soils with otherwise high rates of N_2O production, especially in soils in which nitrification, rather than denitrification, is dominant. This favors soil conditions with water-filled pore space of 40 to 65 percent. (Sanz-Cobena *et al*., 2012; Guardia *et al*., 2017; Feng *et al*., 2016) Nitrification inhibitors are less effective at high soil water, in which denitrification is dominant. (Shi *et al*., 2014) Nitrification inhibitors are ineffective at soil organic carbon concentrations greater than 5 percent. (Mkhabela *et al*., 2006)

In terms of air temperature, nitrification inhibitors are most effective at 20 degrees Celsius (68 degrees Fahrenheit). (Li *et al*., 2014).

Nitrification inhibitors act to delay the conversion of ammonium to nitrate several months into the growing season, when plant nutrient needs are large. Unless limited by a practice like NI, nitrate is usually far in excess of plant needs early in the growing season, leading to large losses of nitrogen to the environment, including N_2O lost to the atmosphere. The use of nitrification inhibitors reduces total nitrogen losses 15 to 30 percent (Yang *et al*., 2016; Qiao *et al*., 2015), while increasing plant nitrogen recovery and crop nitrogen use efficiency. (Guardia *et al*., 2017; Qiao *et al*., 2015)

In this study, avoided-emissions from the use of nitrification inhibitors are calculated as the product of the estimated percentage change in emissions resulting from use of nitrification inhibitors and average Minnesota cropland N_2O emissions. Average Minnesota cropland N_2O emissions are taken from the MPCA Greenhouse Gas Inventory. To estimate the percentage change in N_2O emissions from the use of nitrification inhibitors, we reviewed 111 studies with 111 study results. Of these, 16 studies were meta-analyses of the results of published controlled site studies, two were derived statistical studies of roughly the same pool of empirical site studies, seven were modeling studies, five were literature or expert reviews, and 81 were empirical site studies, mostly controlled site studies (see Table 84).

We used the mean estimate from the 16 meta-analyses and the two derived statistical analyses as the best estimate of the percentage change in N_2O emission with the use of nitrification inhibitors. Using the mean estimate from these 18 studies, the use of nitrification inhibitors is estimated to reduce N_2O emissions by 41 ± 4 percent, a fairly substantial reduction. Of the sixteen meta-analyses and the two derived statistical analyses, 17 reported emissions reductions from nitrification inhibitor use, one an increase (again see Table 84). As noted in the methodology section of this report (Section II), meta-analysis is a powerful statistical tool used to integrate results of experiments of different designs and draw overall conclusions at broad spatial scales.

By study type, the estimated percentage change associated with the use of nitrification inhibitors ranged from (-) 26 to (-) 41 percent. Of the 111 studies reviewed, five reported increased emissions, and 106 reported reductions.

The descriptive statistics for nitrification inhibitor use are given in Table 84. As elsewhere in this report, the estimates given in Table 84 are reported in metric units, and have been converted to English units for use in Table 83.

We stratified the studies by nitrogen type (synthetic nitrogen, manure), fertilizer placement depth (surface placement, subsurface placement), and by numbers of application per growing season (single application split application). The response rate of N_2O emissions to the use of nitrification inhibitors was largely invariant to type of nitrogen applied, the number of times it was applied during the growing season and when, or its depth of application (see Table 84). The length of the monitoring period for N_2O emissions also had little effect on the average emission rate.

Finally, we examined response rates of N_2O to the combined application of nitrification and urease inhibitors (see Section IV, Subsection T for urease inhibitors), using both published meta-analyses and a broader array of studies. Response rates with combined use of nitrification and urease inhibitors were generally consistent with those from the use of nitrification inhibitors alone, a 35 ± 2 percent reduction in N_2O emissions in the meta-analyses from the combined use of nitrification and urease inhibitors, as against a 41 ± 4 percent reduction for nitrification inhibitors use alone. Of the wider array of 49 studies of the combined use of nitrification and urease inhibitors, the mean reduction in N_2O emissions was 28 percent, with 45 studies reporting reductions.

The evidence supports a robust estimate of avoided N_2O emissions from the use of nitrification inhibitors of 25 to 50 percent, centering on a 40 percent reduction as a best estimate.

Table 84. Descriptive statistics: Nitrification inhibitors - N_2O

	emissions: % change in emissions per hectare or acre	number of study results [a]	change in emissions, ratio positive-to-negative: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses and other derivative statistical studies or statistical summaries [b]	-41%	18	1/17	4%	-48%	-33%
empirical site studies	-39%	81	4/77	2%	-44%	-34%
modeling studies	-26%	7	0/7	4%	-34%	-18%
literature reviews/expert judgment	-33%	5	0/5	2%	-37%	-29%
synthetic nitrogen	-37%	62	5/57	3%	-43%	-31%
manure/urine nitrogen	-40%	31	1/30	3%	-46%	-34%
synthetic nitrogen plus manure/urine	-51%	5	0/5	15%	-81%	-21%
surface nitrogen application	-34%	65	3/62	3%	-40%	-29%
subsurface nitrogen application	-38%	14	1/13	6%	-49%	-26%
split application	-40%	47	3/44	3%	-46%	-33%
single application	-39%	35	2/33	4%	-46%	-31%
growing season and subgrowing season flux monitoring/modeling	-40%	54	2/52	3%	-46%	-34%
annual flux monitoring/modeling	-37%	52	2/50	3%	-42%	-32%
nitrification plus urease inhibitors- meta-analyses	-35%	9	0/9	2%	-40%	-31%
nitrification plus urease inhibitors- all studies [c]	-28%	49	4/45	3%	-34%	-22%
urease inhibitors-only - all studies	-14%	32	10/22	5%	-24%	-5%

[a] nitrification inhibitors-only: 111 study results, 111 studies (16 meta-analyses, 2 statistical summaries or derivative statistical analyses, 7 modeling studies, 81 empirical site studies, 5 literature reviews)

[b] statistical summaries or derivative statistical analyses other than meta-analyses

[c] 49 study results, 49 studies (10 meta-analyses, 1 modeling studies, 35 empirical site studies, 3 literature reviews)

b. Methane

The estimated annual change in soil CH_4 oxidation resulting from the use of nitrification inhibitors is small, a 248 CO_2-equivalent short ton increase in oxidation (see Table 83). This was calculated using the average percent change in soil CH_4 oxidation from the results of a single available meta-analysis. Formal meta-analysis is probably the most powerful tool now available for aggregating estimates across study types with differing designs. Baseline CH_4 oxidation rates in temperate cropland soils were taken from Aronson and Helliker (2010).

Using the single meta-analysis estimate, developed by Yang *et al.* (2016) from a global database, the use of nitrification inhibitors on cropland fertilized with synthetic nitrogen is estimated to increase CH_4 oxidation slightly, by 12 percent (see Table 85).

In general, relatively few studies have been directed toward changes in CH_4 soil oxidation resulting from the use of nitrification inhibitors. We identified eleven empirical site studies and one modeling study. Using the results from the empirical site studies, soil CH_4 uptake and oxidation might be expected to decline by 31 percent, which diverges greatly from the conclusion drawn from the single meta-analysis. The estimates for soil CH_4 oxidation from the empirical site studies range from (-) 200 to (+) 68 percent. In general, the change in CH_4 fluxes resulting from the use of nitrification inhibitors is poorly understood. It seems possible that the oxidation of CH_4 cin soils ould increase or decline. More research is this area is needed.

Table 85. Descriptive statistics: Nitrification inhibitors - CH_4

	emissions: % change in soil CH_4 oxidation per hectare	number of study results [a]	change in emissions, ratio positive-to-negative: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	12%	1	1/0	NA	NA	NA
empirical site studies	-31%	11	3/8	20%	0%	0%
modeling studies	0%	1	1/0	NA	NA	NA
all studies	-25%	13	5/8	17%	-58%	7%
growing season and subgrowing season flux monitoring/modeling	-52%	8	1/7	23%	-97%	-7%
annual flux monitoring/modeling	17%	5	3/1/1	13%	-9%	43%
urease inhibitors-only	-9%	2	0/2	1%	-11%	-7%
nitrification and urease inhibitors	-46%	6	0/6	30%	-105%	12%

[a] 13 study results, 13 studies (1 meta-analyses, 1 modeling studies, 11 empirical site studies)

T. Urease inhibitors

Urease inhibitors are chemical additives to urea-based nitrogen fertilizer that act to inhibit the hydrolysis of urea to ammonium. Plant available forms of nitrogen include ammonium (NH_4^+) and nitrate (NO_3^-). Urea is made available to plants as ammonium through the action in soils of the urease enzyme. With rapid, early season hydrolysis of urea to NH_4^+, ammonium accumulates in soils in excess of early season plant needs, resulting in large losses of nitrogen to the atmosphere in the form of volatilized ammonia and N_2O. Urease inhibitors act to delay the time of urea hydrolysis to NH_4^+, allowing urea to diffuse through precipitation or irrigation into soil column, where urea hydrolysis is further inhibited or otherwise slowed.

N_2O is produced in soils in part during the nitrification of ammonium to nitrite (NO_2^-) and nitrate. By limiting early season soil NH_4^+ excess, urease inhibitors act to inhibit early season, nitrification-based N_2O production in soils, pushing it further into the growing season, when, due to plant nitrogen uptake, the pool of excess soil NH_4^+ is more limited.

Urease inhibitors include NBPT (N-(n-butyl)thiosphosphate Triamide), NPPT (N-(n-propyl)thiosphosphate Triamide), PDD/PDDA (phenylphosphorodiamidate), and hydroquinone. The most popular of these, NBPT, is marketed under various trade names, including Agrotain, ANVOL, LIMUS and Arborite Ag.

Estimated greenhouse gas-avoidance from the use of urease inhibitors is shown in Table 86. For each 100,000 acres of crops receiving urea with a urease inhibitor, an estimated 18,000 CO_2-equivalent short tons of greenhouse gas emissions would be avoided, or at a per acre rate of 0.18 CO_2-equivalent short tons per acre per year. Virtually all of this would be avoided in-state, and almost all avoidance results from avoided direct N_2O soil emissions.

As in the case of nitrification inhibitors (see Section IV, Subsection S above), no effect of the use of urease inhibitors on soil carbon has been identified in the scientific literature. No change in fuel use accompanies the use of urease inhibitors. For reasons discussed in the preceding section (Section IV, Subsection S), and also in the chapter on methods (Section II), no estimate is given for avoided-emissions resulting from improved crop nitrogen use efficiency under urease inhibitor practice. Finally, the methods and data sources used to estimate avoided indirect N_2O emissions from nitrate leaching and ammonia volatilization were discussed in the methodology section of this report (Section II, Subsection E).

a. Nitrous oxide

Urease inhibitors act to inhibit urease hydrolysis, slowing the rate of conversion of urea to ammonium (NH_4^+). This limits the pool of nitrogen available for nitrification, as well as the downstream pool nitrate. During denitrification, nitrate from this pool is reduced to dinitrogen (N_2) and to N_2O, which is then emitted to the atmosphere. During nitrification, nitrogen in an ammonium form is oxidized to nitrate, with N_2O produced as a byproduct. Urease inhibitors deactivate the urease enzyme, lowering soil ammonium levels, which early in the growing season usually are in excess of plant needs, and otherwise limiting the pool of available ammonium and nitrate for nitrification and denitrification.

The application of NBPT, the most employed urease inhibitor, in conjunction with urea, acts to delay urea hydrolysis one to two weeks, which allows for diffusion of urea into soils. (Sanz-Cobena *et al.,* 2008; Wang *et al*., 2021) In soils, urea hydrolysis is slower in comparison to surface urea hydrolysis.

The use of urease inhibitors also acts to conserve total applied urea nitrogen. When applied to soils, urea is quickly converted to ammonium, inducing an increase in soils pH, which promotes the conversion of ammonium to ammonia, and ammonia volatilization. The IPCC estimates that between 10 and 20 percent of applied nitrogen is lost through ammonia volatilization. (IPCC 2006) The use of urease inhibitors acts to reduce those loses by about one-half. (Pan *et al*., 2016; Xia *et al*., 2017)

Over an entire year, this may act to increase, rather than decrease, the pool of available soil ammonium and nitrate.

In this study, avoided-emissions from the use of urease inhibitors are calculated as the product of the estimated percentage change in emissions resulting from use of urease inhibitors and average Minnesota cropland N_2O emissions. Average Minnesota cropland N_2O emissions are taken from the MPCA Greenhouse Gas Inventory. We reviewed 43 studies. Of these, seven studies were meta-analyses of the results of published controlled site studies, one was a modeling study, and 28 were empirical site studies, mostly controlled site studies (see Table 87). We used the mean estimate from the seven meta-analyses as the best estimate of the percentage change in N_2O emission resulting from the use of urease inhibitors.

Using the meta-analysis mean estimate, the use of urease inhibitors is estimated to reduce N_2O emissions by 27 ± 8 percent (see Table 87). Of the seven meta-analyses reviewed, six reported emissions reductions from urease inhibitor use, one an increase. Across all study types, estimated N_2O emission reductions ranged from no change in emissions in the case of the one modeling study, to 27 percent in the case of the seven meta-analyses. The mean response rate of N_2O emissions to the use of urease inhibitors for all 43 studies was (-) 14 percent. In these 43 studies, N_2O emissions declined in 24 studies, and increased in twelve.

Table 86. Urease inhibitors: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(17,111)	no inhibitors
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	(1,072)	no inhibitors
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	not known	no inhibitors
CH_4 [b]	soils	(248)	no inhibitors
CO_2 [c]	carbon accumulation in soils	-	no inhibitors
CO_2	cultivated soils from lime or urea use	-	no inhibitors
GHGs-energy	fossil fuel and electricity use in crop production	-	no inhibitors
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	-	no inhibitors
Total		**(18,368)**	

[a] positive = emissions increase, negative = emissions reduction

[b] increase in soil CH_4 oxidation = relative decrease in emissions

[c] carbon accumulation in soils = net removal of CO_2 from the atmosphere = net emission reduction

Meta-analysis is a powerful statistical tool used to integrate results of experiments of different designs and draw conclusions at broad spatial scales. Agreement among six of the seven meta-analyses provide some confidence in the direction of the response of N_2O emissions to the use of urease inhibitors, as well as its broad magnitude. Troubling, however, are the results from studies by nitrogen placement depth, which, while supportive of a negative response rate, cannot be said to evince a high or even moderate degree of certainty (see Table 87). The same is true of the results from studies with year-long monitoring of N_2O emissions, as against monitoring that is restricted solely to the growing season.

This suggests that caution be exercised with respect to the results from the meta-analyses. Clearly more empirical site studies, particularly those with year-long monitoring protocols, are needed. It seems possible that, with more studies, the true response rate of N_2O to urease inhibitors may prove to be different from what is suggested in Table 87. Provisionally, the weight of the evidence suggests a negative response rate of N_2O emissions to urease inhibitors in the range of 10 to 30 percent, subject to this caveat.

The descriptive statistics for urease inhibitor use are given in Table 87. As elsewhere in this report, the estimates given in Table 87 in are reported in metric units, and have been converted to English units for use in Table 86.

Table 87. Descriptive statistics: Urease inhibitors - N_2O

	emissions: % change in emissions per hectare or acre	number of study results [a]	change in emissions, ratio positive-to-negative: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses and other derivative statistical studies or statistical summaries [b]	-27%	7	1/6	8%	-42%	-11%
empirical site studies	-12%	28	10/18	5%	-23%	-1%
modeling studies	0%	1	1/0	NA	NA	NA
all studies	-14%	36	12/24	5%	-23%	-5%
manure/urine nitrogen	0%	5	2/3	10%	-19%	19%
synthetic nitrogen	-15%	27	8/19	6%	-26%	-4%
surface nitrogen application	-6%	18	9/9	7%	-20%	8%
subsurface nitrogen application	-6%	5	3/2	18%	-41%	29%
split application	-4%	15	6/9	5%	-13%	6%
single application	-22%	12	3/9	10%	-43%	-2%
growing season and subgrowing season flux monitoring/modeling	-21%	19	5/14	7%	-33%	-8%
annual flux monitoring/modeling	-9%	16	7/9	6%	-21%	3%

[a] 43 study results, 43 studies (7 meta-analyses, 0 statistical summaries or derivative statistical analyses, 1 modeling studies, 28 empirical site studies)

[b] statistical summaries or derivative statistical analyses other than meta-analyses

U. Controlled release fertilizers

Greenhouse gas-avoidance from the use of controlled release fertilizer (CRF) is shown in Table 88 by source of avoidance. We estimate GHG-avoidance on 100,000 acres of CRF practice of roughly 18,000 CO_2-equivalent short tons annually. Avoided direct emissions of N_2O from cultivated soils account for about 70 percent of this. Avoided indirect N_2O emissions from avoided nitrate leaching account for most of the remainder.

Controlled release fertilizer is a type of slow release fertilizer, in which nitrogen fertilizer is encapsulated in a permeable polymer coating that, after a delay of several months, releases nitrogen to soils in a soluble form. In part, N_2O emissions from soils result in part from the accumulation in soils of ammonium (NH_4^+). N_2O is microbially-produced in soils during soil processing involving nitrification and denitrification. During nitrification, excess NH_4^+ (excess to plant nutrient needs) is oxidized to nitrite and nitrate. Controlled release fertilizers act to limit the early season accumulation of excess ammonium, thus minimizing early growing season N_2O emissions.

Polymer coated urea (PCU) is the most commonly used controlled release fertilizer. Polymer coatings include various thermoplastic resins like polyurethane, polyethylene or alkyd resin, which typically delay the release of nitrogen to soils 50 to 70 days. (Lawrencia *et al*, 2021) PCU is commercially available under various trade names, such as ESN, Nutricote, Multicote, Floricote and Polyon.

Biodegradable polymer coatings have been developed or are under development, using a variety of coating materials, such as bio-based polyurethane, latex or polysulfone. Besides controlled release fertilizers, the class of slow release fertilizers includes sulfur-coated urea and methylene urea.

As noted above, most avoided-emissions from CRF are from avoided direct N_2O soil emissions. No emissions-avoidance is expected from fuel use. While CRF is expected to improve crop nutrient use efficiency (NUE) and yields (Xia *et al*., 2016; Zhang *et al*., 2019; Zhang et *al*., 2022; Zhu *et al*., 2020), whether and the degree to which this results in reduced per acre nitrogen applications is uncertain. To our knowledge, a behavioral response to CRF on the part of farmers has yet to be identified in crop production data. Finally, regarding avoided indirect N_2O emissions, methods and sources were delineated in Section II, Subsection E above (Methodology section).

Table 88. Controlled release fertilizers: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(12,585)	urea
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	(1,210)	urea
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(3,927)	urea
CH_4	soils	not known	urea
CO_2 [b]	carbon accumulation in soils	-	urea
CO_2	cultivated soils from lime or urea use	-	urea
GHGs-energy	fossil fuel and electricity use in crop production	-	urea
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	-	urea
Total		**(17,722)**	

[a] positive = emissions increase, negative = emissions reduction

[b] carbon accumulation in soils = net removal of CO_2 from the atmosphere = net emission reduction

a. Nitrous oxide

In controlled release fertilizers, soil nitrogen fertilizer, often urea, is packed into a small capsule, called a prill, surrounded by a semi-permeable coating. This coating allows water vapor to penetrate, dissolving the solid fertilizer, which in a highly concentrate dilute form is released to soils through minute cracks in the prill coating. The process is triggered by soil temperature, typically mid-growing season temperature. The timing and rate of release is controlled by the thickness and type of the coating.

Nitrogen in CRF is designed to be released to coincide with peak plant needs two to four months into the growing season. With the completion of the growing season, about 15 to 20 percent of nitrogen in the prill remains in the prill, and is only subsequently released on the fall or later. (Lawrencia *et al*, 2021)

As noted in the introduction to this subsection on controlled release fertilizers, polymer coated urea is the most common CRF, with a thermoplastic cover and delayed release of between 50 and 70 days after fertilization.

Nitrogen fertilizer undergoes a series of bacteria-mediated transformations, starting with, in the case of urea, urea hydrolysis, and including nitrification and denitrification. In urea hydrolysis, urea is oxidized to ammonium (NH_4^+). In denitrification, ammonium is oxidized to nitrate (NO_3^-), while NO_3^- is reduced to gaseous dinitrogen (N_2) and N_2O during denitrification, both of which then are emitted to the atmosphere. Nitrous oxide is produced as a by-product of nitrification and as an end-product of denitrification.

Controlled release fertilizers delay this chain of linked transformations two to three months into the growing season, limiting early and mid-season N_2O emissions from synthetic fertilizer application. Nitrogen in synthetic fertilizer accounts for about one-quarter of the nitrogen that, in any given year, is available in cropped soils for the microbial production of N_2O. Because about one-fifth of prill nitrogen is retained in the prill into the fall, some early- and mid-season N_2O avoidance may be offset later in the year as residual prill urea becomes available to soil bacteria after harvest.

It also might be noted that the rate of N_2O formation in soils, whether during nitrification or denitrification, is a function of temperature, increasing with higher daily temperatures, particularly deep into the growing season. With abundant soil pools of ammonium and nitrate at mid-growing season, conditions for N_2O formation would be optimal with CRF, with higher mid-season N_2O formation and emissions potentially offsetting reduction earlier in the growing season. Large plant uptake of available ammonium and nitrate might reasonably be expected to offset some or all of this, the result of generally smaller available pools of NH_4^+ and NO_3^- at mid-growing season.

In this study, avoided-emissions from the use of controlled release fertilizer are calculated as the product of the estimated percentage change in emissions resulting from use of CRF and average Minnesota cropland N_2O emissions. Average Minnesota cropland N_2O emissions are taken from the MPCA Greenhouse Gas Inventory. We used the mean estimate from the eleven meta-analyses of published controlled site studies as the best estimate of the percentage change in N_2O emission with the use of CRF.

In developing this work, we reviewed 64 studies with 75 study results. A number of studies included results using multiple study types. Of the 64 studies, four were modeling studies, 47 were empirical site studies, mostly controlled site studies, two were literature reviews, and, as already mentioned, eleven were meta-analyses (see Table 89). Across all study types, the change in estimated N_2O emissions with CRF ranged from, in the case of the four modeling studies, an 18 percent increase in N_2O emissions to a reduction of 37 percent in the two literature reviews. The mean response rate of N_2O emissions to the use of urease inhibitors for all 64 studies was (-) 10 percent.

Using the meta-analysis mean estimate, the use of controlled release fertilizer is estimated to reduce N_2O emissions by 20 ± 10 percent (see Table 89). Of the eleven meta-analyses reviewed, ten reported emissions reductions from the use of CRF, one an increase.

As noted elsewhere in this report, meta-analysis is a powerful statistical tool used to integrate results of experiments of different designs and draw overall conclusions at broad spatial scales. Agreement among ten of the eleven meta-analyses provide some confidence in the direction of the response of N_2O emissions to the use of controlled release fertilizer and its broad magnitude. Troubling, however, are the results from studies by nitrogen placement depth (surface placement, subsurface placement) and by the number of nitrogen applications (single application at planting, split application), which, while supportive of a negative response rate, cannot be said to evince a high or even moderate degree of certainty (see Table 89).

The same is also true of the results for all 47 empirical site studies and studies with year-long monitoring of N_2O emissions, as against monitoring that is restricted solely to the growing season.

The results from the modeling studies move in the opposite direction to the results from the meta-analyses and the empirical site studies, which might suggest that our understanding of the basic CRF biochemical processes is still lacking.

Table 89. Descriptive statistics: Controlled release fertilizer - N_2O

	emissions: % change in emissions per hectare	number of study results [a]	change in emissions, ratio positive-to-negative: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	-20%	11	1/10	10%	-39%	-1%
modeling studies	18%	4	1/3	27%	NA	NA
empirical site studies	-8%	58	18/40	8%	-24%	7%
literature reviews/expert judgement	-37%	2	0/2	5%	-45%	-28%
surface nitrogen application	6%	18	5/13	16%	-25%	38%
subsurface nitrogen application	-4%	26	11/15	11%	-29%	20%
single nitrogen application	7%	31	12/19	12%	-16%	30%
split nitrogen application	-23%	16	4/15	10%	-43%	-3%
<1 to 2 years of observations or simulations	1%	35	14/21	10%	-18%	20%
3 years-plus of observations or simulations	-8%	23	4/19	12%	-30%	15%
annual flux monitoring/modeling	-3%	27	7/20	9%	-21%	15%
growing season and subgrowing season flux monitoring/modeling	-12%	47	14/33	9%	-29%	6%

[a] 75 study results, 64 studies (11 meta-analyses, 4 modeling studies, 47 empirical site studies, 2 literature reviews)

These considerations suggest that caution be exercised with respect to the results from the meta-analyses. Clearly many more empirical site studies are needed. It seems possible that, with more studies, the true response rate of N_2O to controlled release fertilizers may prove to be different from what is suggested in Table 89. Provisionally, the weight of the evidence suggests a negative response rate of N_2O emissions to CRF, perhaps, in the range of 10 to 20 percent, subject to this caveat.

The descriptive statistics for controlled release fertilizer use are given in Table 89. As elsewhere in this report, the estimates given in Table 89 are reported in metric units, and then converted to English units for use in Table 88.

V. Split nitrogen application

It is conventional to apply nitrogen fertilizer in a single application at planting or just prior to planting. Between that initial application and the time of peak plant needs for nitrogen, 30 percent or more of applied nitrogen is lost to the environment in the form of leached nitrate (NO_3^-), ammonia (NH_4^+) volatilized and emitted to the atmosphere, and direct atmospheric emissions of nitrous oxide and dinitrogen (N_2). In the case of emitted nitrous oxide, N_2O is produced in soils with levels of soil ammonium and/or soil nitrate in excess of plant nutrient needs. In cropped soils, ammonium can be directly introduced to soils in the form of ammonium-based fertilizers, or indirectly to soils as a result of the hydrolysis of urea-based fertilizer. Nitrate is produced microbially in soils from NH_4^+ during soil nitrification. With large plant nitrogen uptake later in the growing season, the pool of available NO_3^- and NH_4^+ contracts. But until that drawdown, large excesses of nitrogen in these forms develop, driving N_2O production.

In split fertilizer application, nitrogen is applied in two three smaller applications, once at planting or pre-plant, a second time closer to the time of peak plant needs, which for corn is near the six leaf stage, and a third time, if there is a third application, later still. Of these successive applications, nitrogen fertilizer applications at planting tend to be small, with the result that early season excess levels of NO_3^- and NH_4^+ do not form or, if they do form, form at lower levels than with single application of nitrogen at planting. With lower levels of soil NO_3^- and NH_4^+, early growing season N_2O emissions are lessened.

Depending on soil texture and other factors, crop yields may or may not benefit from split nitrogen application. (Clark, *et al*., 2020; Davies *et al*., 2020; Nafzinger and Rapp, 2021; Zhang *et al*. 2019) The effects of split application practice are similarly ambiguous with respect to nutrient use efficiency.

Greenhouse gas-avoidance is assessed for N_2O directly emitted from soils, N_2O indirectly emitted following nitrate leaching and ammonia volatilization and deposition, CH_4 soil oxidation and fuel use. No soil carbon sequestration effects have been identified in the scientific literature. No changes are expected from upstream out-of-state agricultural chemicals manufacture. As just noted, yield changes from split application practice are uncertain.

The budget for greenhouse gas-avoidance from split application practice is shown in Table 90. Avoidance is evaluated per 100,000 acres in split application practice. We estimate that, for each 100,000 acres in which split fertilizer application is practiced, roughly 11,000 CO_2-equivalent short tons of greenhouse gas emissions would be avoided annually. Of this GHG-avoidance, almost all (95 percent) results from avoided direct N_2O emissions from cropped soils. The contribution of all other sources of avoidance is small.

Avoided direct N_2O emissions from soils are treated below, as are the effects of split application practice on CH_4 soil oxidation. Methods and data sources used to estimate avoided indirect N_2O emissions from nitrate leaching and ammonia volatilization, as well as emissions from increased field fuel use, are discussed in the methodology section of this report (Section II, Subsection E).

Table 90. Split nitrogen fertilizer application: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(11,173)	single application
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	108	single application
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(1,006)	single application
CH_4	soils	206	single application
CO_2 [b]	carbon accumulation in soils	-	single application
CO_2	cultivated soils from lime or urea use	-	single application
GHGs-energy	fossil fuel and electricity use in crop production	568	single application
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	-	single application
Total		**(11,296)**	

[a] positive = emissions increase, negative = emissions reduction

[b] carbon accumulation in soils = net removal of CO_2 from the atmosphere = net emission reduction

a. Nitrous oxide

With split nitrogen application, crop nitrogen needs are met with nitrogen applied in two or three separate applications, a small initial application at planting or preplant and one or two relatively larger large applications further into the growing season. For a crop like corn, the principal consumer of nitrogen in the Minnesota, the second application occurs near the sixth vegetative stage, five to seven weeks after planting.

Split nitrogen applications act similarly to controlled release fertilizers. As note in Section IV, Subsection U.a, nitrogen fertilizer undergoes a series of bacteria-mediated transformations, starting with, in the case of urea, urea hydrolysis, and including nitrification and denitrification. In urea hydrolysis, urea is oxidized to ammonium (NH_4^+). In nitrification, ammonium is oxidized to nitrate (NO_3^-), while during denitrification, NO_3^- is reduced to gaseous dinitrogen (N_2) and N_2O, both of which then are emitted to the atmosphere. Nitrous oxide is produced as a by-product of nitrification and as an end-product of denitrification.

Like controlled release fertilizers, split nitrogen applications act to delay this chain of linked transformations into the growing season limiting early season N_2O emissions from synthetic fertilizer application.

With split application, the farmer has some control over the timing of the second or third application, so may be better placed to respond to environmental conditions as they unfold. But, as noted frequently in the scientific literature, nitrogen that is made plant-available in mid-growing season is subject to higher temperature, which promotes N_2O formation during nitrification and denitrification. (Ma *et al*., 2010) This may act to offset a part of avoided early-season N_2O emissions.

Finally, N_2O production in soils responds to ammonium and nitrate concentrations in soils in excess of plant needs. But in any given location and time, this response is often modulated by soil physical and chemical properties, including soil structure and porosity, soil bulk density, soil organic carbon content, soil texture and pH, soil temperature, and soil water content, as well as management practices, like inversion tillage. N_2O formation during denitrification is also quite sensitive to precipitation events, their timing and intensity. (Aita *et al*., 2015; Wang *et al*., 2016) These factors introduce variability into the experimental data for N_2O response to soil ammonium and nitrate availability.

Unlike nitrification inhibitors, which inhibit nitrification generally in cropped soils, split nitrogen application affects only about one-quarter of soil nitrogen that is available for the formation of N_2O. In light of this limited effect, and given the variability introduced by site-specific soil properties and weather, the effort to identify with certainty the effect of split nitrogen application on N_2O formation may meet with some difficulty. (Burton *et al*., 2008; Aita *et al.,* 2015)

In this study, avoided-emissions from split nitrogen application are calculated as the product of the estimated percentage change in emissions resulting from split applications and average Minnesota cropland N_2O emissions. Average Minnesota cropland N_2O emissions are taken from the MPCA Greenhouse Gas Inventory. To estimate the percentage change in N_2O emissions from the split nitrogen application, we reviewed 41 studies with 41 study results. Of these, 7 studies were meta-analyses of the results of published controlled site studies, seven were modeling studies, and 27 were empirical site studies, mostly controlled site studies (see Table 91).

We used the mean estimate from the seven meta-analyses as the best estimate of the percentage change in N_2O emission with split nitrogen applications. Using the mean estimate from these seven studies, split application is estimated to reduce N_2O emissions by 17 ± 8 percent. Of the seven meta-analyses, five reported emissions reductions from split nitrogen application, two reported an increase in emissions (again see Table 91). As noted throughout this report (Section II), meta-analysis is a powerful statistical tool used to integrate results of experiments of different designs and draw conclusions at broad spatial scales.

By study type, the estimated percentage change associated with split nitrogen application ranged from (-) 1 to (-) 17 percent (see Table 91). Of the 41 studies reviewed, 29 reported reduced N_2O emissions, and 14 reported increased N_2O emissions. The mean response rate of N_2O to split nitrogen application in modeling studies was a mere (-) 1 percent, an estimate that cannot be said in any formal statistical sense to be significantly different from a zero response rate (see Table 91).

We separated those site studies that compared split application to single application at planting (or preplant) from those that compared multiple applications of a greater to a lesser number. In both instances, N_2O emissions declined with split nitrogen application or with more intensive split application practice, although any conclusions that might be drawn from the comparison of multiple applications of a greater to a lesser number were limited by the small number (eight) of study results.

We stratified the studies by fertilizer placement depth (surface placement, subsurface placement). Estimated mean N_2O emissions declined across the studies with split application, irrespective of fertilizer placement depth. However, neither estimate, based on simple averaging of study results, can be said to be established with a high degree of certainty.

Table 91. Descriptive statistics: Split nitrogen fertilizer application - N_2O

	emissions: % change in emissions per hectare	number of study results [a]	change in emissions, ratio positive-to-negative: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	-17%	7	2/5	8%	-25%	-10%
empirical site studies	-12%	27	11/18	5%	-23%	-2%
modeling studies	-1%	7	1/6	6%	-14%	11%
single split versus no splits	-13%	36	11/25	4%	-22%	-4%
more splits versus fewer splits	-5%	8	3/5	6%	-16%	7%
surface nitrogen application	-8%	10	2/8	7%	-23%	6%
subsurface nitrogen application	-14%	18	6/12	7%	-29%	1%
growing season and subgrowing season flux monitoring/modeling	-13%	20	6/14	6%	-25%	-1%
annual flux monitoring/modeling	-11%	25	5/20	5%	-20%	-2%
1 year or less of observations or simulations	-16%	11	2/9	7%	-30%	-1%
>1 to 2 years of observations or simulations	-17%	14	4/10	7%	-31%	-2%
more than 2 years of observations or simulations	0%	11	3/8	7%	-13%	12%

[a] 41 study results, 41 studies (1 meta-analysis, 7 modeling studies, 27 empirical site studies)

These considerations suggest that caution be exercised with respect to the results from the meta-analyses. Clearly more empirical site studies are needed. It seems possible that, with more studies, the true response rate of N_2O to split application may prove to be different from what is suggested in Table 91. Agreement among five of the seven meta-analyses provides some confidence in the direction of the response of N_2O emissions to split nitrogen application and its broad magnitude. Provisionally, the weight of the evidence suggests a negative response rate of N_2O emissions to urease inhibitors generally in the range of 5 to 15 percent, subject to this caveat.

b. Methane

The estimated annual change in soil CH_4 oxidation resulting from the split application of nitrogen fertilizer is small, a 206 CO_2-equivalent short ton increase in oxidation (see Table 90). This was calculated using the average percent change in soil CH_4 oxidation from a single available meta-analysis. Baseline CH_4 oxidation rates in temperate cropland soils were taken from Aronson and Helliker (2010).

Using the single meta-analysis estimate, developed by Sun *et al*. (2016) for Chinese corn and wheat production, the use of split nitrogen application on cropland formerly fertilized with a single application at planting is estimated to increase CH_4 oxidation slightly, by 10 percent (see Table 92).

In general, relatively few studies have been directed toward changes in CH_4 soil oxidation resulting from split nitrogen application practice. We identified five empirical site studies. Using the results from the empirical site studies, soil CH_4 uptake and oxidation might be expected to increase by 4 percent, but based on a very few number of studies, showing widely scattered results (-38 to +56 percent change in soil CH_4 oxidation). A good deal more study is necessary. The change in CH_4 soil oxidation has little effect on overall avoidance totals (see Table 90).

Table 92. Descriptive Statistics: Split fertilizer application - CH_4

	emissions: % change in oxidation per hectare	number of study results [a]	change in emissions, ratio positive-to-negative: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	10%	1	1/0	NA	NA	NA
empirical site studies	4%	6	5/2	13%	-21%	29%
all studies	5%	7	6/2	11%	-16%	26%

[a] 7 study results, 6 studies (1 meta-analysis, 5 empirical site studies)

W. Deep nitrogen placement

To reduce losses of nitrogen applied to cropland as a nutrient, in either a synthetic mineral form or in an organic manure-based form, nitrogen is placed deep in the soil column near the roots of the crop. This is in contrast to surface application of nitrogen fertilizer, whether in the form of surface broadcast or surface banding of fertilizer in a solid form or liquid foliar application. Surface-applied nitrogen is subject to losses to the atmosphere after ammonification of urea, or as in the case of ammonium (NH_4) fertilizers or manure, immediately upon application from ammonia (NH_3) volatilization. Losses from NH_3 volatilization are often estimated to be in the range of 10 to 20 percent. (IPCC, 2006) Upon nitrification of NH_4 to nitrite and then nitrate, applied nitrogen is subject to loss through nitrate leaching to groundwater and, through groundwater flows, to surface water. With deep soil placement, much of this loss is eliminated. Placement of nitrogen near plant roots acts to maximize plant uptake of nitrogen, thereby constraining the pool of available soil nitrate subject to groundwater loss.

Nitrogen can be placed deep in the soil column through injection as a liquid or, for applied nitrogen in a solid form, through incorporation after surface broadcast by tillage or through granular placement with air drills. Applied nitrogen also may be fertigated, applied as a liquid with irrigation waters and removed to deeper soil layers with the downward movement of irrigation water. Placement depths are typically 4 to 8 inches below the soil surface, with some shallower placement of 2 or 3 inches.

Soils deeper in the soil column are wetter with higher bulk density, factors that encourage soil nitrate denitrification. During denitrification, soil nitrate is reduced microbially to gaseous N_2O and dinitrogen (N_2), which then are emitted to the atmosphere. In very wet soil layers, fully anaerobic conditions promote nitrate reduction solely to N_2, omitting N_2O production entirely, and clouding outcomes. Factors that promote N_2O production with deep placement include: soil wetness (though not extreme soil wetness), the presence of clays in soils, the presence resulting from inversion tillage of large amounts of soil organic carbon, particularly in the form of crop residues or manure, and high bulk density. Generally lower soil temperatures act to minimize N_2O production, as does, inversion tillage aside, generally lower soil carbon content in deeper soil layers.

While not fully conclusive, the scientific literature tends in the direction of enhanced N_2O production in soils with deep nitrogen placement.

A budget for estimated avoided-emissions from deep placement is presented in Table 93. Based on the results from Table 93, greenhouse gas emissions would increase with deep placement, rather than decline. We estimate that, for each 100,000 acres of deep placement practice, on an annual basis, greenhouse gas emissions would increase by roughly 28,000 CO_2-equivalent short tons, most of this plus a little resulting from increased direct N_2O production in deeper soil layers. Emissions-avoidance from indirect N_2O sources, including N_2O from leaching and N_2O from NH_3 volatilization, offsets about 10 percent of increased direct N_2O emissions from cropped soils.

Table 93. Deep nitrogen fertilizer placement: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	33,436	surface or shallow fertilizer placement
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	(1,187)	surface or shallow fertilizer placement
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(4,999)	surface or shallow fertilizer placement
CH_4	soils	not known	surface or shallow fertilizer placement
CO_2 [b]	carbon accumulation in soils	-	surface or shallow fertilizer placement
CO_2	cultivated soils from lime or urea use	-	surface or shallow fertilizer placement
GHGs-energy	fossil fuel and electricity use in crop production	405	surface or shallow fertilizer placement
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	90	surface or shallow fertilizer placement
Total		**27,746**	

[a] positive = emissions increase, negative = emissions reduction

[b] carbon accumulation in soils = net removal of CO_2 from the atmosphere = net emission reduction

Increased direct N_2O emissions from cropped soils are treated below. No change in soil organic carbon from deep nitrogen fertilizer placement is expected, and little is known about the response of CH_4 oxidation to deep nitrogen placement. Of methods and sources used to estimate indirect emissions from nitrate leaching and ammonia volatilization, as well as direct emissions from fuel use, again these were discussed in the methodology section (Section II, Subsection E) of this report.

Finally, nitrogen placement near the roots of the crop acts to increase crop nitrogen use efficiency (NUE) and crop yields. A case can be made that increased NUE may lead to reduced per acre rates of synthetic nitrogen application, reducing out-of-state greenhouse gas emissions associated with the manufacture and transport of synthetic fertilizer. No estimate of this effect is offered here due to a lack of information of a quantitative nature on the response of per acre fertilizer use to deep placement, particularly that drawn from observation of actual farmer practice.

a. Nitrous oxide

Denitrification is promoted in deeper soil layers through the greater propensity for anaerobic conditions, both episodic and sustained, at deeper soil layers. During heterotrophic denitrification, ammonium is microbially reduced to N_2O and dinitrogen (N_2) in low oxygen, anaerobic environments. The formation of anaerobic conditions in subsurface soils is promoted by higher soil bulk density and soil wetness. In general, denitrification is the dominant N_2O forming microbial process in wetter soils, soils with water-filled pore space (WFPS) at or greater than 60 to 65 percent. (Liu *et al.*, 2007; Metivier *et al.*, 2009) By contrast in drier soils, nitrification is more important, dominating N_2O formation, for instance in Mediterranean and semi-arid climates.

Soil wetness inhibits the diffusion of oxygen into subsoils. Deeper soils are generally wetter due to lower temperatures and reduced evaporative losses.

Of the two processes, nitrification and denitrification, the yield of N_2O (and its emission rate) from denitrification is as much as 100-fold greater than that for nitrification. (Vilain *et al.*, 2014) In itself, the denitrification potential of soils is the same order of magnitude as soil's nitrification potential. With a much higher N_2O yield, denitrification in wet soils is often associated with some of the largest observed rates of per hectare N_2O emissions. Maximum N_2O production in soils typically occurs at water-filled pore space of somewhere between 60 and 85 percent, which also generally coincides with soil wetness at which N_2O production is mostly or entirely through denitrification. (Almaraz *et al*., 2009; Davidson *et al*., 1991; Liu *et al*., 2007) Denitrification potential is the soil's maximum capacity to dissimilate nitrate under anaerobic conditions, while nitrification potential is maximum capacity of a soil's nitrifying microorganisms to transform ammonium to nitrate.

N_2O formation in deeper soil payers is highest following large episodic rainfall events. (Akiyama *et al*., 2013) Episodic rainfall events create the necessary anaerobic conditions for the conversion of nitrate, produced by aerobic nitrifying bacteria in drier intervals between rainfall events, to N_2O and N_2. In humid and subhumid climates, large sporadic pulses of N_2O to the atmosphere arising from episodic rainfall events are common, and often dominate annual nitrous oxide soil emission totals.

By contrast, sustained high soil water conditions in sub-surface soils in agricultural fields act to suppress N_2O emissions. In such conditions, N_2O, escaping from deeper soil layers, is further reduced to N_2.

The formation of N_2O emissions in subsurface soils is promoted by the deep placement of fertilizer in soils with a propensity for anaerobic conditions. Factors that contribute to the propensity of subsurface soils for anaerobic conditions include: high bulk density, fine soil texture, high clay soil content, poor field drainage, and suppressed evaporative losses from deeper soil depths. The presence of readily decomposable carbon substrate in the form of incorporated crop residues is also important, as is the injection or incorporation of semi-dilute manure slurry.

Emissions-avoidance with respect to deep nitrogen placement is calculated as the product of the estimated percentage change in emissions resulting from deep nitrogen fertilizer placement and average Minnesota cropland N_2O emissions. Average Minnesota cropland N_2O emissions are taken from the MPCA Greenhouse Gas Inventory. We reviewed 66 studies, including eleven meta-analyses of the results of published controlled site studies, five modeling studies, one literature review, and 48 empirical site studies, mostly site-by-side studies (see Table 94). We used the mean estimate from the eleven meta-analyses as the best estimate of the percentage change in nitrous oxide emissions from deep nitrogen fertilizer placement.

Using the mean estimate from these seven studies, deep nitrogen placement is estimated to reduce N_2O emissions by 52 ± 25 percent. Of the seven meta-analyses, eight reported increased emissions with deep nitrogen placement, three reported an increase in emissions. Across study types, the increase in N_2O emissions ranged from 9 to 100 percent. Across all study types, 44 studies reported increased N_2O emissions with deep nitrogen placement, 20 reported declining emissions.

We stratified the studies by nitrogen fertilizer type (synthetic nitrogen, manure), tillage (no till, reduced tillage, conventional inversion tillage), and practice counterfactual (surface nitrogen placement, shallow subsurface nitrogen placement). Despite variations in nitrogen type, tillage, and practice counterfactual, in no instance did estimated mean N_2O emissions decline with deep placement. N_2O under the stratified results increased between 7 percent (no till) and 143 percent (manure nitrogen).

N_2O emissions, when measured on an annual basis, are less intense than those measured on a growing season basis, although still quite similar in percentage increase to the percentage increase suggested by the results of the meta-analyses. There is a suggestion in the data that, with no till tillage, the projected N_2O emissions increase might be tempered, but based on a relatively few studies (twelve). Deep placement of manure seems to result in a larger increase in N_2O emissions with deep placement than is true for synthetic nitrogen.

The weight of the evidence favors an increase in N_2O emissions with deep nitrogen placement in the range of 25 to 75 percent, with a best estimate of 50 percent.

The descriptive statistics for deep nitrogen fertilizer placement are given in Table 94. As elsewhere in this report, the estimates given in Table 94 are reported in metric units, and then converted to English units for use in Table 93.

Table 94. Descriptive statistics: Deep nitrogen fertilizer Placement - N_2O

	emissions: % change in emissions per hectare	number of study results [a]	change in emissions, ratio positive-to-negative: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	52%	11	8/3	25%	3%	101%
meta-analyses (synthetic nitrogen-only)	17%	3	2/1	13%	-9%	43%
empirical site studies	67%	47	32/15	23%	22%	112%
modeling studies	9%	5	3/2	18%	-27%	44%
literature reviews/expert judgment	100%	1	1/0	NA	NA	NA
synthetic nitrogen	25%	35	21/14	12%	0%	49%
manure nitrogen	143%	29	26/3	42%	60%	225%
conventional tillage	100%	9	5/4	59%	-16%	217%
reduced tillage	12%	9	5/4	11%	-9%	34%
no till tillage	7%	12	7/5	12%	-16%	30%
surface versus deep application	77%	51	36/15	22%	34%	121%
shallow versus deep application	21%	16	11/5	9%	3%	39%
annual flux monitoring/modeling	47%	28	20/8	14%	20%	73%
growing season and subgrowing season flux monitoring/modeling	79%	36	24/12	30%	21%	137%

[a] 65 study results, 65 studies (11 meta-analyses, 5 modeling studies, 48 empirical site studies, 1 literature reviews)

X. 15 percent nitrogen fertilizer reduction to corn-soybean rotations

N_2O production in and emission from cultivated soils result from the presence in soils of excess nitrogen in the form of nitrate (NO_3^-) and ammonium (NH_4^+) In soils, heterotrophic facultative bacteria reduce nitrate to N_2O, gaining energy for growth and maintenance. This occurs in anaerobic environments. In aerobic soil conditions, autotrophic nitrifying bacteria gain energy through the nitrification of ammonium, producing N_2O as a byproduct. N_2O is also produced microbially in soils through nitrifier denitrification and codenitrification. N_2O production is generally proportional to the amount of excess NO_3^-- or NH_4^+, in particular locations (and times) modulated, sometimes substantially, by the effects of soil temperature and pH, soil organic carbon and soil water. Soil water determines the oxidative state of the soil, and is itself affected by meteorology, soil type and bulk density, and soil organic carbon content. In most greenhouse gas emission inventories, N_2O emissions are derived as a function of excess soil nitrogen.

As discussed in the prior subsection (Subsection W), excess soil nitrogen, particularly soil NO_3^-, leads to nitrate leaching to groundwater and, through groundwater flows, to surface waters.

A good part of the applied research on emissions-avoidance from nutrient management has been focused on the effects of systematic over-application of synthetic nitrogen on croplands in the form of mineral fertilizers. But synthetic nitrogen inputs to soils constitute but one source of nitrogen that, when in excess of plant needs, is available for microbial production of N_2O. Others include: mineralized soil organic nitrogen, crop residue, atmospherically deposited nitrogen in the form of nitrogen oxides (NO_x) or NH_3, and organic manure nitrogen. In the Minnesota greenhouse gas inventory, synthetic fertilizer accounts for only about 25 percent of nitrogen inputs to soils leading to the production in soils of N_2O.

In Minnesota, much of applied synthetic nitrogen is directed toward corn-soybean production in a two-year rotation. Over application is measured by the Maximum Return to Nitrogen (MRTN) index, an economic measure of excess application that accounts for the respective market prices of nitrogen, corn and soybeans. In the most recently available assessment (MDA 2017), over-applications of nitrogen to corn-soybeans in Minnesota were between 15 and 30 lbs. of nitrogen per acre, or about 10 to 20% of total application.[18]

Here we estimate the greenhouse gas avoidance from a 15 percent reduction in synthetic nitrogen applications to a 2-year corn-soybean rotation. This is shown in Table 95 for greenhouse gas avoidance on 100,000 acres, which, for the assumptions used, comes to some 5,000 CO_2-equivalent short tons annually. Included in the budget for avoidance are avoided direct N_2O soil emissions, avoided indirect N_2O emissions from leaching and ammonia volatilization, emissions of CO_2 from soils, and avoided out-of-state emissions associated with the foregone manufacture of synthetic nitrogen fertilizer.

This practice – a fifteen percent reduction in synthetic nitrogen applications - addresses only the synthetic nitrogen piece of total nitrogen inputs to soils, which, with the smallness of the percentage reduction in per acre synthetic nitrogen use, accounts for the relative smallness of estimated emissions-avoidance from this practice.[19]

From Table 95, avoided direct N_2O soil emissions are the largest source of emissions avoidance. These were calculated using the 2006 Intergovernmental Panel on Climate Change guidance for the preparation of national greenhouse gas inventories (IPCC 2006), which was also used throughout this report to estimate avoided N_2O soil emissions (see Section II, Subsection B above). For a consistent representation of the relative effectiveness of the 27 best practices reviewed in this report, we used the IPCC (2006) for estimates shown in Table 95.

For soil organic carbon, we used the Midwest response rate of soil organic carbon for corn-soybeans to marginal changes in nitrogen applications from Poffenbarger *et al*. (2017). As noted on multiple occasions in this report, methods and sources used to estimate indirect emissions from nitrate leaching and ammonia volatilization, as well as avoided-emissions from the manufacturer of nitrogen fertilizer foregone, are discussed in summary form in the methodology section (Section II, Subsection E) of this report.

In 2019, the IPCC published a revised inventory guidance, which includes a revised emission factor for N_2O from applied synthetic nitrogen. Using this, emissions avoidance from a 15 percent reduction in per acre synthetic nitrogen applications to corn-soybeans increases by about 40 percent, on 100,000 acres to about 7,000 CO_2-equivalent short tons annually. For reasons noted just above, this estimate is not included in the inter-practice comparisons of practice effectiveness shown in summary Tables 2, 7, 8, 9 and 103.

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[18] at a nitrogen price-to-crop value ratio of 0.1 to 0.15.

[19] net change in emissions = (-) 15% * 25% or -3.8%.

Table 95. 15% Synthetic nitrogen reduction to corn-soybean rotations: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(2,528)	no nitrogen reduction
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	(253)	no nitrogen reduction
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(569)	no nitrogen reduction
CH_4	soils	not known	no nitrogen reduction
CO_2 [b]	carbon accumulation in soils	636	no nitrogen reduction
CO_2	cultivated soils from lime or urea use	(385)	no nitrogen reduction
GHGs-energy	fossil fuel and electricity use in crop production	-	no nitrogen reduction
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(2,106)	no nitrogen reduction
Total		**(5,205)**	
Emissions with IPCC (2019) emission factor			
GHGs	all sources and sinks	**(7,228)**	no nitrogen reduction

[a] positive = emissions increase, negative = emissions reduction

[b] carbon accumulation in soils = net removal of CO_2 from the atmosphere = net emission reduction

Lastly, it is a debated point in the scientific literature whether the response of direct N_2O soil emissions is linear over the range of possible per acre nitrogen application, or whether, beyond a certain application threshold, N_2O emissions increase exponentially or near-exponentially with application rate. (IPCC 2006; Millar *et al*., 2010; Philibert *et al*., 2012; Shcherbak *et al*.. 2014) Over small increments of change, for instance the 15 percent reduction treated in this best practice, this is probably not a factor. However, should much larger changes in application rates be considered, the conclusions drawn in this subsection might not hold, and emissions-avoidance might be much larger than is suggested by the results shown in Table 95. This may suggest that, in future versions of this report, avoidance might better be estimated for different classes of application, by quintiles of possible per acre application rates, focusing on the 80 percentile, or the likely high-emitters.

Y. Avoided conversion to cropland: peatlands

Drained cropped or pastured peatlands are subject to accelerated rates of mineralization, leading to peatland subsidence and large losses of organic carbon and nitrogen to the atmosphere in the form of CO_2 and N_2O emissions. In an undisturbed natural state, peatland soils are protected from extensive mineralization by waterlogged, anaerobic conditions. Respiration losses of carbon and organic nitrogen proceed at rates an order of magnitude slower than under aerobic conditions. With drainage, peatland soils dry and oxygen is introduced throughout the drained peatland soil column, creating conditions for rapid microbial decomposition of peat.

In Minnesota, this results in large present-day emissions of CO_2 and N_2O, which in the latest Minnesota Pollution Control Agency Greenhouse Gas Inventory were estimated at 9.5 and 1.5 million CO_2-equivalent short tons per year, respectively. This is based on an USEPA-estimated 800,000 acres, about one-half cropped and one-half pastured. (USEPA 2017)

Additional drainage for agricultural purposes would add to present-day emissions. In addition to CO_2 and N_2O emissions from peat mineralization, other sources of greenhouse gases under drainage and cultivation or pasturing include: N_2O emitted from soils following the exogenous input to soils of synthetic nitrogen or manure; indirect N_2O emissions from nitrate leached from cropped peatland soils; and CO_2, CH_4 and N_2O emitted during fuel use in agricultural production and during the out-of-state manufacture of fuels and agricultural chemicals used in crop production. Methane emissions decline substantially with drainage, offsetting a part of increased CO_2 and N_2O emissions.

The pasturing of beef and dairy cattle on peatlands also adds to greenhouse gas emissions. In the case of pastured ruminants like beef cattle, CH_4 is produced in and released from livestock digestive tracts.

Avoided greenhouse gas emissions from peatland soils not converted to agricultural purposes (beyond those already in agricultural production) are calculated as the difference between undisturbed peatland emissions and greenhouse gas emissions from drained cropped or pastured peatland soils. This is shown in Table 96 for 100,000 acres of avoided peatland conversion, which in the case of avoided conversion to cultivated cropland would result in annual greenhouse gas-avoidance of 1.5 million CO_2-equivalent short tons. Greenhouse gas-avoidance would be less for the avoided conversion of peatlands to drained pastureland, still an impressive 1.1 million CO_2-equivalent short tons.

From Table 96, most greenhouse gas-avoidance from the avoided drainage and conversion of peatlands to agricultural purposes results from the avoided loss of carbon to the atmosphere in the form of CO_2 emissions. In the case of cropped peatland soils, avoided CO_2 emissions account for about 90 percent of total avoided-emissions, while avoided N_2O emissions account for much of the remainder. In absence of peatland drainage, CH_4 emissions from undisturbed peatlands continue, adding back to emissions totals about 150,000 CO_2-equivalent short tons of emissions.

Atmospheric fluxes of CO_2, $N_2O$and CH_4 from drained peatland in agricultural use were treated in Subsection G. To avoid repetition, the reader is referred to Section IV, Subsection G.a.ii through G.c.ii for emissions estimates for these drained soils. The reader is likewise referred to Section IV, Subsection E for CO_2 emissions estimates for fuel use on cropped or pastured acres, as well as for out-of-state GHG emissions from the manufacture of fuels and agricultural chemicals used in agricultural production and indirect N_2O emissions from drainage-induced nitrate leaching. To avoid repetition, that earlier discussion will not be repeated here.

Below we treat terrestrial carbon sequestration in undisturbed peatlands, along with CH_4 emissions from undisturbed peatland sites. For N_2O emissions from undisturbed peatland soils, we use the flux estimates for these soils taken from three meta-analysis, using the mean of these three results. For these flux estimates, see: Leppelt *et al*. (2014), Minkkinen, *et al.,* (2020), and Tan *et al*. (2019).

Table 96. Avoided conversion of peatlands to cropland: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils or sediments	(240,215)	crop production
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	(2,169)	crop production
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(7,186)	crop production
CH_4	soils or sediments	147,061	crop production
CO_2 [b]	soils or sediments	(1,397,065)	crop production
CO_2	cultivated soils from lime or urea use	(2,808)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	(6,849)	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(20,184)	crop production
Total		**(1,529,415)**	
Avoided Conversion of Peatland to Pastureland			
GHGs	all sources and sinks	**(1,094,950)**	pasture

[a] positive = emissions increase, negative = emissions reduction

[b] CO_2 emissions-avoided from avoided conversion to cropland

a. Carbon sequestration in soils and biomass

The biogeochemical processes leading to the sequestration of carbon in peatland soil, were discussed in Section IV, Subsection G.a.i. That discussion will not be repeated. Suffice it to note here that, during photosynthesis, CO_2 is removed from the atmosphere and incorporated into plant biomass and, through root exudation and senescence and plant litter fall, into soils. In waterlogged environments, microbial decomposition of organic matter proceeds through anaerobic processes, which dramatically slows the rate of decomposition, allowing organic carbon to accumulate in saturated soils. Over long periods of time, substantial amounts of CO_2 can be removed from the atmosphere, resulting in a long-term cooling effect of peatland soils on climate.

Annual carbon sequestration in undisturbed 'natural' peatland is an estimated 0.94 ± 0.4 metric tons of carbon per hectare (0.42 ± 0.18 short tons per acre per year). This is the mean estimate of results from two formal meta-analyses of published studies of sequestration in undisturbed peatlands, plus nine additional statistical analyses of results from a similar body of studies. As elsewhere in this report, these estimates are reported in metric units, and have been converted to English units for use in Table 96.

Overall, we reviewed 25 studies with 30 study results. Of these 25 studies, three were modeling studies, twelve were empirical site studies, and two were literature review-type studies. These are in addition to the two meta-analyses and nine other statistical analyses noted immediately above. The mean sequestration rate of these 25 studies was an estimated 0.97 ± 0.14 metric tons of carbon per hectare (0.43 ± 0.06 short tons per acre per year), or quite close to the value taken from the eleven meta-statistical studies.

Mean rates of sequestration taken from the empirical site studies, modeling studies and literature-type reviews were 1.1, 0.65 and 0.81 metric tons of carbon per hectare per year, respectively. In most cases, calculated 95 percent confidence intervals were not excessively broad. In general, rates of organic carbon sequestration in undisturbed wetlands appear to be well understood. Overall, in the calculation of avoided CO_2 emissions from the avoided conversion of peatlands soils to cropland, the role of sequestration in undisturbed peatlands soils is minor, with the predominant influence exercised by emissions from drained, cropped peatland soils.[20] Any uncertainties in sequestration rates in undisturbed peatlands soils are best understood in the context of that limited role.

The descriptive statistics for sequestration in undisturbed peatlands are given in Table 97.

Also shown in Table 97 are the descriptive statistics for studies by study-type of sequestration in undisturbed mineral wetlands. To determine a mean rate of carbon sequestration in undisturbed mineral wetlands we reviewed 24 studies. The mean rate of sequestration across all 24 studies was 1.65 ± 0.34 metric tons of carbon per hectare (0.74 ± 0.15 short tons per acre per year). In comparison to sequestration in undisturbed peatlands, rates of sequestration in undisturbed mineral wetlands are higher, in the case of the entire pool of studies that were reviewed for study, about two-thirds higher. In the 24 studies that were reviewed, 28 study results were reported, of which 27 indicated net sequestration.

We identified two formal meta-analyses of the results of studies of mineral wetland sequestration found in the scientific literature, as well as six other related statistical analyses of these studies. Consistent with the approach taken throughout this study, for an estimate of carbon sequestration in undisturbed mineral wetlands, we selected the mean rate of sequestration from these eight studies as our best estimate of sequestration in undisturbed mineral wetlands. The mean rate of sequestration for these eight studies was some 2.2 ± 0.87 metric tons of carbon per hectare (0.98 ± 0.39 short tons per acre per year), or twice the rate given in Table 97 for undisturbed peatland soils.

Of the remaining 19 studies, twelve were empirical site studies, one was a modeling study, and two were literature review-type studies. Mean rates of sequestration were 1.52, 0.83 and 1.22 metric tons of carbon per hectare per year in the site, modeling and literature review-type studies, respectively.

Taken together, the results given in Table 97 for undisturbed peatland and mineral wetland soils provide an impressive window into carbon sequestration in these systems, and into the state of our knowledge in this area across wetland types. Undisturbed wetlands are unambiguously larger sequesterers of organic carbon, with a sequestration intensity of 1 to 2 metric tons of carbon per hectare per year (0.45 to 0.90 short tons per acre pear year). While the estimates for sequestration in undisturbed peatland and mineral wetland soils cannot be used interchangeably, the relatively tight range in the estimates indicate a degree of understanding of sequestration in these systems that in most regards seems adequate to underpin the avoided loss estimates given in Table 96.

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[20] CO_2 emissions from drained, cropped or pastured peatland soils are an order of magnitude larger than sequestration rates in undisturbed peatland soils.

Table 97. Descriptive statistics: Unmanaged peatlands and mineral wetlands - carbon sequestration in soils and biomass [a]

Peatlands						
meta-analyses and other derivative statistical analyses or statistical summaries	0.94	11	11/0	0.14	0.67	1.21
meta-analyses	0.92	2	2/0	0.44	0.05	1.78
other derivative statistical analyses [d]	0.95	9	9/0	0.15	0.65	1.25
modeling studies	0.65	3	3/0	0.33	0.00	1.30
literature reviews/expert judgment	0.81	3	3/0	0.37	0.09	1.53
site studies	1.10	13	13/0	0.26	0.60	1.61
all studies	0.97	30	30/0	0.14	0.70	1.24
Freshwater Mineral Wetlands						
meta-analyses and other derivative statistical analyses or statistical summaries	2.20	8	8/0	0.87	0.50	3.90
meta-analyses	5.63	2	2/0	2.18	1.36	9.90
other derivative statistical analyses [d]	1.06	6	6/0	0.21	0.65	1.47
modeling studies	0.83	1	1/0	NA	NA	NA
literature reviews/expert judgment	1.22	4	4/0	0.37	0.49	1.95
site studies	1.52	15	14/1	0.42	0.69	2.36
all studies	1.65	28	27/1	0.34	0.98	2.32

[a] counterfactuals to drained cropped peatlands and mineral wetlands used to evaluate avoided emissions from avoiding the conversion of unmanaged peatlands and mineral wetlands to cropland

[b] unmanaged peatlands: 30 study results, 25 studies (2 meta-analyses, 5 statistical summaries or derivative statistical analyses, 3 modeling studies, 12 empirical site studies, 2 literature reviews); unmanaged mineral wetlands: 28 study results, 24 studies (2 meta-analyses, 6 statistical summaries or derivative statistical analyses, 1 modeling studys, 12 empirical site studies, 3 literature reviews)

[c] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[d] derivative statistical studies other than meta-analyses

b. Methane

The conditions and processes leading to CH_4 emissions from undisturbed peatlands, as well as rewetted peatlands, were discussed in Section IV, Subsection G.c.i. See Section IV, Subsection G.c.i. for that discussion.

We estimate annual per hectare CH_4 emissions from undisturbed peatlands to be 166.24 ± 33.69 kilograms per hectare (148.31 ± 30.06 lbs. CH_4 per acre per year). This is the mean estimate drawn from three formal meta-analyses of the results of published studies of CH_4 emission from undisturbed peatlands, plus an additional 15 other statistical analyses of the results of a similar body of studies.

Overall we reviewed 29 studies, including 14 empirical site studies, 3 literature reviews or studies that reported results developed on the basis of expert judgement, 3 meta-analyses and fifteen other derivative analyses. The mean rate of CH_4 emission from undisturbed peatlands in those 29 studies was 213.06 ± 30.76 kilograms per hectare (190.09 ± 27.44 lbs. CH_4 per acre per year). Across all study types, mean CH_4 emissions ranged from 99.72 to 291.75 kilograms per hectare.

The descriptive statistics for the results from the studies that we reviewed are shown in Table 98 by study type.

Table 98 also gives the descriptive statistics for the studies of CH_4 emissions from undisturbed mineral wetlands. We reviewed 24 studies of CH_4 emissions from undisturbed mineral wetlands. Of these 24 studies, eleven were empirical site studies, three were modeling studies, three were literature reviews or studies where conclusions had been developed on the basis of expert judgment, and seven were statistical analyses of results given in the scientific literature. The mean estimate from these 29 studies of CH_4 emissions from undisturbed wetlands was 624.41 ± 168.1 kilograms per hectare per year (556.82 ± 149.98 lbs. CH_4 per acre per year). For the seven statistical analyses, the mean rate of emission was 402.62 ± 55.9 kilograms of CH_4 per hectare per year.

For an estimate of emissions from undisturbed mineral wetlands, we selected the mean rate of emission from the seven statistical studies as our best estimate of CH_4 emissions from undisturbed mineral wetlands. Of the seven statistical studies, two were formal meta-analyses of the results of published studies of CH_4 emission from undisturbed peatlands. The other five were other statistical analyses of the results from undisturbed mineral wetlands from a similar body of studies.

Based on this estimate - 402.62 ± 55.9 kilograms of CH_4 per hectare per year - and our estimate of annual per hectare CH_4 emissions from undisturbed peatlands, undisturbed mineral wetlands emit annually twice the amount of CH_4 that undisturbed peatlands emit.

By study type, estimated emissions from undisturbed mineral wetlands range from 194.37 kilograms of CH_4 per hectare per year, in the case the modeling studies, to 1,160.83 kilograms per hectare per year, in the case the eleven empirical site studies. In no instance do the calculated confidence intervals shown in Table 98 straddle the zero value. Our best estimate of per hectare CH_4 emissions was chosen in deference to the statistical power of formal meta-analysis and related forms of cross-study statistical analyses.

The results given in Table 97 for undisturbed peatland and mineral wetland soils provide a compelling window into CH_4 emissions from these systems, and the state of our knowledge in this area across wetland types. Undisturbed wetlands are unambiguously large emitters of CH_4, with an emissions intensity of 100 to 600 kilograms per hectare per year (89 to 535 lbs. of CH_4 per acre per year), depending on wetland type and study type. Confidence in that conclusion is high. The availability of estimates from formal meta-analyses and related forms of cross-study statistical analyses plays no small role in this, allowing the integration of results across widely divergent conditions and geographies and, based on that integration, enabling conclusions to be drawn. In general, the role of undisturbed wetlands in the formation of CH_4 is fairly well understood.

While higher or lower estimated CH_4 flux rates are unlikely to impinge substantially on the calculation of avoided-emissions from the avoided conversion of peatland soils to agricultural use, the estimates shown in Table 98 might be usefully fine-tuned to Minnesota conditions.

Table 98. Descriptive statistics: Unmanaged peatlands and unmanaged mineral wetlands - CH_4 [a]

	emissions (kg CH_4/ hectare/yr) [b]	number of study results [c]	ratio, positive to negative results: study numbers [d]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
Peatlands						
meta-analyses and other derivative statistical analyses or statistical summaries	166.24	18	18/0	33.69	100.22	232.27
meta-analyses	99.72	3	3/0	31.90	37.20	162.24
other derivative statistical analyses [e]	179.55	15	15/0	39.35	102.42	256.68
literature reviews/expert judgment	128.61	4	4/0	38.19	53.77	203.46
site studies	291.75	15	15/0	58.00	178.08	405.43
all studies	213.06	37	37/0	30.76	152.76	273.36
Freshwater Mineral Wetlands						
meta-analyses and other derivative statistical analyses or statistical summaries	402.82	12	12/0	55.91	285.29	520.36
meta-analyses	664.50	2	2/0	96.85	474.68	854.31
other derivative statistical analyses [e]	350.49	10	10/0	50.50	251.51	449.47
literature reviews/expert judgment	194.37	4	4/0	91.53	14.98	373.77
modeling studies	241.71	4	4/0	94.60	56.31	427.12
site studies	1,160.83	11	11/0	424.91	328.03	1,993.63
all studies	624.11	31	31/0	168.10	294.64	953.58

[a] counterfactuals to drained cropped peatlands and mineral wetlands used to evaluate avoided emissions from avoiding the conversion of unmanaged peatlands and mineral wetlands to cropland

[b] negative emissions = removal from atmosphere and destruction in soils

[c] unmanaged peatlands: 37 study results, 29 studies (3 meta-analyses, 9 statistical summaries or derivative statistical analyses, 14 empirical site studies, 3 literature reviews); unmanaged mineral wetlands: 31 study results, 24 studies (2 meta-analyses, 5 statistical summaries or derivative statistical analyses, 3 modeling studies, 11 empirical site studies, 3 literature reviews)

[d] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[e] statistical analyses other than meta-analyses of study results in the published literature

Z. Avoided conversion to cropland: mineral wetlands

Drained cropped mineral wetland soils also are subject to accelerated rates of mineralization, leading to large losses of organic carbon and nitrogen to the atmosphere in the form of CO_2 and N_2O emissions. As in the case of peatlands, in an undisturbed state, mineral wetland soils are protected from extensive mineralization by waterlogged, anaerobic conditions. Respiration losses of carbon and organic nitrogen under anaerobic conditions are slow, which allows substantial amounts of organic carbon and organic nitrogen to accumulate in mineral wetland sediments. With drainage, mineral wetland soils dry and oxygen is introduced throughout the drained mineral wetland soil column, creating conditions for rapid microbial decomposition of mineral wetland soils.

In addition to CO_2 and N_2O emissions, other sources of greenhouse gases under drainage and cultivation of mineral wetlands include: N_2O emitted from soils following the exogenous input to soils of synthetic nitrogen or manure; indirect N_2O emissions from nitrate leached from cropped peatland soils; and CO_2, CH_4 and N_2O emitted during fuel use in agricultural production and during the out-of-state manufacture of fuels and agricultural chemicals used in crop production. Methane emissions decline substantially with drainage, offsetting a part of increased CO_2 and N_2O emissions.

Avoided greenhouse gas emissions from mineral wetland soils not converted to agricultural purposes are calculated as the difference between emissions from undisturbed mineral wetlands and greenhouse gas emissions from drained cropped mineral wetland soils. Avoided-emissions are shown in Table 99 for 100,000 acres of mineral wetlands not converted to cropland. From Table 99, this would come to some 209,000 CO_2-equivalent short tons of greenhouse gas-avoidance, or 2.09 CO_2-equivalent short tons per acre per year.

Table 99. Avoided conversion of mineral wetlands to cropland: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils or sediments	(66,914)	crop production
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	(2,169)	crop production
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(7,186)	crop production
CH_4	soils or sediments	338,701	crop production
CO_2 [b]	soils or sediments	(441,847)	crop production
CO_2	cultivated soils from lime or urea use	(2,808)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	(6,849)	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(20,184)	crop production
Total		**(209,256)**	

[a] positive = emissions increase, negative = emissions reduction

[b] CO_2 emissions-avoided from avoided conversion to cropland

Avoided CO_2 emissions account for about 442,000 CO2-equivalent short tons of greenhouse gas avoidance, while avoided N_2O emission account for about 67,000 CO_2-equivalent tons of avoidance. Increased annual CH_4 fluxes to the atmosphere reduce net avoidance by some 339,000 CO_2-equivalent tons.

The information from which the estimates shown in Table 99 were developed has been variously presented in different subsections of Section IV, including:

- Carbon sequestration in undisturbed mineral wetlands: Section IV, Subsection Y.a.
- N_2O emitted from undisturbed mineral wetlands: Section IV, Subsection H.a.i (Table 42)
- CH_4 emitted from undisturbed mineral wetlands: Section IV, Subsection Y.a
- CO_2 emitted from drained mineral wetlands: Section IV, Subsection H.a.ii
- N_2O emitted from drained mineral wetlands: Section IV, Subsection H.b.ii
- CH_4 emitted from drained mineral wetlands: Section IV, Subsection H.b.ii

Avoided CO_2 emissions from the avoided conversion of mineral wetlands to cropland are calculated as the difference between CO_2 emissions from drained cropped mineral wetlands and soil organic carbon sequestration in undisturbed mineral wetlands. In the case of N_2O and CH_4, avoided-emissions are calculated as the difference in what is emitted from undisturbed mineral wetlands and what is emitted from drained mineral wetland soils in agricultural use.

For a discussion of the emissions or sequestration estimates that were used to develop the information given in Table 99, the reader is referred to the subsections noted just above, which also include a listing of estimates themselves, as well, in most instances, of the descriptive statistics for the bodies of studies from which the estimates were developed. The biogeochemical processes leading to GHG emission or carbon sequestration are discussed in Section IV, Subsections G, H, and Y. For the methods and sources used to estimate avoided indirect N_2O emissions from nitrate leaching and ammonia volatilization, as well as a discussion of avoided-emissions from fuel use, and a discussion of avoided-emissions from foregone agricultural chemicals and fuels manufacture, the reader is referred to the Methodology section (Section II, Subsection E) of this report .

AA. Avoided conversion to cropland: upland grasslands

Once converted to cultivation, former cropland that had been set aside for conservation purposes, for the instance in the Conservation Reserve Program (CRP), emits large amounts of CO_2 and N_2O to the atmosphere. The same is true for native prairie converted to cropland. This results principally from, in the case of CO_2, the disruption to soils from tillage. Accelerated emission of N_2O results from the input to soils of large amounts of synthetic nitrogen as plant nutrients, as well as tillage-induced soil organic nitrogen mineralization.

The conversion of undisturbed upland grassland to pasture acts similarly to promote the production in soils of greenhouse gases and their subsequent emission to the atmosphere, albeit at a lower rate.

In this subsection, we treat avoided-emissions from idled upland grassland or native prairie not converted to grassland. Avoided-emissions are emissions that would have occurred with the conversion of unmanaged upland grassland to cropland or pasture, but that, through the effect of set-asides, easements and similar programmatic mechanisms, are otherwise averted. Between 2007 and 2018, about 760,000 acres of upland unmanaged grassland was removed from the federal CRP program, presumably for purposes of cultivation or for pasture.

We limit the analysis of emissions-avoidance from the avoided upland conversation to upland grassland not converted to cropland. The results of the analysis are shown in Table 100. We estimate that, for each 100,000 acres of unmanaged upland grassland not converted to cropland, 378,000 CO_2-equivalent short tons of greenhouse gas emissions would be avoided annually, or at a per acre rate of 3.78 CO_2-equivalent short tons per acre per year. Of this annual avoidance, a little more than three-quarters results from avoided soil carbon loss in the form of avoided emitted CO_2, and a little more than 10 percent from the avoided emission of N_2O. Most emissions-avoidance from this practice, about 95 percent, occurs in-state.

Below we discuss the range of studies used to develop the estimates for avoided soil carbon loss and avoided N_2O emission. Section II, Subsection E contains a discussion of the methods and sources used to develop the estimated avoided indirect N_2O emissions from nitrate leaching and ammonia volatilization and land deposition, as well as a discussion of estimated avoided fuel use emissions, and a further discussion of estimated avoided-emissions from foregone agricultural chemical and fuels manufacture.

Table 100. Avoided conversion of retired or natural grassland: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(42,756)	crop production
N_2O-indirect volatilization	indirect emission-ammonia (NH_3) volatilization, redeposition	(2,107)	crop production
N_2O-indirect leaching	indirect emission-nitrogen leaching or runoff	(11,703)	crop production
CH_4 [b]	soils	520	crop production
CO_2 [c]	soils or sediments	(291,974)	crop production
CO_2	cultivated soils from lime or urea use	(2,808)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	(6,849)	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(20,184)	crop production
Total		**(377,861)**	

[a] positive = emissions increase, negative = emissions reduction

[b] reduction in soil CH_4 oxidation = relative increase in emissions

[c] CO_2 emissions-avoided from avoided conversion to cropland

a. Carbon sequestration in soils and biomass

The biogeochemical processes that are involved in the loss of soil organic carbon during the cultivation of cropland were discussed above in Section IV, Subsections A.a and J.a. This discussion will not be repeated. Suffice it here to note that, in undisturbed grassland soils, soil organic carbon is protected from microbial decomposition in soil pores of soil macroaggregates that, due to their small size, are inaccessible bacteria and fungi (or water soluble enzymes). (Jones and Donnelly, 2004) Soil carbon is also chemically protected by clay and silt particles, which bind to soil organic matter and, in the long-term, by various metals and anions and cations that biochemically bind to organic to form organomineral complexes. (Six et al., 2002a) Once adsorbed on to mineral surfaces, organic matter is highly recalcitrant and remains resident in the soil profile for hundreds to thousands of years. Tillage acts to break up protective soil macroaggregates, exposing soil to microbial decomposition.

It is estimated that, with cultivation, native grassland loses between 20 and 60 percent of its initial organic carbon content, over periods as short as 20 years. (Guo and Gifford, 2002; Mann, 1986; Poeplau et al., 2011; Post and Kwan, 2000)

Avoided-emissions are emissions that would have occurred with the conversion of unmanaged upland grassland to cropland or pasture, but that, through the effect of set-asides, easements and similar programmatic mechanisms, are avoided.

In Table 10, we estimate that, on 100,000 acres, the avoided conversion of upland grasslands to cropland would result in an avoided emission of 292,000 short tons of CO_2 to the atmosphere. This estimate was developed from ten studies of the change in total ecosystem carbon resulting from the conversion of grasslands to cropland. Total ecosystem carbon accounting is probably the best approach for approximating rates of either organic carbon loss or carbon sequestration in natural and managed ecosystems with large amounts of carbon stored belowground in live and dead biomass, as in the case of upland grasslands. Total ecosystem gain or loss of carbon is estimated as the difference between gross primary productivity and ecosystem respiration, adjusting for, in unmanaged natural systems, the export of organic carbon in the form of DOC (dissolved organic carbon) or methane, and in the case of cropland, additionally the import of manure and harvest removals.

In total ecosystem carbon (TEC) studies that were reviewed, the mean value for annual carbon loss resulting from grassland conversion to cropland was an estimated 1.79 ± 0.44 metric tons of carbon per hectare (0.80 ± 0.20 short tons of carbon per acre). Ten TEC studies were reviewed. Of these, five were eddy-covariance-based, while an additional four were modeling studies and one was a literature review (see Table 101). Of these, the eddy covariance-type site studies reported a mean emission of 2.54 metric tons of carbon per hectare (1.13 short tons of carbon per acre), while a mean emission of 0.5 metric tons of carbon per hectare per year was reported in the modeling studies.

Overall, we reviewed 35 studies. Most of these studies (24 studies) reported on changes solely in soil organic carbon, omitting changes in belowground biomass carbon, and, as such, were of lower utility. In these studies, a mean rate of loss of 1.19 metric tons of carbon per hectare per year (0.53 short tons per acre per year) was reported.

By study type, five meta-analyses and one other derivative statistical summaries or analyses were reviewed, as were the seven soil sampling-type site studies, eleven modeling studies, the five eddy-covariance studies noted above, and eight literature reviews or studies that report results developed on basis of expert judgment. The meta-analyses were mostly limited to soil sampling-type studies of soil carbon change with grassland conversion to cropland. By study type, estimated rates of per hectare CO_2 emission with grassland conversion to cropland ranged from 0.64 to 2.1 metric tons of carbon per hectare per year (0.29 to 0.94 short tons of carbon per acre per year). Within our 20-year window for evaluating the effects of carbon sequestration, sequestration was more rapid in younger grassland restorations (0 to 14 years old), but not substantially.

The descriptive statistics for the studies by study type, by soil sampling depth, and by age of grassland restoration are shown in Table 101. As elsewhere in this report, the estimates given in Table 101 are reported in metric units, and then converted to English units for use in Table 100.

Overall, the weight of evidence supports per hectare CO_2-emissions avoidance of 0.9 to 2.1 metric tons of carbon per year, with a best estimate near 1.8 metric tons per hectare per year. There is little support in the scientific literature for an estimate well below this.

Table 101. Descriptive statistics: Avoided grassland conversion to cropland - carbon sequestration in soils and biomass

	biogenic carbon sequestration (Mg C/ha/yr)	number of study results [a]	ratio of sequestration to emission: number of studies [b]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
total ecosystem carbon	1.79	11	11/0	0.44	0.92	2.65
soil organic carbon-only [c]	1.16	24	24/0	0.21	0.74	1.57
meta-analyses and other derivative statistical analyses or statistical summaries [d]	0.91	6	6/0	0.26	0.41	1.42
all studies	1.36	37	37/0	0.19	0.98	1.73
empirical site studies	1.87	11	11/0	0.41	1.07	2.67
modeling studies	0.64	11	11/0	0.23	0.20	1.08
literature reviews/expert judgment	2.10	8	8/0	0.39	1.33	2.87
CRP sites-only	1.14	8	8/0	0.38	0.40	1.88
1 to 9 year average emission-avoided rate	1.42	7	7/0	0.43	0.57	2.27
10 to 30 year average emission-avoided rate	1.27	22	22/0	0.27	0.75	1.80

[a] 37 study results, 35 studies (5 meta-analyses, 1 statistical summaries or derivative statistical analyses, 11 modeling studies, 11 empirical site studies, 6 literature reviews, 1 other)

[b] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

[c] results for lowest reported sampling depth

[d] statistical summaries or analyses other than meta-analyses

b. Nitrous oxide

In Section IV, Subsection D, we estimate that, by converting 100,000 acres of cropland to grassland, we would avoid 42,756 CO_2-equivalent short tons of N_2O emissions. This was calculated as the difference, on 100,000 acres, in emissions from restored upland grasslands and average Minnesota cropland emissions (see Section IV, Subsection A.b). Avoided-emissions of N_2O from the avoided conversion of grasslands to cropland are assumed to be the same as avoided-emissions resulting from the conversion of cropland to unmanaged grassland, or 42,756 CO_2-equivalent short tons. Using this value, N_2O emissions from preserved upland grasslands would be about one-third of average emissions from cropland.

N_2O is produced in soils as a byproduct of nitrification of ammonium to nitrate and as a terminal co-product of nitrate denitrification. Soil N_2O production in cultivated soils is proportional to excess soil NH_4^+ and NO_3^-, other environmental conditions being equal. The presence of NH_4^+ and NO_3^- in cultivated soil is sustained by large anthropogenic inputs of mineral and organic nitrogen in the form of synthetic fertilizer, manure and crop residues.

Relatively few direct measurements exist of the change in N_2O emissions resulting from the conversion of upland grasslands to cropland. Table 102 gives descriptive statistics for avoided-emissions from avoided grassland conversion to cropland, as derived from those studies that were we able to identify. Six studies were identified, one modeling study and five empirical sites studies. Across all studies, avoided-emissions equal about 70 percent of N_2O emissions from cropland that would otherwise have occurred under grassland conversion to cropland, or a value quite near to what we assume in developing the Table 100 calculation.

The numbers of studies shown in Table 102 are obviously insufficient, but do provide some comfort that the estimate given in Table 100 estimate is reasonable. More work is needed here.

Table 102. Descriptive statistics: Avoided grassland conversion to cropland - N_2O

	emissions: % change in emissions per hectare	number of study results[a,b]	ratio of positive-to-negative results: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	-72%	8	1/7	13%	-97%	-46%
site studies	-86%	6	0/6	4%	-94%	-79%
modeling studies	-28%	2	1/1	44%	-114%	59%

[a] 8 study results, 6 studies (1 modeling study, 5 empirical site studies)

[b] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

AB. Conclusion

In this report, we review the greenhouse gas emission reduction potential of 27 agricultural best management practices designed to slow rates of soil erosion and reduce the movement of nutrients from cropland to groundwater and surface water and sediments from cropland to surface water. Our intent is to determine the effectiveness, if any, of the GHG reduction co-benefits of these 27 practices.

We used a conventional lifecycle framework for estimating the emissions-avoidance potential of the 27 practices evaluated here. Emissions-avoidance was estimated for all direct cropland sources of GHGs, as well as indirect cropland sources, emissions from fuel use in cropland farm equipment, and emissions from the manufacture of fertilizers, other agricultural chemicals and fuels used in crop production. Total avoided-emissions are the sum of avoided-emissions from all sources. These were calculated in carbon dioxide-equivalent (CO_2-equivalent) short tons per 100,000 acres per year. Given some specific practice, they represent the estimated annual emissions-avoidance in the present that result from the implementation of that practice.

The 27 practices fall into four broad groups: practices that involve cropland idling or related conservation uses of cropland; tillage and cropping change practices; nutrient management practices; and practices the involve the avoidance of certain conversions of land in a natural conditions to agricultural uses. The results for the 27 practices are shown in Table 103, organized under these four headings.

For practices that involve cropland idling or related conservation uses of cropland, calculated greenhouse gas-avoidance on 100,000 acres ranges from 77,000 to 1.54 million CO_2-equivalent short tons per year. The retirement and rewetting of cropped drained peatland results in the largest reductions, at an annual rate of 15.4 CO_2-equivalent short tons per acre. For tillage and cropping best practices, calculated greenhouse gas-avoidance on 100,000 acres ranges from 7,000 to 157,000 CO_2-equivalent short tons per year. For these practices, annual emissions-avoidance is an estimated 0.07 to 1.57 CO_2-equivalent short tons per acre. One cropping practice, the conversion of continuous corn to corn-soybean rotation, results in increased greenhouse gases.

Table 103. Estimated annual greenhouse gas avoidance from agricultural practices (CO_2-equivalent short tons per 100,000 acres per year)

Cropland Idling or Related Conservation Land-Uses	tons per 100,000 acres per year [a,b,c]	Tillage and Cropping Changes	tons per 100,000 acres per year [a,b,c]
Retired/rewet peatlands	(1,478,636)	Short rotation woody crops	(157,447)
Shelterbelts/hedges	(298,377)	Cropland to hayland conversion	(120,897)
Cropland idling in trees	(255,863)	Crop rotation with perennial forages	(41,392)
Retired/rewet mineral wetlands	(221,637)	Cover crops	(26,712)
Forested riparian buffers	(220,528)	No-till, reduced tillage counterfactual	(20,259)
Cropland idling in grass	(159,184)	Crop residue return	(17,171)
Field borders and related	(157,810)	No-till	(14,291)
Riparian grass buffers	(76,872)	Reduced tillage	(7,019)
		Corn and soybean in rotation replacing continuous corn	34,883
Avoided Loss and Other	**tons per 100,000 acres per year [a,b,c]**	**Nutrient Management Practices**	**tons per 100,000 acres per year [a,b,c]**
Avoided peatland conversion	(1,529,415)	Nitrification inhibitors	(30,097)
Avoided upland grassland conversion	(377,861)	Urease inhibitors	(18,368)
Avoided mineral wetlands conversion	(209,256)	Controlled release fertilizers	(17,722)
		Split fertilizer application	(11,296)
Biochar soil amendments (annualized)[e]	(127,582)	15% fertilizer reduction	(5,205)
		Subsurface N fertilizer application	27,746

[a] negative = emissions-avoided; positive = emissions increase

For nutrient best management practices, GHG-avoidance is an estimated 6,000 to 30,000 CO_2-equivalent short tons per acre. One best practice–subsurface nitrogen fertilizer placement–results in increased emissions. Finally, based on the analysis presented in this report, the avoided conversion of undisturbed peatland soils, mineral wetland soils or upland grassland to agricultural uses would result in emissions-avoidance of 209,000 to 1.53 million CO_2-equivalent short tons per year.

In general, agricultural practices, if well designed, can reduce GHG emissions to the atmosphere. Leaving aside retired/rewet peatlands, the average rate of avoidance for the seven practices that involve cropland idling or conversion of cropland to a supporting role in the form of buffers and related land-uses, is an estimated 1.99 CO_2equivalent tons per acre. If implemented in Minnesota on half a million acres, these practices could result in the avoidance of about 995,000 CO_2-equivalent short tons of GHG emissions annually. For retired/rewet formerly drained, cropped peatlands, average GHG-avoidance is an estimated 14.8 CO_2-equivalent short tons per acre of restoration. At an estimated 400,000 acres of drained peatlands currently in cultivation in Minnesota, 90 percent restoration would result in the avoidance of 5.9 million CO_2-equivalent short tons annually. For cropping and tillage practices, the average rate of avoidance is about 0.5 CO_2-equivalent short tons per acre. If implemented on 10 million acres, these practices would result in the avoidance of about 5 million CO_2-equivalent short tons of GHGs per year. These totals seem generally indicative of at least a modest potential for GHG-avoidance from improved cropland practices, on the order of 7 million CO_2-equivalent short tons annually, or about 25 percent of estimated 2016).

A wide array of agricultural and land-use practices have been proposed for GHG mitigation beyond the 27 that we considered here. Based on our extensive review of the literature, in most instances the scientific literature probably could not today support the development of an estimate of emissions-avoidance. Due to the inherent noisiness of the data that is customarily encountered in the development of avoidance factors, very large data sets are required, spanning a wide range of environmental conditions and practice designs. With the exception of the practices considered in this study, plus a scattered few others, conditions cannot met.

In Table 104, we list the practices for which, in our judgment, the science will now not support the development of a quantitative emissions-avoided estimate. At least five year accumulation of research findings will be necessary before a quantitative estimate of emissions-avoidance might be developed using the literature-mining approach taken in this study.

Finally, we are more sanguine about practices like integrated crop-livestock production and biofuels development, for both of which a surfeit of information is available. Practices for which the science may now support the development of a quantitative GHG emissions-avoided estimate are listed in Table 105.

Table 104. Agricultural practices for which the scientific literature now will not support a quantitative emissions-avoided estimate

Practice	NRCS Conservation Practice Standard	Principal GHG Potentially Impacted
Diversifying crop rotations	NR	N_2O, CO_2 (carbon sequestration)
Double cropping with perennials	NR	N_2O, CO_2 (carbon sequestration)
Grassed waterways/terraces	412, 600	N_2O, CO_2 (carbon sequestration)
Organic crop production	NR	N_2O, CO_2 (carbon sequestration)
Perennial grains	NR	N_2O, CO_2 (carbon sequestration)
Sediment control basins	350	uncertain
Silvoculture	NR	N_2O, CO_2 (carbon sequestration)
Two-stage ditches	582	N_2O, CH_4
Improved pastures	NR	CO_2 (carbon sequestration)
Rotational grazing	528	N_2O, CO_2 (carbon sequestration)
Silvopasture	381	N_2O, CO_2 (carbon sequestration)
Alternative forms of nitrogen fertilizer	NR	N_2O
Controlled drainage	554	N_2O
Denitrifying bioreactor	605	N_2O
Precision agriculture	NR	N_2O
Substitution of manure for synthetic fertilizer	NR	N_2O, CO_2 (carbon sequestration)
Combined practices: cover crop and no till	NR	N_2O, CO_2 (carbon sequestration)
Combined practices: no-till and deep fertilizer placement	NR	N_2O, CO_2 (carbon sequestration)
15% synthetic nitrogen fertilizer reduction, deep fertilizer placement, split fertilizer application	NR	N_2O, CO_2 (carbon sequestration)

Table 105. Additional Agricultural Practices that Involve Cross-Sector and Cross-Subsector Calculations for Which the Scientific Literature May Support an Emissions-Avoided Estimate

Practice	Principal GHGs Potentially Impacted
Biofuels production and fuel substitution	N_2O, CO_2 (carbon sequestration, fuel-use emissions)
Conversion of cropland to pastureland	N_2O, CH_4, CO_2 (carbon sequestration)
Replacement of crop-fallow rotation with continuous cropping	N_2O, CO_2 (carbon sequestration)
More intensively integrated livestock/cropping systems	N_2O, CH_4, CO_2 (carbon sequestration)
Existing analysis redone on a crop yield-basis (as opposed to an area-wide basis)	all GHGs

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See ‘Crop residue retention/residue removal-SOC/CO_2’ above

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See 'Retired/rewet peatlands-drained peatland counterfactual-CH_4' above

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