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Greenhouse gas reduction potential of agricultural best management practices

This technical report provides a description of the methodologies used to estimate greenhouse gas emissions reduction potential from 21 practices related to changing land use, cropping practices, and nutrient reduction.
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Executive summary

Agriculture and climate change in Minnesota

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?

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 21 agricultural best management practices. 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 5-10%.

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 0.20 tons/acre.
Biochar

Biochar is charcoal produced from crop residues. When placed in soil, it can improve soil fertility and reduce greenhouse gas emissions by 1.23 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.

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Agricultural best Practices: Terms to know

**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 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 wetlands* are drained 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.

**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.

**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 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.

**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.

**Spring fertilizer application**: application of nitrogen fertilizer in early or later spring, in lieu of fall applications. To make use of available free time in the fall, some crop producers apply fertilizer in the fall months in advance of the next cropping season.

**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.
A. 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.²

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 13 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. A further eight practices are reviewed for their effectiveness in mitigating GHGs on a preliminary basis. Our intent in either instance is to determine the effectiveness, if any, of the GHG reduction co-benefits of these 21 practices.

We used a conventional lifecycle framework for estimating the emissions-avoidance potential of the 21 practices evaluated here, on a final or preliminary basis. 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 (CO₂-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. 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).³

Greenhouse gases emitted to the atmosphere during crop production include nitrous oxide (N₂O) and carbon dioxide (CO₂). N₂O is produced in fertilized and tilled cropland rich in ammonium (NH₄⁺), nitrate (NO₃⁻), 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. N₂O can be produced in

³ 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 CO₂ 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.(Poepplau et al., 2011) Less is known about soil emissions of N₂O and CH₄ (or soil CH₄ oxidation), besides some initial indications that, with time, cropped soils under no-tillage practice may become progressively lower emitters of N₂O.(Six et al., 2004)
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.

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. Practices for which we provide only preliminary results are listed at the bottom. 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, the analysis was completed on six. Preliminary results are available for constructed and restored wetlands. These are shown in Table A.1 in Appendix A.

Six of the practices that were reviewed involve tillage and cropping change. Under these practices, cropland remains in production.

Nutrient reduction practices for which only preliminary results are available comprise the last category of practices. While not strictly speaking a nutrient reduction practice, biochar does generally act to improve nutrient use efficiency, in addition to enhancing other soil qualities.

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.
In developing these estimates, most attention was paid to emissions-avoided from soils, either in terms of avoided (or increased) emissions of N\textsubscript{2}O or CH\textsubscript{4} or biogenic carbon sequestration. Emissions from fuel use in crop production are small, as are emissions in the form of CO\textsubscript{2} from the use of urea fertilizer or crushed limestone. The same is true for indirect N\textsubscript{2}O emissions from leached nitrate or NH\textsubscript{3} volatilization and downwind deposition.

Table 1. Agricultural practices examined in this study

<table>
<thead>
<tr>
<th>Practice</th>
<th>NRCS Conservation Practice Standard</th>
<th>Principal GHG Impacted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Practices that Involve Land-Use Change from Cropland to Cropland-Supporting Role or Long-term Idling *</td>
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<tr>
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<tr>
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<tr>
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<td>N\textsubscript{2}O, CO\textsubscript{2} (carbon sequestration)</td>
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<tr>
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<td>N\textsubscript{2}O</td>
</tr>
<tr>
<td>Nitrification and Urease Inhibitors</td>
<td>590</td>
<td>N\textsubscript{2}O</td>
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<tr>
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<td>Subsurface Fertilizer Placement</td>
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<tr>
<td>Spring Fertilizer Application</td>
<td>590</td>
<td>N\textsubscript{2}O</td>
</tr>
<tr>
<td>Biochar</td>
<td>NA</td>
<td>N\textsubscript{2}O, CO\textsubscript{2} (carbon sequestration)</td>
</tr>
</tbody>
</table>

* Often also result in reduced nutrient run-off and leaching to surface and groundwater.

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 1,248 published scientific studies. In addition, for practices for which we provide only preliminary results, we compiled a database from an additional 525 studies. Using the results of these 1,773 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. We accompanied each budget with an extended discussion of the physical, biological and biochemical processes that underlie estimated emissions or emissions-avoidance. 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.

The results of the analysis are shown in Table 2 in abbreviated form. Of practices for which we have results, all but one of these 13 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 2.7 CO₂-equivalent short tons per acre of practice. Of practices involving tillage and cropping change, six of seven 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.

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?

Of practices for which we have only preliminary results, three practices – constructed and restored wetlands, subsurface nitrogen fertilizer placement and spring nitrogen fertilizer application – result in increased emissions, although the results are preliminary and may change with further analysis. According to the analysis, GHG emissions are avoided in five of the practices for which we have preliminary results.

Preliminary results should be treated with caution, as they may change as the analysis is better developed. For the practices for which we have only preliminary results, there exists a dearth of research, excepting the results for nitrification and urease inhibitors and controlled release fertilizers. For some of these practices, other researchers may have come to conclusions different from ours based on different choices in how the problem is set-up and in data.
Table 2. Estimated annual greenhouse gas-avoidance from agricultural practices (CO₂-equivalent short tons per 100,000 acres per year)

<table>
<thead>
<tr>
<th>Cropland Idling or Related Conservation Land-Uses</th>
<th>Tons per 100,000 acres per year a,b,c</th>
<th>Tillage and Cropping Changes</th>
<th>Tons per 100,000 acres per year a,b,c</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Final Results</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shelterbelts/hedges</td>
<td>269,000</td>
<td>Cropland to hayland</td>
<td>121,000</td>
</tr>
<tr>
<td>Cropland idling in trees</td>
<td>263,000</td>
<td>Crop rotation with perennial forages</td>
<td>50,000</td>
</tr>
<tr>
<td>Forested riparian buffers</td>
<td>203,000</td>
<td>No-till, reduced tillage</td>
<td></td>
</tr>
<tr>
<td>Cropland idling in grass</td>
<td>162,000</td>
<td><strong>counterfactual d</strong></td>
<td>23,000</td>
</tr>
<tr>
<td>Field borders and related</td>
<td>161,000</td>
<td>Cover crops</td>
<td>20,000</td>
</tr>
<tr>
<td>Riparian grass buffers</td>
<td>77,000</td>
<td>Reduced tillage</td>
<td>15,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No-till</td>
<td>14,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Continuous corn to corn-soybean rotation</td>
<td>40,000</td>
</tr>
<tr>
<td><strong>Preliminary Results-Only</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cropland Idling or Related Conservation Land-Uses</td>
<td>Tons per 100,000 acres per year a,b,c</td>
<td>Nutrient Reduction Practices</td>
<td>Tons per 100,000 acres per year a,b</td>
</tr>
<tr>
<td>Constructed/restored wetlands</td>
<td>66,000</td>
<td>Biochar</td>
<td>120,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Controlled release fertilizers</td>
<td>27,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nitrification inhibitors</td>
<td>24,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Split fertilizer application</td>
<td>13,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15% fertilizer reduction</td>
<td>6,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spring N fertilizer application</td>
<td>2,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Subsurface N fertilizer application</td>
<td>31,000</td>
</tr>
</tbody>
</table>

a negative = emissions-avoided; positive = emissions increase


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

The estimates given in Table 2, in Section II below (Tables 7 and 8) 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 CO₂-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 CO₂-equivalent short tons per acre. (Eagle et al., 2012; Gelford and Robertson, 2015; Robertson et al., 2000; Swan et al., 2015) For cropland idling and related conservation land-use change, the annual avoidance estimates reported in this study range from 0.77 to 2.69 CO₂-equivalent short tons per acre, while those for tillage and
cropping practices range from 0.14 to 1.21 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 10, 32, 37, 49 and 56).

In general, agricultural practices, if well designed, can reduce GHG emissions to the atmosphere. The average rate of avoidance for the six practices that involve cropland idling or conversion of cropland to a supporting role in the form of buffers and related land-uses, and for which we have results, is 1.7 CO$_2$-equivalent tons per acre. If implemented in Minnesota on half a million acres, these practices would result in the avoidance of about 850,000 CO$_2$-equivalent short tons of GHG emissions. For cropping and tillage practices, again for which we have results, the average rate of avoidance is 0.3 CO$_2$-equivalent short tons per acre. If implemented on 10 million acres, these practices would result in the avoidance of about 3 million CO$_2$-equivalent short tons of GHGs per year or about 10 percent of the estimated 2016 emissions from Minnesota crop agriculture (26.9 CO$_2$-equivalent million short tons). These totals seem generally indicative of at least a modest potential for GHG avoidance from improved cropland practices.

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$_2$O 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$_2$-equivalent 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.

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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).

avoidance as a result of specific downstream uses of field commodities, for instance, in livestock operations or biofuels production.

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 6 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, emissions-avoidance is evaluated against a cropland counterfactual; emissions under changed practice less emissions from cropland under average current conditions gives the level of emissions-avoidance for each practice. Due to a scarcity of published research, it was not possible to evaluate emissions-avoidance against a pastureland or grassland counterfactual, particularly with respect to changes in soil carbon. The restoration of degraded grassland was not evaluated as one of our 21 options, but, in future versions of this report, it may be addressed, along with other improved livestock grazing practices.

The estimates of emissions-avoidance account for net changes in emissions that result from soil carbon sequestration. During photosynthesis, CO₂ is removed from the atmosphere and incorporated into plant biomass and, potentially, through roots and crop residue inputs to soil, to soil organic carbon. This results in a net drawdown of atmospheric CO₂ levels, which, as with most other researchers, we treat as a negative emission.

CH₄ is treated similarly. Atmospheric methane is oxidized in cropland soils, removing it from the atmosphere. An increase in CH₄ oxidation from a change in agricultural practice results in a drawdown of atmospheric CH₄ 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 CO₂. 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, the 2007 weightings were superseded by a updated version in the IPCC Fifth Scientific Assessment. (IPCC, 2013)

In converting nominal units of sequestered soil carbon (or rates of sequestration) to CO₂-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

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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.
the 0.4 global warming potential value derives from an estimate of CO₂ retention in the atmosphere for emitted CO₂ from fossil fuel combustion. Once emitted to the atmosphere, a unit of mass of CO₂, 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 CO₂ 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 CO₂ 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.\footnote{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 CO₂ if placed back into intensive cultivation. (Gelfand et al., 2011) Based 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.}

Regarding the larger lifecycle approach using GWP-weightings, this is a longstanding approach in the scientific literature stretching back to 2000. (Adventio-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 13 agricultural and land-use practices for which we have final results. Of these, the sources with the greatest influence on estimated GHG-avoidance, across all evaluated practices are: soil carbon sequestration, soil N₂O emissions, and soil CH₄ 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.
Table 3. Sources of emissions-avoidance or increase for agricultural practices

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Emission Source or Sink</th>
<th>Dominant Term in Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>carbon accumulation in soils and biomass</td>
<td>all practices but one evaluated</td>
</tr>
<tr>
<td>N₂O</td>
<td>soils</td>
<td>9 out of 13 practices evaluated</td>
</tr>
<tr>
<td>CH₄</td>
<td>soils</td>
<td>grassland and forested riparian buffers</td>
</tr>
<tr>
<td>N₂O-indirect</td>
<td>indirect emissions-surface waters from leached soil nitrate</td>
<td>cover crops</td>
</tr>
<tr>
<td>leaching</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N₂O indirect</td>
<td>indirect emission-downwind soils from nitrogen volatilization/ redeposition</td>
<td>none</td>
</tr>
<tr>
<td>volatilization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>lime and urea use (soils)</td>
<td>none</td>
</tr>
<tr>
<td>CO₂, N₂O, CH₄</td>
<td>fossil fuel and electricity use in crop production</td>
<td></td>
</tr>
<tr>
<td>CO₂, CH₄</td>
<td>upstream agricultural chemicals and fossil fuel production</td>
<td>grass riparian buffers, perennials added to rotation, continuous corn to corn-soybean rotation</td>
</tr>
</tbody>
</table>

The remainder of emissions and emissions-avoidance--from indirect N₂O 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.

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 CO₂ 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. 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-analysis 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 below ground 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\textsubscript{2}O and CH\textsubscript{4} response rates

N\textsubscript{2}O and CH\textsubscript{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, 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\textsubscript{2}O, drawn from the MPCA Greenhouse Gas Emission Inventory, and, for CH\textsubscript{4}, from Aronson and Helliker (2010) for average temperate cropland soils.

Most emission estimates for N\textsubscript{2}O 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\textsubscript{4} is produced in and emitted from wet soils in which anaerobic conditions predominate, while, in well-drained upland soils, CH\textsubscript{4} generally is oxidized. CH\textsubscript{4} fluxes can be expressed in terms of emissions or oxidation. As in the case of N\textsubscript{2}O, most estimates of CH\textsubscript{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\textsubscript{2}O and CH\textsubscript{4} are the product of average cropland net annual flux rates and the estimated percentage change in that annual flux under the new practice. Practices that involve a change in cropping tillage practice include: use of cover crops, conversion from conventional tillage to no-till and reduced tillage, 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.

To calculate response rates, for the cropland counterfactual we use flux or emission rates from, for N\textsubscript{2}O, the MPCA Greenhouse Gas Emission Inventory, and, for CH\textsubscript{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\textsubscript{2}O and CH\textsubscript{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 13 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. Preliminary information on the GHG effects of an additional eight practices is included in the appendices.

To support this analysis, we have assembled a database of the results of 1,248 studies for the 13 practices reviewed thus far. An additional 525 studies have been reviewed to support the analyses that appear, in preliminary form in the appendices, bringing the total number of studies included in the database to 1,773. While not exhaustive, the database accounts for a large 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 flood field rice paddy agricultural also are excluded as involving fundamentally different soil conditions than found in upland croplands, as is crop production on highly organic soils.

To estimate changes in soil carbon sequestration, CH₄, or N₂O 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 at least 10 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.

To simplify the data housed in the database, wherever possible within studies we average results across environmental and management conditions. For the 13 studies discussed below, we commonly 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.

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.)

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.

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 30, exist for GHG-avoidance across the 21 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 N₂O and CH₄ emissions-avoidance and CO₂-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$_2$O emissions, emissions from fuel use and upstream manufacturing emissions

Finally, in most instances, the contribution of indirect N$_2$O 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$_2$O 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. The reduction rates are, in the case of nitrate loading, taken from MPCA, Minnesota Nutrient Reduction Strategy (MPCA, 2014), and, for NH$_3$, from Pan et al. (2016). In some instances, response rates for these sources are calculated as the difference in average N$_2$O 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).

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.

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>
<thead>
<tr>
<th>GHG</th>
<th>Calculative Approach to Emissions-avoidance</th>
<th>Base emission level</th>
</tr>
</thead>
</table>
| N₂O-Indirect, nitrate leaching, NH₃ redeposition | % reduction in NO₃- runoff to surface waters \(^a\), \(^b\); \% reduction in NH₃ volatilization and redeposition \(^a\), \(^c\)  
(N₂O-leaching under changed land-use) – (average N₂O-leaching rate from cropland) \(^d\);  
(N₂O-NH₃ deposition under changed land-use) – (average N₂O-NH₃ deposition to cropland) \(^g\)  
Data sources for reduction potential: nitrate leaching -- MPCA (2014),\(^6\) MPCA GHG emission inventory (MPCA GHG EI) \(^5\); NH₃ redeposition—Pan et al., (2015); Bouwman et al. (1997); MPCA GHG EI | Minnesota N₂O emissions from NO₃-leaching and from NH₃ deposition to cropland, 2012-2015 average \(^9\)  
Data source: MPCA GHG emission inventory                                                                 |
| CO₂-urea use, liming          | urea: (no urea use, idled cropland) – (CO₂ from urea use on cropland) \(^b\); liming: (CO₂ from crushed limestone applications to alfalfa) – (CO₂ from crushed limestone applications to average MN cropland) \(^1\)  
Data source for reduction potential: Russelle (1997)                                                      | Minnesota N₂O and CO₂ 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 N₂O from surface waters and NH₃ volatilization and downwind redeposition is the same as the estimated percentage reduction in NO₃ runoff and volatilization, respectively, after IPCC (2006) methodology  
\(^b\) cover crops, no-till, reduced tillage, riparian buffers, shelterbelts/hedges, afforestation on idled cropland  
\(^c\) no till, reduced tillage  
\(^d\) field borders, grassland restoration, cropland conversion to hayland, expanded rotations with perennials  
\(^g\) grassland restoration, afforestation on idled upland cropland, shelterbelts/hedges, field borders/vegetative barriers, riparian buffers  
\(^1\) cropland to hayland conversion, extended rotations with perennials  
\(^9\) 0.75 percent of leached nitrogen is assumed to be emitted to the atmosphere as N₂O, 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 N₂O, again after IPCC (2006)
Table 5. Fuel use changes by agricultural or land-use practice

<table>
<thead>
<tr>
<th>Practice</th>
<th>Equations Giving the Basis for the Calculated Change in Emissions from Fuel Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>No-till, Reduced tillage</td>
<td>(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</td>
</tr>
<tr>
<td>No-till with Reduced Tillage Counterfactual</td>
<td>(weighted fuel intensity per acre, no-till) – (weighted fuel intensity per acre, conventional till) for corn, soybeans, corn silage, wheat and alfalfa</td>
</tr>
<tr>
<td>Cover Crops</td>
<td>add 1 seed drill operation, 1 roller packer operation</td>
</tr>
<tr>
<td>Cropland to Hayland Conversion</td>
<td>(weighted fuel use intensity per acre, alfalfa) – (weighted fuel use intensity, all Minnesota cropland)</td>
</tr>
<tr>
<td>Extended Rotations with Alfalfa or Other Hay or Grass</td>
<td>(weighted fuel use intensity per acre, corn-corn-alfalfa-alfalfa rotation) – (weighted fuel use intensity, all Minnesota cropland)</td>
</tr>
<tr>
<td>Continuous Corn to Corn-Soybean Rotation</td>
<td>(weighted fuel use intensity per acre, continuous corn) – (weighted fuel use intensity, corn-soybean rotation)</td>
</tr>
<tr>
<td>All Other</td>
<td>(no fuel use) - (weighted fuel use intensity, all Minnesota cropland)</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Practice</th>
<th>Equation Giving the Basis for the Calculated Change in Emissions from Avoided Manufacture of Agricultural Chemicals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover Crops</td>
<td>– (Nitrogen credit for cover crops) – (–15% reduction, herbicide use) + (energy input to cover crop seed production)</td>
</tr>
<tr>
<td>Cropland to Hayland Conversion</td>
<td>(P,K and lime applications to alfalfa) – (N, P, K, lime, herbicide, insecticide applications to cropland)</td>
</tr>
<tr>
<td>Extended Rotations with Alfalfa or Other Hay or Grass</td>
<td>(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 year after alfalfa</td>
</tr>
<tr>
<td>Continuous corn to corn-soybean rotation</td>
<td>no N applications to soybean phase of corn-soybean rotation, plus N credit 35 lbs. N/acre credit to corn after soybeans</td>
</tr>
<tr>
<td>All Other</td>
<td>(no fertilizer or chemical use) - (N, P, K, lime, herbicide, insecticide applications to cropland)</td>
</tr>
</tbody>
</table>

*a* a small amount of upstream emissions from oil production and the refining and transport of fuels used in crop production is included in the totals in Table 2, but is not shown above.
III. Results

As noted in the Introduction, thirteen agricultural practices have been reviewed thus far, falling into two basic categories: practices that involve land-use change from cropland to a cropland-supporting role in buffers and related land-uses, or long-term idling; and practices that retain land in crops with changes in tillage and cropping rotations. An additional eight agricultural practices have been reviewed on a preliminary basis.

The results of the analyses are shown Table 7. Results are given in CO$_2$-equivalent short tons of GHG-avoided for each practice per 100,000 acres. Emissions-avoided are shown for both in-state sources of avoidance and total avoidance, both in-state and out-of-state. Of the 13 practices that have been reviewed, all but one results in per acre greenhouse gas reductions. Only rotational change from continuous corn to 2-year corn-soybean rotation increases GHG emissions. Six of the seven largest estimated per acre emission reductions involve changing land-uses 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.

Of the 13 practices reported on in the main body of this report, the practices that yield the largest per acre greenhouse gas-avoidance are shelterbelts, long-term cropland idling in trees and in forested and multispecies riparian buffers. In the case of each, 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 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 2.7, 2.6, 2.0, 1.6, 1.6, and 0.8 short CO$_2$-equivalent tons per acre, respectively.

With the exception of cropland to hayland conversion and, to a lesser extent, extended crop rotations with forage perennials like alfalfa, changed tillage and cropping practices are an order of magnitude less effective on a per acre basis in reducing GHG emissions than practices that idle or retire cropland to buffers, field borders, vegetative barriers or conservation plantings. These practices do allow cropland to remain in production, which allows them to be implemented across the Minnesota landscape potentially on millions of acres. 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.

Of cropping and tillage practices, cropland to hayland conversion results in the largest per acre annual GHG-avoidance. Cropland to hayland conversion acts similarly to cropland idling, with per acre greenhouse gas-avoidance of 1.2 CO$_2$-equivalent short tons per acre per year. In both instances, most intensive tillage ceases, which acts to create conditions in soils in which microbial decomposition of organic matter slows, allowing organic carbon to accumulate.
Table 7. Emissions-avoided from agricultural practices (short CO\textsubscript{2}-e tons per 100,000 acres per year)

<table>
<thead>
<tr>
<th>Practices that Involve Land-Use Change from Cropland to Cropland-Supporting Role or Long-term Idling (^{d,e})</th>
<th>Emissions-avoided (^{a,b})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>in-state plus out-of-state</td>
</tr>
<tr>
<td>Shelterbelts, Hedgerows</td>
<td>(269,265)</td>
</tr>
<tr>
<td>Land Retirement/Long-term Idling: Afforestation</td>
<td>(262,611)</td>
</tr>
<tr>
<td>Forested and Multispecies Riparian Buffers</td>
<td>(203,251)</td>
</tr>
<tr>
<td>Land Retirement/Long-term Idling: Grassland Restoration</td>
<td>(162,411)</td>
</tr>
<tr>
<td>Field Borders, Contour Buffer Strips, Vegetated Barriers, Herbaceous Wind Barriers</td>
<td>(161,038)</td>
</tr>
<tr>
<td>Grassland Riparian Buffers</td>
<td>(77,299)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cropping and Tillage Practices (^{d,e})</th>
<th>Emissions-avoided (^{a,b})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cropland to Hayland</td>
<td>(121,339)</td>
</tr>
<tr>
<td>Add a Perennial Grass to Crop Rotation</td>
<td>(49,685)</td>
</tr>
<tr>
<td>No-Till Tillage-reduced tillage counterfactual</td>
<td>(22,565)</td>
</tr>
<tr>
<td>Winter Cover Crops/Catch Crops</td>
<td>(20,474)</td>
</tr>
<tr>
<td>Reduced Tillage</td>
<td>(14,543)</td>
</tr>
<tr>
<td>No-Till Tillage</td>
<td>(13,807)</td>
</tr>
<tr>
<td>Corn-Soybean Rotation Replacing Continuous Corn</td>
<td>39,830</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Preliminary Results-Only: (^{f})</th>
<th>Emissions-avoided (^{a,b})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Practices that Involve Land-Use Change from Cropland to Cropland-Supporting Role or Long-term Idling (^{d,e})</td>
<td></td>
</tr>
<tr>
<td>Contracted and Restored Wetlands</td>
<td>65,17</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nutrient Reduction Practices</th>
<th>Emissions-avoided (^{a,b})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biochar</td>
<td>(119,713)</td>
</tr>
<tr>
<td>Controlled Release Fertilizers</td>
<td>(27,369)</td>
</tr>
<tr>
<td>Nitrification and Urease Inhibitors</td>
<td>(24,033)</td>
</tr>
<tr>
<td>Split Fertilizer Application</td>
<td>(13,455)</td>
</tr>
<tr>
<td>15% Fertilizer Use Reduction</td>
<td>(5,878)</td>
</tr>
<tr>
<td>Spring Fertilizer Application</td>
<td>2,115</td>
</tr>
<tr>
<td>Subsurface Fertilizer Placement</td>
<td>31,060</td>
</tr>
</tbody>
</table>

Of practices for which we have only preliminary results, the most effective is the use of biochar in soils. At a one-time rate of application of about 6.5 tons of biochar per acre, the use of biochar results in annual GHG-avoidance that is roughly similar to that of cropland idling, an estimated 120,000 CO\textsubscript{2}-equivalent tons per 100,000 acres or 1.2 CO\textsubscript{2}-equivalent tons per acre. Nitrification and urease inhibitors are shown for in Tables 11-13, 15-17, 19-21, 28-30, 33-35, 38-40, 42-44, 46-47, 50-51, 53-54 and 57-58 and Appendices A-H.

\(^{a}\) positive = emissions increase, negative = emissions reduction

\(^{b}\) descriptive statistics for the soil organic carbon, direct soil N\textsubscript{2}O and soil CH\textsubscript{4} oxidation components of each emissions-avoided estimate are shown for in the borders of Minnesota

\(^{c}\) 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

\(^{f}\) see appendices A-H
and controlled release fertilizers are the next most effective of measures for which we have only preliminary results. GHG-avoidance for these measures is an estimated 0.2 and 0.3 CO₂-equivalent short tons per acre, respectively (24,000 and 27,000 CO₂-equivalent short tons per 100,000 acres).

It is likely that the use of restored and constructed wetland to control nitrate-loading of surface waters will act to increase emissions through enhanced CH₄ emission, though more research on alternative wetland designs, particularly with respect to vegetation, might temper this conclusion. Wetlands that are seasonally inundated may act similarly to riparian buffers, resulting in net GHG reductions upon restoration. Preliminary results suggest that subsurface placement of nitrogen fertilizer also may act to increase GHG emissions to the atmosphere.

Tables with these preliminary conclusions can be found in Appendices A-H.

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 is largest contributor to greenhouse gas-avoidance in the practices for which the analysis is final, typically accounting for 40 to 90 percent of total GHG avoidance under those 13 practices. Expressed as an offset of emitted CO₂ from fossil fuel combustion, rates of sequestration fall into a range of 0.5 to 2 tons of CO₂ per acre for practices that idle cropland or move cropland to a supporting role in production, as with shelterbelts or riparian buffers. Expressed as carbon, annual rates of sequestration for these practices range from 0.13 to 0.5 short tons of carbon per acre. As noted in the Methodology section of this report, these were 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 0.4 CO₂-equivalent tons per acre per year (13,000 to 43,000 CO₂-equivalent short tons per 100,000 acres), or in short tons of carbon, 0.04 to 0.1 ton of carbon per acre per year.

After sequestration, avoided direct emissions of N₂O are next in importance, often accounting in the practices examined for between 5 and 30 percent of total GHG-avoidance.

N₂O emissions do not always decline under the practices that were examined. Emissions of N₂O 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, N₂O 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 0.04 and 0.08 CO₂-equivalent short tons per acre, respectively (3,800 and 7,500 CO₂-equivalent short tons per 100,000 acres).

Avoided-emissions from the avoided out-of-state manufacture of agricultural fertilizers, chemicals and fuels are the third largest source of avoided-emissions.
<table>
<thead>
<tr>
<th>Practices that Involve Land-Use Change from Cropland to Cropland-Supporting Role or Long-term Idling</th>
<th>N₂O-direct</th>
<th>N₂O-indirect volatilization</th>
<th>N₂O-indirect leaching</th>
<th>CH₄</th>
<th>CO₂-carbon sequestration</th>
<th>CO₂-urea, liming</th>
<th>GHGs-energy</th>
<th>Out-of-State Upstream GHGs</th>
<th>In-State Upstream GHGs</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shelterbelts, Hedgerows</td>
<td>(48,242)</td>
<td>(2,148)</td>
<td>(14,020)</td>
<td>(184)</td>
<td>(174,780)</td>
<td>(2,808)</td>
<td>(6,892)</td>
<td>(20,190)</td>
<td>-</td>
<td>(269,265)</td>
</tr>
<tr>
<td>Land Retirement/Long-term Idling: Afforestation</td>
<td>(48,242)</td>
<td>(2,148)</td>
<td>(14,020)</td>
<td>(184)</td>
<td>(168,126)</td>
<td>(2,808)</td>
<td>(6,892)</td>
<td>(20,190)</td>
<td>-</td>
<td>(262,611)</td>
</tr>
<tr>
<td>Forested and Multispecies Riparian Buffers</td>
<td>7,033</td>
<td>(2,148)</td>
<td>(13,653)</td>
<td>33,466</td>
<td>(198,058)</td>
<td>(2,808)</td>
<td>(6,892)</td>
<td>(20,190)</td>
<td>-</td>
<td>(203,251)</td>
</tr>
<tr>
<td>Land Retirement/Long-term Idling: Grassland Restoration</td>
<td>(41,091)</td>
<td>(2,107)</td>
<td>(11,703)</td>
<td>468</td>
<td>(78,089)</td>
<td>(2,808)</td>
<td>(6,892)</td>
<td>(20,190)</td>
<td>-</td>
<td>(162,411)</td>
</tr>
<tr>
<td>Field Borders, Contour Buffer Strips, Vegetated Barriers, Herbaceous Wind Barriers</td>
<td>(41,091)</td>
<td>(2,107)</td>
<td>(11,703)</td>
<td>468</td>
<td>(78,089)</td>
<td>(2,808)</td>
<td>(6,892)</td>
<td>(20,190)</td>
<td>-</td>
<td>(161,038)</td>
</tr>
<tr>
<td>Grassland Riparian Buffers</td>
<td>(9,405)</td>
<td>(2,107)</td>
<td>(13,653)</td>
<td>27,176</td>
<td>(49,420)</td>
<td>(2,808)</td>
<td>(6,892)</td>
<td>(20,190)</td>
<td>-</td>
<td>(77,299)</td>
</tr>
<tr>
<td>Cropping and Tillage Practices</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cropland to Hayland</td>
<td>(52,012)</td>
<td>(2,107)</td>
<td>(11,703)</td>
<td>NK</td>
<td>(43,040)</td>
<td>(2,786)</td>
<td>3,681</td>
<td>(13,373)</td>
<td>-</td>
<td>(121,339)</td>
</tr>
<tr>
<td>Add a Perennial Grass to Crop Rotation</td>
<td>(2,897)</td>
<td>(1,053)</td>
<td>(6,826)</td>
<td>NK</td>
<td>(32,490)</td>
<td>(1,393)</td>
<td>6,861</td>
<td>(11,886)</td>
<td>-</td>
<td>(49,685)</td>
</tr>
<tr>
<td>No-Till Tillage-reduced tillage counterfactual</td>
<td>(8,260)</td>
<td>553</td>
<td>-</td>
<td>NA</td>
<td>(13,575)</td>
<td>-</td>
<td>(1,051)</td>
<td>(233)</td>
<td>-</td>
<td>(22,565)</td>
</tr>
<tr>
<td>Winter Cover Crops/Catch Crops</td>
<td>7,511</td>
<td>NK</td>
<td>(7,329)</td>
<td>131</td>
<td>(20,118)</td>
<td>-</td>
<td>519</td>
<td>(1,187)</td>
<td>-</td>
<td>(20,474)</td>
</tr>
<tr>
<td>Reduced Tillage</td>
<td>(102)</td>
<td>553</td>
<td>-</td>
<td>52</td>
<td>(13,026)</td>
<td>-</td>
<td>(1,653)</td>
<td>(366)</td>
<td>-</td>
<td>(14,543)</td>
</tr>
<tr>
<td>No-Till Tillage</td>
<td>3,815</td>
<td>553</td>
<td>-</td>
<td>(263)</td>
<td>(14,589)</td>
<td>-</td>
<td>(2,704)</td>
<td>(599)</td>
<td>-</td>
<td>(13,807)</td>
</tr>
<tr>
<td>Corn-Soybean Rotation Replacing Continuous Corn</td>
<td>(11,147)</td>
<td>NK</td>
<td>NK</td>
<td>NK</td>
<td>69,182</td>
<td>-</td>
<td>(909)</td>
<td>(17,296)</td>
<td>-</td>
<td>39,830</td>
</tr>
<tr>
<td>Preliminary Results-Only</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biochar</td>
<td>(17,996)</td>
<td>(325)</td>
<td>(5,174)</td>
<td>(572)</td>
<td>(138,936)</td>
<td>-</td>
<td>13,224</td>
<td>2,929</td>
<td>27,136</td>
<td>(119,713)</td>
</tr>
<tr>
<td>Controlled Release Fertilizers</td>
<td>(21,152)</td>
<td>(1,475)</td>
<td>(4,743)</td>
<td>NK</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(27,369)</td>
</tr>
<tr>
<td>Nitrification and Urease Inhibitors</td>
<td>(20,415)</td>
<td>(995)</td>
<td>(2,012)</td>
<td>(612)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(24,033)</td>
</tr>
<tr>
<td>Split Fertilizer Application</td>
<td>(13,125)</td>
<td>108</td>
<td>(1,006)</td>
<td>NK</td>
<td>-</td>
<td>-</td>
<td>568</td>
<td>-</td>
<td>-</td>
<td>(13,455)</td>
</tr>
<tr>
<td>15% Fertilizer Use Reduction</td>
<td>(2,545)</td>
<td>(255)</td>
<td>(573)</td>
<td>NK</td>
<td>-</td>
<td>(385)</td>
<td>-</td>
<td>(2,120)</td>
<td>-</td>
<td>(5,878)</td>
</tr>
<tr>
<td>Spring Fertilizer Application</td>
<td>2,236</td>
<td>116</td>
<td>(237)</td>
<td>NK</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2,115</td>
</tr>
<tr>
<td>Subsurface Fertilizer Placement</td>
<td>36,750</td>
<td>(1,187)</td>
<td>(4,999)</td>
<td>NK</td>
<td>-</td>
<td>-</td>
<td>409</td>
<td>90</td>
<td>-</td>
<td>31,060</td>
</tr>
<tr>
<td>Constructed and Restored Wetlands</td>
<td>(4,856)</td>
<td>(2,169)</td>
<td>(7,186)</td>
<td>218,640</td>
<td>(109,022)</td>
<td>(2,808)</td>
<td>(6,892)</td>
<td>(20,190)</td>
<td>-</td>
<td>65,517</td>
</tr>
</tbody>
</table>

*a* positive = emissions increase, negative = emissions reduction

*b* see appendices A-H
Finally, looking at practices for which we have only preliminary results, with the exception of biochar and constructed and restored wetlands, the results are dominated by the response of direct N\textsubscript{2}O emissions to various nutrient reduction practices. In the published literature, the analysis of GHG-avoidance with these practices is largely restricted to direct N\textsubscript{2}O emissions from soils. Thus, this conclusion may be an artefact of what has and has not been assessed regarding emission sources and sinks. Biochar applications act to lengthen the mean residence time of crop residue carbon in soils, adding large amounts of long-lived carbon to soils. As noted above, wetlands are large producers of methane. Biogenic carbon is sequestered in wetland soils, but this removal of carbon from the atmosphere to wetland soils is often overwhelmed in permanently inundated constructed and restored wetlands by enhanced rates of CH\textsubscript{4} emission, making these wetlands a net GHG source. As noted above, wetlands that are seasonally inundated may act similarly to riparian buffers, resulting in net GHG reductions upon restoration.

IV. Detailed results and discussion

Below we treat in depth the GHG emission reduction potential of the 13 practices for which we provide final avoidance estimates, 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 our judgement, is in the case of each emissions source 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\textsubscript{2}O soil emissions and CH\textsubscript{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\textsubscript{2}O 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 F house this discussion. These are followed by Subsections G through M, which house the discussion of per acre emission-avoidance potential of seven practices involving potential cropping and tillage change.
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 N₂O emissions. As was noted there, for nitrate control, the source of emissions-avoidance for indirect N₂O from nitrogen run-off and leaching, we defer to the expertise on nitrate control embedded in the MPCA, Nutrient Reduction Strategy. (MPCA, 2014)

Results from the eight practices for which only preliminary results are available are provided in table form in Appendices A through H. Included are emissions-avoidance budgets and descriptive statistics for the body of research results on emissions or emissions-avoidance developed from the scientific literature.

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.

In Table 9 are shown the emissions-avoidance effects of the temporarily idling of 100,000 acres of cropland as restored grassland. For each 100,000 acres of cropland retired to grass, an estimated 162,000 CO₂-equivalent short tons of greenhouse gases are avoided annually within the 20-year window of analysis discussed in the preceding sections, or 1.6 short CO₂-equivalent tons per acre.

A little less than 90 percent of emissions annually avoided through grassland restoration are avoided in state at the field level, with the remainder avoided out-of-state and 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 occur. Of total avoided-emissions from cropland idling in unmanaged grass, roughly 85 percent derives from soil organic carbon accumulation in soils and live biomass, avoided-emissions of N₂O from soils, and avoided GHGs from unneeded out-of-state production of agricultural chemicals and fertilizer (see Table 9).

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 can safely 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 162,000 CO₂-equivalent short tons. Had a 40-year period of assured storage been assumed, avoided-emissions from grassland restoration would have totaled 241,000 CO₂-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 475,000 CO₂-equivalent short tons (see Table 9). The approach that we

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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)
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 9, 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.

Table 9. Land retirement/Long-term idling - Grassland restoration: Emissions-avoided

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Emission Source or Sink</th>
<th>Emission (CO$_2$-e short tons per 100,000 acres per year) $^a$</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>N$_2$O-direct</td>
<td>soils</td>
<td>(41,091)</td>
<td>crop production</td>
</tr>
<tr>
<td>N$_2$O-indirect volatilization</td>
<td>indirect emission-Nitrogen volatilization, redeposition</td>
<td>(2,107)</td>
<td>crop production</td>
</tr>
<tr>
<td>N$_2$O-indirect leaching</td>
<td>indirect emission-Nitrogen leaching or runoff</td>
<td>(11,703)</td>
<td>crop production</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>soils</td>
<td>468</td>
<td>crop production</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>carbon accumulation in soils and biomass</td>
<td>(78,089)</td>
<td>crop production</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>cultivated soils from lime or urea use</td>
<td>(2,808)</td>
<td>crop production</td>
</tr>
<tr>
<td>GHGs-energy</td>
<td>fossil fuel and electricity use in crop production</td>
<td>(6,892)</td>
<td>crop production</td>
</tr>
<tr>
<td>Out-of-State Upstream GHGs</td>
<td>upstream agricultural chemicals and fossil fuel production</td>
<td>(20,190)</td>
<td>crop production</td>
</tr>
<tr>
<td>Total</td>
<td>all sources and sinks</td>
<td>(162,411)</td>
<td></td>
</tr>
</tbody>
</table>

Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass

| 40 year storage | all sources and sinks | (240,501) | crop production |
| 100 year storage | all sources and sinks | (474,769) | 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 10 in CO$_2$-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 CO$_2$-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 N$_2$O from soils and the effects of grassland restoration on soil CH$_4$ oxidation. The methods and sources used to estimate avoided indirect N$_2$O 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 (Section II, Subsection E) of this report.

Table 10. Published estimates of greenhouse gas-avoidance from cropland idling in unmanaged grassland

<table>
<thead>
<tr>
<th>Study</th>
<th>Type of study</th>
<th>CO2-eq. short tons per acre per year</th>
<th>CO2-eq. short tons per 100,000 acres per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gelfand and Robertson (2015)</td>
<td>site study</td>
<td>1.92</td>
<td>192,007</td>
</tr>
<tr>
<td>Miao et al. (2015)</td>
<td>site study</td>
<td>1.09</td>
<td>108,916</td>
</tr>
<tr>
<td>Robertson et al. (2000)</td>
<td>site study</td>
<td>1.23</td>
<td>122,653</td>
</tr>
<tr>
<td>Del Grosso et al. (2002)</td>
<td>modeling study</td>
<td>0.10</td>
<td>9,561</td>
</tr>
<tr>
<td>Del Grosso et al. (2005)</td>
<td>modeling study</td>
<td>0.83</td>
<td>83,350</td>
</tr>
<tr>
<td>Desjardins et al. (2005)</td>
<td>modeling study</td>
<td>1.80</td>
<td>180,129</td>
</tr>
<tr>
<td>Grant et al. (2004)</td>
<td>modeling study</td>
<td>1.14</td>
<td>113,733</td>
</tr>
<tr>
<td>Robertson (2011)</td>
<td>modeling study</td>
<td>0.74</td>
<td>73,544</td>
</tr>
<tr>
<td>Smith et al. (2008) b,c</td>
<td>modeling study</td>
<td>2.39</td>
<td>239,061</td>
</tr>
<tr>
<td>Swan et al. (2015) b</td>
<td>literature review/expert judgment</td>
<td>1.39</td>
<td>138,866</td>
</tr>
<tr>
<td>Eagle et al. (2012)</td>
<td>derivative statistical analysis</td>
<td>1.59</td>
<td>159,226</td>
</tr>
<tr>
<td>Kim and Kirschbaum (2015) b,d</td>
<td>derivative statistical analysis</td>
<td>1.18</td>
<td>117,573</td>
</tr>
<tr>
<td>This report</td>
<td>literature review</td>
<td>1.62</td>
<td>162,411</td>
</tr>
</tbody>
</table>

* results as reported without adjustments
  b partial difference, accounting for direct soils emissions and soil carbon 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

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 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 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 CO2. (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. The soils also are exposed to much 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.

Factors besides reduced disturbance 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, harvest removals for annual crops 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, again 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 9, an estimate for annual carbon sequestration in restored grasslands of 78,089 short tons of CO$_2$ or 21,311 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 9 was developed from 18 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, additionally the import of manure and harvest removals.

The mean value for carbon sequestration in restored grassland from total ecosystem carbon studies is an estimated 1.24 ± 0.3 metric tons of carbon per hectare (0.55 ± 0.13 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. 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, 13 were eddy-covariance-based, while the remainder were chamber-based studies.

Overall, 126 studies were reviewed. Most of these studies (107 studies) reported on changes in soil organic carbon only and, as such, were of limited utility. Only a handful of the 126 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, 13 meta-analyses and other derivative statistical summaries or analyses were reviewed, as were the 48 soil sampling-type site studies, 20 modeling studies, the 13 eddy-covariance and 4 chamber studies noted above, and 27 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 1.3 metric tons of carbon per hectare (0.27 to 0.60 short tons of carbon per acre).

The average sequestration rate for the literature and expert reviews was 0.71 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 11.
Table 11. Descriptive statistics: Land retirement/Long-term idling - Grassland restoration, carbon sequestration in soils and biomass

<table>
<thead>
<tr>
<th>Description</th>
<th>Biogenic carbon sequestration (Mg C/ha/yr)</th>
<th>Number of studies</th>
<th>Ratio of sequestration to emission: number of studies</th>
<th>Standard error of mean (+/-)</th>
<th>Lower 95% confidence interval</th>
<th>Upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total ecosystem carbon (soil organic carbon, above and belowground biomass)</td>
<td>1.24</td>
<td>18</td>
<td>17/1</td>
<td>0.30</td>
<td>0.66</td>
<td>1.82</td>
</tr>
<tr>
<td>Soil organic carbon-only</td>
<td>0.59</td>
<td>107</td>
<td>100/7</td>
<td>0.05</td>
<td>0.49</td>
<td>0.68</td>
</tr>
<tr>
<td>Meta-analyses</td>
<td>0.69</td>
<td>6</td>
<td>6/0</td>
<td>0.10</td>
<td>0.49</td>
<td>0.89</td>
</tr>
<tr>
<td>Other derivative statistical analyses or statistical summaries a</td>
<td>0.68</td>
<td>7</td>
<td>7/0</td>
<td>0.14</td>
<td>0.41</td>
<td>0.95</td>
</tr>
<tr>
<td>Eddy covariance empirical site studies (NECB/NBP) b</td>
<td>1.32</td>
<td>13</td>
<td>12/1</td>
<td>0.40</td>
<td>0.55</td>
<td>2.10</td>
</tr>
<tr>
<td>Modeling studies</td>
<td>0.73</td>
<td>20</td>
<td>19/1</td>
<td>0.13</td>
<td>0.47</td>
<td>0.99</td>
</tr>
<tr>
<td>Empirical site studies-soil sampling</td>
<td>0.47</td>
<td>48</td>
<td>42/6</td>
<td>0.08</td>
<td>0.31</td>
<td>0.63</td>
</tr>
<tr>
<td>Expert judgment/literature reviews</td>
<td>0.71</td>
<td>27</td>
<td>27/0</td>
<td>0.06</td>
<td>0.59</td>
<td>0.83</td>
</tr>
<tr>
<td>Restored grasslands</td>
<td>0.66</td>
<td>118</td>
<td>110/8</td>
<td>0.06</td>
<td>0.54</td>
<td>0.78</td>
</tr>
<tr>
<td>Existing grasslands</td>
<td>0.81</td>
<td>9</td>
<td>9/0</td>
<td>0.27</td>
<td>0.27</td>
<td>1.35</td>
</tr>
<tr>
<td>10 to 30 cm soil sampling/modeling depth c</td>
<td>0.55</td>
<td>48</td>
<td>47/1</td>
<td>0.06</td>
<td>0.44</td>
<td>0.67</td>
</tr>
<tr>
<td>&gt; 40 cm soil sampling/modeling depth c</td>
<td>0.54</td>
<td>16</td>
<td>12/4</td>
<td>0.20</td>
<td>0.14</td>
<td>0.94</td>
</tr>
<tr>
<td>15 to 25 year annual sequestration rate</td>
<td>0.47</td>
<td>33</td>
<td>30/3</td>
<td>0.09</td>
<td>0.29</td>
<td>0.66</td>
</tr>
<tr>
<td>0 to 14 year annual sequestration rate</td>
<td>0.70</td>
<td>42</td>
<td>37/5</td>
<td>0.13</td>
<td>0.45</td>
<td>0.95</td>
</tr>
<tr>
<td>25 year-plus annual sequestration rate</td>
<td>0.32</td>
<td>10</td>
<td>10/0</td>
<td>0.08</td>
<td>0.17</td>
<td>0.48</td>
</tr>
</tbody>
</table>

a) Statistical summaries or analyses other than meta-analyses
b) NECB = Net Ecosystem Carbon Balance; NBP = Net Biome Productivity
c) Results for lowest reported sampling depth
d) 126 study results, 126 studies

e) Ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

In the set of 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 tended to focus on total ecosystem carbon storage, while most of the restored grassland studies, as noted above, reported on 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 0.5 to 1.5 metric tons of carbon per hectare per year (0.22 to 0.70 short tons per acre), with a best estimate near 1.25 metric tons per hectare per year.

b. Nitrous oxide

Nitrous oxide is produced microbially in soils during nitrification, during which ammonium is oxidized to nitrate, and denitrification, during which nitrate is reduced to N₂O. N₂O is produced in converted grassland soils and cropland soils. N₂O 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. As a
consequence, in part of tillage, a large amount of nitrogen also is made available to soil bacteria through soil nitrogen mineralization. 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 N₂O emissions, taken from the MPCA Greenhouse Gas Emission Inventory. For each 100,000 acres of cropland converted to grassland, an estimated 41,000 CO₂-equivalent short tons of emissions are avoided or some 138 tons of N₂O.

N₂O 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 N₂O emission rate for unmanaged grasslands, 53 studies were reviewed with 55 study results. These included 35 empirical site studies, 11 modeling studies, 5 derivative statistical summaries or analyses and 2 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 N₂O from restored grassland. No other study attribute pointed to one study type as clearly superior in estimating N₂O 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 1.71 ± 0.6 kg N₂O per hectare (1.52 ± 0.54 lbs. N₂O per acre).

By contrast, the estimated annual rate of N₂O emission from Minnesota cropland, from the MPCA GHG emission inventory, was, for 2013-2015, 4.8 kg N₂O per hectare (4.3 lbs. N₂O per acre).

The descriptive statistics for the various studies that were reviewed are shown in Table 12. In these studies, annual emission rates for restored and existing grasslands ranged from 0.8 to 2 kg N₂O per hectare (0.71 to 1.78 lbs. N₂O 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 half those of studies conducted over a single year, although quite near both to the mean value reported in Table 12 for all studies and the value used in this analysis to calculate N₂O emissions from cropland converted to grass. The results from restored grassland were about two-those of existing grasslands, but again were within 10 percent of the mean value reported in Table 12 for all studies.

Thirty-four 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 3.1 kg N₂O per hectare (2.77 lbs. N₂O per acre) less than cropland or pastureland. In the calculation for avoided N₂O emissions shown in Table 9, the difference between cropland emissions and emissions from restored grassland is some 3.2 kg N₂O per hectare per year (3.64 lbs. N₂O per acre per year), or quite near the literature estimate.

The weight of the evidence generally supports an N₂O emission from restored grassland that is one-quarter to 40 percent that of fertilized cropland. Given the high variability of N₂O from different land surfaces, it is not clear that additional research can do much to further narrow this estimate.
Table 12. Descriptive statistics: Land retirement/Long-term idling - Grassland restoration, N₂O

<table>
<thead>
<tr>
<th>Study Type</th>
<th>Emissions (kg N₂O/hec/yr)</th>
<th>Number of Study Results</th>
<th>Ratio of Positive-to-Negative Results: Number of Study Results</th>
<th>Standard Error of Mean (±)</th>
<th>Lower 95% Confidence Interval</th>
<th>Upper 95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Studies</td>
<td>1.71</td>
<td>55</td>
<td>55/0</td>
<td>0.58</td>
<td>0.59</td>
<td>2.84</td>
</tr>
<tr>
<td>Empirical Site Studies</td>
<td>2.02</td>
<td>36</td>
<td>36/0</td>
<td>0.88</td>
<td>0.30</td>
<td>3.74</td>
</tr>
<tr>
<td>Modeling Studies</td>
<td>1.22</td>
<td>12</td>
<td>12/0</td>
<td>0.37</td>
<td>0.49</td>
<td>1.94</td>
</tr>
<tr>
<td>Derivative statistical analyses or statistical summaries</td>
<td>1.00</td>
<td>5</td>
<td>5/0</td>
<td>0.29</td>
<td>0.43</td>
<td>1.57</td>
</tr>
<tr>
<td>Expert judgment/literature reviews</td>
<td>0.79</td>
<td>2</td>
<td>2/0</td>
<td>0.29</td>
<td>0.23</td>
<td>1.35</td>
</tr>
<tr>
<td>Grassland restorations</td>
<td>1.18</td>
<td>31</td>
<td>31/0</td>
<td>0.23</td>
<td>0.74</td>
<td>1.63</td>
</tr>
<tr>
<td>Existing grasslands</td>
<td>2.80</td>
<td>18</td>
<td>18/0</td>
<td>1.73</td>
<td>(0.59)</td>
<td>6.18</td>
</tr>
<tr>
<td>Annual flux monitoring/modeling</td>
<td>2.20</td>
<td>36</td>
<td>36/0</td>
<td>0.88</td>
<td>0.48</td>
<td>3.92</td>
</tr>
<tr>
<td>Growing season and subgrowing season flux monitoring/modeling</td>
<td>0.75</td>
<td>18</td>
<td>18/0</td>
<td>0.14</td>
<td>0.48</td>
<td>1.02</td>
</tr>
<tr>
<td>1 year of observations or simulations</td>
<td>4.18</td>
<td>11</td>
<td>11/0</td>
<td>2.77</td>
<td>(1.25)</td>
<td>9.61</td>
</tr>
<tr>
<td>&gt; 1 year of observations or simulations</td>
<td>1.10</td>
<td>36</td>
<td>36/0</td>
<td>0.22</td>
<td>0.66</td>
<td>1.54</td>
</tr>
<tr>
<td>Grassland restorations against cropland or pastureland counterfactual</td>
<td>(3.07)</td>
<td>34</td>
<td>34/0</td>
<td>0.90</td>
<td>(4.83)</td>
<td>(1.31)</td>
</tr>
</tbody>
</table>

- Negative emissions = removal from atmosphere and destruction in soils
- Statistical summaries or analyses other than meta-analyses
- 55 study results, 53 studies (5 statistical summaries or derivative statistical analyses, 11 modeling studies, 35 empirical site studies, 2 expert reviews)
- 2 studies report multiple results by study type or grassland status (existing vs restored)

### 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 CH₄ 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 CH₄ destruction that occurs in soils from the conversion of cropland to grassland is calculated as the difference in CH₄ soil oxidation in cropland and 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, CH₄ oxidation is estimated to decrease slightly, 468 CO₂-equivalent short tons or some 19 tons of CH₄.

In developing the average soil CH₄ oxidation rate for unmanaged grasslands, 30 studies were reviewed with 31 study results. These included 19 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 1.43 ± 0.33 kg CH$_4$ per hectare (1.28 ± 0.29 lbs. CH$_4$ per acre).

The descriptive statistics for the various studies that were reviewed are shown in Table 13. In the studies, annual CH$_4$ oxidation rates for restored and existing grasslands range from 0.6 to 3 kg CH$_4$ per hectare (0.54 to 2.68 lbs. CH$_4$ per acre). In not quite 90 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 (12). 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 1 year of observations was about 3-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 13 for all studies, while results from empirical site-studies a somewhat lower value.

**Table 13. Descriptive statistics: Land retirement/Long-term idling - Grassland restoration, CH$_4$**

<table>
<thead>
<tr>
<th>Type of Study</th>
<th>Soil CH$_4$ Oxidation (kg CH$_4$/hectare/yr)</th>
<th>Ratio of Positive-to-Negative Results: Number of Study Results</th>
<th>Standard Error of Mean (±)</th>
<th>Lower 95% Confidence Interval</th>
<th>Upper 95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>All studies</td>
<td>1.43 ± 0.33</td>
<td>26/5</td>
<td>0.33 ± 0.79</td>
<td>2.07</td>
<td></td>
</tr>
<tr>
<td>Empirical site studies</td>
<td>0.80 ± 0.33</td>
<td>15/5</td>
<td>0.33 ± 0.16</td>
<td>1.45</td>
<td></td>
</tr>
<tr>
<td>Modeling studies</td>
<td>3.02 ± 0.50</td>
<td>6/0</td>
<td>1.01 ± 1.04</td>
<td>5.00</td>
<td></td>
</tr>
<tr>
<td>Derivative statistical analyses or statistical summaries</td>
<td>2.03 ± 0.39</td>
<td>5/0</td>
<td>0.39 ± 1.26</td>
<td>2.80</td>
<td></td>
</tr>
<tr>
<td>Grassland restorations</td>
<td>0.61 ± 0.26</td>
<td>9/3</td>
<td>0.36 (0.09)</td>
<td>1.31</td>
<td></td>
</tr>
<tr>
<td>Existing grasslands</td>
<td>2.02 ± 0.50</td>
<td>16/1</td>
<td>0.49 ± 1.05</td>
<td>2.99</td>
<td></td>
</tr>
<tr>
<td>Annual flux monitoring/modeling</td>
<td>2.03 ± 0.39</td>
<td>16/2</td>
<td>0.49 ± 1.07</td>
<td>2.98</td>
<td></td>
</tr>
<tr>
<td>Growing season and subgrowing season flux monitoring/modeling</td>
<td>0.61 ± 0.26</td>
<td>10/3</td>
<td>0.28 ± 0.07</td>
<td>1.15</td>
<td></td>
</tr>
<tr>
<td>1 year of observations or simulations</td>
<td>0.50 ± 0.26</td>
<td>5/1</td>
<td>0.31 (0.10)</td>
<td>1.10</td>
<td></td>
</tr>
<tr>
<td>&gt; 1 year of observations or simulations</td>
<td>1.52 ± 0.79</td>
<td>12/4</td>
<td>0.58 ± 0.38</td>
<td>2.66</td>
<td></td>
</tr>
<tr>
<td>Grassland restorations against cropland or pastureland counterfactual</td>
<td>0.20 ± 0.07</td>
<td>8/9/1</td>
<td>0.26 (0.31)</td>
<td>0.71</td>
<td></td>
</tr>
</tbody>
</table>

* CH$_4$ soil oxidation = removal from atmosphere and destruction in soils
  * Statistical summaries or analyses other than meta-analyses
  * 31 study results, 30 studies (5 statistical summaries or derivative statistical analyses, 6 modeling studies, 19 empirical site studies)
  * 1 study reports multiple results by grassland status (existing vs restored)

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, CO₂ 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 263,000 CO₂-equivalent short tons of GHGs are avoided annually, much of it in the form of atmospheric CO₂ removal. More than 90 percent of this is 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 14. The largest sources of emissions-avoidance are, in order of significance: biogenic carbon sequestration (64 percent); avoided direct field emissions of N₂O (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 N₂O from nitrate not leached to surface and groundwater (5 percent). As discussed above, during biogenic carbon sequestration, CO₂ is removed photosynthetically from the atmosphere and is sequestered in live tree biomass, soil organic carbon, tree detritus and the forest floor.

Table 14. Land retirement/Long-term idling - Afforestation: Emissions-avoided

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Emission Source or Sink</th>
<th>Emission (CO₂-e short tons per 100,000 acres per year)²</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂O-direct</td>
<td>soils</td>
<td>(48,242)</td>
<td>crop production</td>
</tr>
<tr>
<td>N₂O-indirect</td>
<td>indirect emission-Nitrogen volatilization, redep.</td>
<td>(2,148)</td>
<td>crop production</td>
</tr>
<tr>
<td>N₂O-indirect leaching</td>
<td>indirect emission-Nitrogen leaching or runoff</td>
<td>(14,020)</td>
<td>crop production</td>
</tr>
<tr>
<td>CH₄</td>
<td>soils</td>
<td>(184)</td>
<td>crop production</td>
</tr>
<tr>
<td>CO₂</td>
<td>carbon accumulation in soils and biomass</td>
<td>(168,126)</td>
<td>crop production</td>
</tr>
<tr>
<td>CO₂</td>
<td>cultivated soils from lime or urea use</td>
<td>(2,808)</td>
<td>crop production</td>
</tr>
<tr>
<td>GHGs-energy</td>
<td>fossil fuel and electricity use in crop production</td>
<td>(6,892)</td>
<td>crop production</td>
</tr>
<tr>
<td>Out-of-State</td>
<td>upstream agricultural chemicals and fossil fuel production</td>
<td>(20,190)</td>
<td>crop production</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>(262,611)</td>
<td></td>
</tr>
</tbody>
</table>

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 263,000 CO₂-equivalent short tons. Had a 40-year period of assured storage been assumed, avoided-emissions from afforestation of former croplands would have totaled 431,000 CO₂-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 935,000 CO₂-equivalent short tons (see Table 14). The approach that we use in converting
observed rates of sequestration to emissions offsets, and by logical extension 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 N₂O from soils and the effects of afforestation of cropland on soil CH₄ uptake and 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.

**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 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 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 ground 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 14, an estimate is given for annual carbon sequestration in afforested former cropland, some 168,126 short tons of CO₂ or 45,882 tons of carbon, covering 100,000 afforested acres. As discussed

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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.
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 CO₂-equivalent tons for inclusion in the summary Table 14. During afforestation, CO₂ is removed from the atmosphere and incorporated into tree biomass and, eventually, into woody detritus and soils. This acts to offset emissions of CO₂ from elsewhere in the economy.

The average sequestration rate per acre was developed from 22 studies of total ecosystem carbon in afforested former croplands. Total ecosystem carbon accounting is probably the best approach to approximating 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 2.67 ± 0.47 metric tons of carbon per hectare (1.19 ± 0.21 short tons of 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, 75 studies were reviewed, including seven meta-analyses, six other derivative statistical summaries or analyses, twelve modeling studies, 33 empirical site studies, 15 literature reviews or studies involving expert judgment, and two eddy covariance-types studies (see Table 15). Of the seven 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 2.67 to 3.62 metric tons of carbon per hectare (1.19 to 1.61 short tons of carbon per acre).

Of the 75 studies that were reviewed, five reported net losses of or no change in organic carbon storage following afforestation, while 70 reported net increases. In general, the evidence overwhelmingly supports a positive annual sequestration rate, prior to truncation for 20-years of assumed storage, in the range of approximately 2.5 to 3.5 metric tons of carbon per hectare (4.1 to 5.7 short tons per acre), with a best estimate a conservative 2.7 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 3.37 to 1.58 metric tons per hectare per year for 0 to 15 year old afforestations and 15 to 25 year old afforestations, respectively.

### b. Nitrous oxide

N$_2$O 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$_2$O 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$_2$O.

Avoided nitrous oxide emissions from the conversion of cropland to forestland are calculated as the difference on 100,000 acres in estimated emissions between forestland converted from cropland and...
average annual \( \text{N}_2\text{O} \) emissions from Minnesota cropland. Annual Minnesota cropland \( \text{N}_2\text{O} \) emissions are taken from the MPCA Greenhouse Gas Emission Inventory.

\( \text{N}_2\text{O} \) 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, 40 studies were reviewed with 41 study results. These included 27 empirical site studies, eight 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 \( \text{N}_2\text{O} \) emissions from afforested former cropland. No formal meta-analysis was available for \( \text{N}_2\text{O} \) from restored grassland. Using the average value for the studies that were reviewed, afforested former croplands are estimated to emit on an annual basis 1.18 ± 0.22 kg of \( \text{N}_2\text{O} \) per hectare (1.05 ± 0.2 lbs. of \( \text{N}_2\text{O} \) per acre). This value is almost identical to what might be estimated using the reviewed empirical site studies and very close to 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 0.97 to 1.39 kg of \( \text{N}_2\text{O} \) per hectare (0.86 to 1.25 lbs. of \( \text{N}_2\text{O} \) per acre).

Average annual cropland \( \text{N}_2\text{O} \) emission rates from the MPCA GHG emission inventory are an estimated 4.8 kg \( \text{N}_2\text{O} \) per hectare (4.3 lbs. \( \text{N}_2\text{O} \) per acre).

The flux or emission rates shown in Table 16 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 40 studies that were reviewed are shown in Table 16, including standard errors and calculated upper and lower 95 percent confidence intervals.

Nine studies evaluated the effect on \( \text{N}_2\text{O} \) emissions of converting cropland to forestland, with a mean annual reduction in emissions across all nine studies of 1.72 kg of \( \text{N}_2\text{O} \) per hectare (1.53 lbs. \( \text{N}_2\text{O} \) per acre). Using the mean for all studies for afforested former cropland and average Minnesota cropland \( \text{N}_2\text{O} \) emissions, taken from the MPCA Greenhouse Gas Emission Inventory, we derive a higher value of 3.67 kg \( \text{N}_2\text{O} \) per hectare per year (3.27 lbs. \( \text{N}_2\text{O} \) per acre per year). The estimates agree that, with afforestation, \( \text{N}_2\text{O} \) 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, \( \text{N}_2\text{O} \) emissions will do anything but decline.

c. Methane

In upland afforested soils, \( \text{CH}_4 \) 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 \( \text{CH}_4 \). (Amadi et al., 2017; Dutaur and Verchot, 2007) \( \text{CH}_4 \) 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 \( \text{CH}_4 \) than restored grassland and far more than cropland. As discussed earlier, \( \text{CH}_4 \) oxidation in cropland is likely suppressed by tillage disruptions to methanotroph communities and by the application of ammonium-based synthetic fertilizers.
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 uptake from afforested former cropland. 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 by afforested former croplands, we reviewed 34 studies with 35 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 2.02 ± 0.52 kg CH$_4$ per hectare (1.80 ± 0.46 lbs. CH$_4$ per acre). Applying this to 100,000 acres, only a small amount of additional CH$_4$ will be oxidized from converting cropland to trees, on an annual basis an estimated 176 CO$_2$-equivalent short tons or some 7 tons of CH$_4$ (see Table 14). 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 17. Annual emission rates for afforested and forest soils range from 1.7 to 3.06 kg CH$_4$ per hectare (1.49 to 3.21 lbs. CH$_4$ per acre). In greater than 90 percent of all observations, upland forested soils oxidized CH$_4$. The derivative statistical summaries reported generally higher rates of oxidation than the mean value taken from all observations, the empirical sites studies generally lower values. Studies reporting on CH$_4$ oxidation in existing forest soils tended to report higher values than afforested soils, but not excessively so.
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 CH₄ oxidation from cropland and land planted to trees indicate rates of CH₄ oxidation above cropland levels of 2.55 kg CH₄ per hectare per year (2.27 lbs. CH₄ per acre per year). This is substantially higher than the 0.3 kg CH₄ per hectare (0.27 lbs. CH₄ per acre per year) additional CH₄ 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. Estimated average annual GHG emissions-avoided from shelterbelts and hedgerows are shown in Table 18 by source. For each 100,000 acres of cropland retired to shelterbelts or hedgerows, an estimated 269,000 CO₂-equivalent short tons of emission that otherwise would have occurred are avoided. Of this, about two-thirds, results from CO₂ 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-fifth, are avoided direct emissions of N₂O from cropland soils. Slightly more than 90 percent of all emissions avoided through the

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¹⁰ Estimated oxidation in afforested soils (see Table 17) minus oxidation in cropland soils, from Aronson and Heliker (2010): 2.02 – 1.85 kg CH₄/ha/yr

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Table 17. Descriptive statistics: Land retirement/Long-term idling - Afforestation, CH₄

<table>
<thead>
<tr>
<th></th>
<th>soil CH₄ oxidation (kg CH₄/ha/yr)</th>
<th>number of study results</th>
<th>ratio of positive-to-negative results: number of study results</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>all studies</td>
<td>2.02</td>
<td>35</td>
<td>32/3</td>
<td>0.52</td>
<td>1.00</td>
<td>3.03</td>
</tr>
<tr>
<td>empirical site studies</td>
<td>1.70</td>
<td>23</td>
<td>20/3</td>
<td>0.73</td>
<td>0.27</td>
<td>3.12</td>
</tr>
<tr>
<td>modeling studies</td>
<td>2.20</td>
<td>6</td>
<td>6/0</td>
<td>0.81</td>
<td>0.61</td>
<td>3.79</td>
</tr>
<tr>
<td>derivative statistical analyses or statistical summaries ¹ ⁵ ⁶ ²</td>
<td>3.06</td>
<td>6</td>
<td>6/0</td>
<td>0.81</td>
<td>1.47</td>
<td>4.64</td>
</tr>
<tr>
<td>afforestation</td>
<td>1.82</td>
<td>16</td>
<td>16/0</td>
<td>0.49</td>
<td>0.86</td>
<td>2.78</td>
</tr>
<tr>
<td>existing forestland</td>
<td>2.18</td>
<td>19</td>
<td>16/3</td>
<td>0.87</td>
<td>0.48</td>
<td>3.88</td>
</tr>
<tr>
<td>annual flux monitoring/modeling</td>
<td>2.19</td>
<td>28</td>
<td>26/2</td>
<td>0.60</td>
<td>1.01</td>
<td>3.36</td>
</tr>
<tr>
<td>growing season and subgrowing season flux monitoring/modeling</td>
<td>1.33</td>
<td>7</td>
<td>6/1</td>
<td>0.98</td>
<td>(0.59)</td>
<td>3.24</td>
</tr>
<tr>
<td>more than 1 year of observations or simulations</td>
<td>2.16</td>
<td>4</td>
<td>4/0</td>
<td>0.64</td>
<td>0.92</td>
<td>3.41</td>
</tr>
<tr>
<td>afforestation against cropland or pastureland counterfactual</td>
<td>1.68</td>
<td>20</td>
<td>18/2</td>
<td>0.83</td>
<td>0.06</td>
<td>3.31</td>
</tr>
<tr>
<td>annual flux monitoring/modeling</td>
<td>2.55</td>
<td>8</td>
<td>8/0</td>
<td>1.30</td>
<td>0.01</td>
<td>5.09</td>
</tr>
</tbody>
</table>

¹ CH₄ soil oxidation – removal from atmosphere and destruction in soils
² statistical summaries or analyses other than meta-analyses
³ 35 study results, 34 studies (6 statistical summaries or derivative statistical analyses, 6 modeling studies, 22 empirical site studies)
⁴ 1 study reports multiple results by forest status (existing vs afforested)
⁵ soil CH₄ oxidation (kg CH₄/ha/yr)
establishment of shelterbelts and hedges are avoided in state, with the remainder avoided out-of-state from avoided agricultural fertilizer, chemicals and fuels production.

In the preceding section on general 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 N₂O and uptake and oxidation of CH₄. (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 N₂O in situ in soils and reduced N₂O emission to the atmosphere. (Amadi et al., 2017)

In developing the emission-avoided estimates shown in Table 18, 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 can safely be assumed for purposes of calculating the more certain effects today of shelterbelt or hedgerow establishment. Under this assumption, avoided-emissions are an estimated 269,000 CO₂-equivalent short tons. Had a 40-year period of assured storage been assumed, avoided-emissions from shelterbelt establishment would have been greater, totaling 444,000 CO₂-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 968,000 CO₂-equivalent short tons (see Table 18). 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 N₂O that are avoided by cropland conversion and generally enhanced rates of CH₄ oxidation in afforested soils. 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 of this report, Section II, Subsection E above.
Table 18. Shelterbelts and hedgerows: Emissions-avoided

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Emission Source or Sink</th>
<th>Emission (CO2-e short tons per 100,000 acres per year) (^a)</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_2O)-direct</td>
<td>soils</td>
<td>(48,242)</td>
<td>crop production</td>
</tr>
<tr>
<td>(N_2O)-indirect volatilization</td>
<td>indirect emission-Nitrogen volatilization, redeposition</td>
<td>(2,148)</td>
<td>crop production</td>
</tr>
<tr>
<td>(N_2O)-indirect leaching</td>
<td>indirect emission-Nitrogen leaching or runoff</td>
<td>(14,020)</td>
<td>crop production</td>
</tr>
<tr>
<td>(CH_4) (^b)</td>
<td>soils</td>
<td>(184)</td>
<td>crop production</td>
</tr>
<tr>
<td>(CO_2) (^c,d)</td>
<td>carbon accumulation in soils and biomass</td>
<td>(174,780)</td>
<td>crop production</td>
</tr>
<tr>
<td>(CO_2)</td>
<td>cultivated soils from lime or urea use</td>
<td>(2,808)</td>
<td>crop production</td>
</tr>
<tr>
<td>GHGs-energy</td>
<td>fossil fuel and electricity use in crop production</td>
<td>(6,892)</td>
<td>crop production</td>
</tr>
<tr>
<td>Out-of-State Upstream GHGs</td>
<td>upstream agricultural chemicals and fossil fuel production</td>
<td>(20,190)</td>
<td>crop production</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>(269,265)</td>
<td></td>
</tr>
</tbody>
</table>

Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass

- **40 year storage**
  - all sources and sinks: (444,044) crop production
- **100 year storage**
  - all sources and sinks: (968,384) 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 in 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 18.

From Table 18, with 100,000 acres of shelterbelts and hedges, roughly 175,000 \(CO_2\)-equivalent short tons of emissions would be offset annually, or 1.75 \(CO_2\)-equivalent short tons per acre.

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 $2.78 \pm 0.73$ metric tons of carbon per hectare ($1.24 \pm 0.33$ short tons of carbon per acre). This estimate was developed from ten studies that provide information on total ecosystem carbon storage in shelterbelts and hedges. (See Table 19 below) Studies that address only changes in soil carbon report rates of annual sequestration that are less than a third 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 26 studies. No published meta-analysis of study results was identified for sequestration in recently established and growing shelterbelts and hedges. Of the total ecosystem studies, three were modeling studies, three 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.

In the majority of studies that involve 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 of limited use in establishing a representative sequestration rate for shelterbelts and hedges.

Of the 26 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 very similar to that for upland afforestation.

The descriptive statistics for the studies that were reviewed are shown in Table 19.

b. Nitrous oxide

$\text{N}_2\text{O}$ 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 $\text{N}_2\text{O}$ 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 $\text{N}_2\text{O}$ per hectare), and then converted to a per acre basis (lbs. $\text{N}_2\text{O}$ per acre) for the calculation of emissions on 100,000 acres.

There exist relatively few published estimates of $\text{N}_2\text{O}$ fluxes from shelterbelts and hedges. In lieu of $\text{N}_2\text{O}$ emission estimates specific to shelterbelts and hedges, in calculating avoided $\text{N}_2\text{O}$ emissions, we use the average emission rate for upland afforestation of former cropland, which is discussed above in Section IV, Subsection Bb. Afforested former croplands are estimated annually to emit 1.18 kg $\text{N}_2\text{O}$ per hectare (1.05 lbs. $\text{N}_2\text{O}$ per acre). Estimated average annual cropland emissions of nitrous oxide are 4.8 kg $\text{N}_2\text{O}$ per hectare (4.3 lbs. $\text{N}_2\text{O}$ 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.
Six studies of N₂O emissions from shelterbelts and hedges were identified in the scientific literature. The mean rate of emission for these six studies is some 0.81 kg N₂O 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 N₂O emissions from shelterbelts and hedges are shown below in Table 20.

### Table 19. Descriptive statistics: Shelterbelts and hedgerows - carbon sequestration in soils and biomass

<table>
<thead>
<tr>
<th></th>
<th>biogenic carbon sequestration (Mg C/ha/yr)</th>
<th>number of studies</th>
<th>ratio of sequestration to emission: number of studies</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>total ecosystem carbon (soil organic carbon, above and belowground biomass)</td>
<td>2.78</td>
<td>10</td>
<td>10/0</td>
<td>0.73</td>
<td>1.15</td>
<td>4.41</td>
</tr>
<tr>
<td>above and belowground live biomass</td>
<td>1.90</td>
<td>3</td>
<td>3/0</td>
<td>0.39</td>
<td>1.14</td>
<td>2.65</td>
</tr>
<tr>
<td>soil organic carbon-only</td>
<td>0.52</td>
<td>8</td>
<td>8/0</td>
<td>0.24</td>
<td>0.05</td>
<td>0.99</td>
</tr>
<tr>
<td>empirical site studies</td>
<td>2.17</td>
<td>9</td>
<td>9/0</td>
<td>1.01</td>
<td>0.20</td>
<td>4.15</td>
</tr>
<tr>
<td>modeling studies</td>
<td>2.03</td>
<td>5</td>
<td>5/0</td>
<td>0.39</td>
<td>1.27</td>
<td>2.80</td>
</tr>
<tr>
<td>aggregate statistical analyses or statistical summaries</td>
<td>1.40</td>
<td>1</td>
<td>1/0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>expert judgment/literature review</td>
<td>0.77</td>
<td>11</td>
<td>11/0</td>
<td>0.31</td>
<td>0.17</td>
<td>1.37</td>
</tr>
<tr>
<td>15 to 25 year annual sequestration rate</td>
<td>1.38</td>
<td>13</td>
<td>13/0</td>
<td>0.34</td>
<td>0.72</td>
<td>2.04</td>
</tr>
<tr>
<td>less than 15 year annual sequestration rate</td>
<td>4.96</td>
<td>2</td>
<td>2/0</td>
<td>4.68</td>
<td>(4.22)</td>
<td>14.14</td>
</tr>
<tr>
<td>25 year-plus annual sequestration rate</td>
<td>1.45</td>
<td>7</td>
<td>7/0</td>
<td>0.37</td>
<td>0.73</td>
<td>2.17</td>
</tr>
</tbody>
</table>

*a statistical summaries or derivative statistical analyses other than meta-analyses

*b 26 study results, 26 studies

c. Methane

Methane is oxidized in both cropland and forested soils. The change in the rate of CH₄ oxidation in soils from establishing shelterbelts and hedges is calculated as the difference in the rate of soil CH₄ oxidation in cropped soils, as taken from Aronson and Helliker (2010), and estimated annual oxidation in shelterbelts and hedges. Relatively few published estimates of CH₄ oxidation rates for soils of shelterbelts and hedges can be found in the literature; we were able to identify five studies. In lieu of an adequate set of estimates for soil CH₄ oxidation rates specific to shelterbelts and hedges, in estimating the change in CH₄ uptake by shelterbelts establishment we use the mean rate of CH₄ oxidation for soils afforested former cropland (see Section IV, Subsection Bc above).
In Table 21, we show the descriptive statistics for the five studies that do provide information on mean annual CH₄ oxidation in shelterbelt soils. These are given in metric units, following general scientific conventions. The mean for these studies is generally lower that was reported in Table 17 for afforested formerly cultivated soils. It is not known whether the difference in the estimates reflects a real difference in soil CH₄ uptake potential between shelterbelt soils and soils of upland afforested former cropland.

As noted in discussing afforestation on idled cropland, the contribution of changes in soil CH₄ oxidation from land-use change to overall GHG-avoidance is small.

Table 21. Descriptive statistics: Shelterbelts and hedgerows - CH₄

<table>
<thead>
<tr>
<th></th>
<th>soil CH₄ oxidation (kg CH₄/ hectare/ yr)</th>
<th>number of study results</th>
<th>ratio, positive-to-negative results: number of study results</th>
<th>standard error of mean (±)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>all studies</td>
<td>0.89</td>
<td>6/0</td>
<td>0.23</td>
<td>0.45</td>
<td>1.34</td>
<td></td>
</tr>
<tr>
<td>empirical site studies</td>
<td>1.00</td>
<td>5/0</td>
<td>0.24</td>
<td>0.52</td>
<td>1.48</td>
<td></td>
</tr>
<tr>
<td>modeling studies</td>
<td>0.35</td>
<td>1/0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>shelterbelts</td>
<td>0.66</td>
<td>6/0</td>
<td>NA</td>
<td>0.00</td>
<td>1.32</td>
<td></td>
</tr>
<tr>
<td>hedgerows</td>
<td>0.50</td>
<td>2/0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>studies with cropland counterfactuals</td>
<td>0.92</td>
<td>1/0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

a CH₄ soil oxidation = removal from atmosphere and destruction in soils
b 6 study results, 5 studies (4 empirical site studies, 1 modeling/empirical site study)
c 1 study reports multiple results by study type

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 N₂O 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 N₂O emission from and CH₄ 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 N₂O emission and CH₄ emission and uptake rates. (Swan et al., 2015; Eagle et al., 2012). We follow this practice.

Table 22 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 the avoided-emissions are slightly different from those...
for cropland temporarily retired to grass (see Table 9 above). Using this approach, for each 100,000 acres of cropland converted to contour buffer strips, field borders, and vegetative and herbaceous wind barriers, an estimated 161,000 CO₂-equivalent short tons of greenhouse gases that otherwise would have occurred are avoided. Of this, a little less than 90 percent is avoided from in-state sources.

Table 22. Field borders, contour buffer strips, vegetative barriers, herbaceous wind barriers: Emissions- avoided a

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Emission Source or Sink</th>
<th>Emission (CO₂-e short tons per 100,000 acres per year) a</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂O-direct</td>
<td>soils</td>
<td>(41,091)</td>
<td>crop production</td>
</tr>
<tr>
<td>N₂O-indirect</td>
<td>indirect emission-Nitrogen volatilization, redeposition</td>
<td>(2,107)</td>
<td>crop production</td>
</tr>
<tr>
<td>N₂O-indirect leaching</td>
<td>indirect emission-Nitrogen leaching or runoff</td>
<td>(11,703)</td>
<td>crop production</td>
</tr>
<tr>
<td>CH₄ b</td>
<td>soils</td>
<td>468</td>
<td>crop production</td>
</tr>
<tr>
<td>CO₂ c,d</td>
<td>carbon accumulation in soils</td>
<td>(78,089)</td>
<td>crop production</td>
</tr>
<tr>
<td>CO₂</td>
<td>cultivated soils from lime or urea use</td>
<td>(2,808)</td>
<td>crop production</td>
</tr>
<tr>
<td>GHGs-energy</td>
<td>fossil fuel and electricity use in crop production</td>
<td>(5,518)</td>
<td>crop production</td>
</tr>
<tr>
<td>Out-of-State</td>
<td>upstream agricultural chemicals and fossil fuel production</td>
<td>(20,190)</td>
<td>crop production</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>(161,038)</td>
<td></td>
</tr>
</tbody>
</table>

Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>40 year storage</td>
<td>all sources and sinks</td>
<td>(239,127)</td>
<td>crop production</td>
</tr>
<tr>
<td>100 year storage</td>
<td>all sources and sinks</td>
<td>(473,395)</td>
<td>crop production</td>
</tr>
</tbody>
</table>

a positive = emissions increase, negative = emissions reduction
b reduction in soil CH₄ oxidation = relative increase in emissions
c carbon accumulation in soil and biomass = net removal of CO₂ 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 0.55 short tons of carbon per acre per year (1.24 metric tons of carbon per hectare per year) was used to calculate this, again taken from the calculations used to estimate the GHG emission reduction potential of temporary cropland idling in perennial grass. 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 0.55 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 N₂O flux rates from N₂O production in upland grass filter strips of 0.89 lbs. N₂O per acre (1 kg N₂O per hectare), which is not too different from the 1.28 lbs. N₂O per acre per year (1.44 kg N₂O per hectare per year) value used in Table 22 to calculate avoided N₂O 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 CH₄ uptake and oxidation for use in evaluating the suitability of the approach taken here on in soil CH₄ removals from the atmosphere.

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 N₂O losses than are upland soils. Whereas upland soils generally act to oxidize CH₄, riparian buffer soils often act as net sources of emission of CH₄ to the atmosphere, although field observations of CH₄ 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 23 shows the estimated net annual greenhouse gas balance from the conversion of cropland to riparian grassland or herbaceous riparian buffers. For each 100,000 acres of cropland retired to grassland buffer, an estimated 77,000 CO₂-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 avoided-emissions 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 CH₄ from generally wetter riparian soils offset reductions in the emission of N₂O from these soils. The average acre of cropland in Minnesota is heavily fertilized with synthetic and manure-based nitrogen. Emissions of N₂O 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 N₂O 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 CO₂ through biogenic carbon sequestration on 100,000 acres of riparian soils are some 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 23, 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 CO₂-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 127,000 CO₂-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 275,000 CO₂-equivalent short tons (see Table 23). 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 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 23 above.

Biogenic carbon sequestration riparian grassland buffers is discussed below, as are avoided direct emissions of N$_2$O 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$_2$O 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 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, 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 above ground 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 23, we estimate that, on 100,000 acres in perennial grasses, riparian buffers on former cropland will sequester 49,000 short tons of carbon as CO₂ (13,000 nominal 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 CO₂-equivalent short tons per acre for summary Table 23.

In developing our estimate of annual sequestration in riparian grassland buffers, we reviewed fourteen studies, including one micro-meteorological (eddy covariance) site study, four other empirical site studies, one derivative statistical study and eight literature reviews or studies that report results developed using expert judgment (see Table 24). Eight 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 14 studies to derive an estimate of annual carbon sequestration from riparian grassland buffers.

Table 24. Descriptive statistics: Grassland riparian buffers - carbon sequestration in soils and biomass

<table>
<thead>
<tr>
<th></th>
<th>biogenic carbon sequestration (Mg C/ha/yr)</th>
<th>number of studies</th>
<th>ratio of sequestration to emission: study numbers</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>all studies</td>
<td>0.79</td>
<td>14</td>
<td>14/0</td>
<td>0.153</td>
<td>0.49</td>
<td>1.09</td>
</tr>
<tr>
<td>total ecosystem carbon (soil organic carbon [SOC], above and belowground biomass)</td>
<td>0.53</td>
<td>3</td>
<td>3/0</td>
<td>0.052</td>
<td>0.43</td>
<td>0.63</td>
</tr>
<tr>
<td>above and belowground biomass, litter, detritus</td>
<td>1.31</td>
<td>2</td>
<td>2/0</td>
<td>0.931</td>
<td>(0.52)</td>
<td>3.13</td>
</tr>
<tr>
<td>soil organic carbon-only a</td>
<td>0.66</td>
<td>9</td>
<td>9/0</td>
<td>0.073</td>
<td>0.52</td>
<td>0.81</td>
</tr>
<tr>
<td>derivative statistical analyses or statistical summaries b</td>
<td>0.54</td>
<td>1</td>
<td>1/0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>expert judgment/literature review</td>
<td>0.55</td>
<td>8</td>
<td>8/0</td>
<td>0.042</td>
<td>0.47</td>
<td>0.63</td>
</tr>
<tr>
<td>empirical site study- eddy covariance (NECB/NBP)</td>
<td>0.63</td>
<td>1</td>
<td>1/0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>empirical site study-destructive biomass sampling</td>
<td>1.73</td>
<td>2</td>
<td>2/0</td>
<td>0.931</td>
<td>(0.09)</td>
<td>3.56</td>
</tr>
<tr>
<td>empirical site studies-soil sampling</td>
<td>0.99</td>
<td>2</td>
<td>2/0</td>
<td>0.094</td>
<td>0.81</td>
<td>1.18</td>
</tr>
<tr>
<td>average 20 year rate of sequestration</td>
<td>0.56</td>
<td>2</td>
<td>2/0</td>
<td>0.098</td>
<td>0.37</td>
<td>0.76</td>
</tr>
<tr>
<td>average 5 to 10 year rate of sequestration</td>
<td>1.25</td>
<td>5</td>
<td>5/0</td>
<td>0.357</td>
<td>0.55</td>
<td>1.95</td>
</tr>
</tbody>
</table>

* estimates for empirical site studies, soil sampling, soil organic carbon-only, and average 5 to 10 year rate of sequestration developed against a cropland counterfactual
b statistical summaries or derivative statistical analyses other than meta-analyses
c 14 study results, 14 studies
d ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

Based on the fourteen studies, the idling of cropland in riparian grassland buffer is estimated to sequester 0.79 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 14 studies range from 0.55 to 1.73 metric tons of carbon per hectare (0.25 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 CO₂ 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 in groundwater flows. (Hinslow and Dahlgren, 2016) Nitrate in groundwater is...
the principal form in which excess nitrogen is removed from cropland. During denitrification, nitrate is microbially reduced to N\textsubscript{2}O or N\textsubscript{2} under anaerobic conditions. Riparian buffers are much wetter that the soils of upland croplands. Maximum N\textsubscript{2}O production in soils occurs around water-filled pore space of 70 to 80 percent, which is also optimal soil wetness for denitrification. (Hefting \textit{et al.}, 2006; Machefert \textit{et al.}, 2002) Nitrate-laden groundwater flows from cropland to riparian grassland buffers sustain substantial emissions of N\textsubscript{2}O from buffers to the atmosphere. (Schelde \textit{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\textsubscript{2}O production and emissions are the unintended byproduct of that use of riparian buffers for nitrate control.

N\textsubscript{2}O 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 \textit{et al.}, 2014; Jacinthe \textit{et al.}, 2012) The availability of large amounts of organic carbon substrate in riparian buffers also promotes N\textsubscript{2}O production, as does the presence of fine textured soils.

In general, N\textsubscript{2}O emissions from riparian buffers, grassland or forestland, are higher than emissions from upland unmanaged grassland, but lower than N\textsubscript{2}O emissions from adjacent cropland. (Ambus and Christensen, 1995; Dunmola \textit{et al.}, 2010; Groh \textit{et al.}, 2018; Kim \textit{et al.}, 2009; Vllain \textit{et al.}, 2012) Riparian grassland buffers are largely unmanaged, with little intentional input of synthetic fertilizer or manure and no tillage, resulting in much lower N\textsubscript{2}O emissions than are found in adjacent croplands.

Avoided-emissions from the conversion of cropland to riparian grassland buffers are calculated as the difference in emissions on 100,000 acres between estimated emissions from riparian grassland buffers and average Minnesota cropland N\textsubscript{2}O 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\textsubscript{2}O 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\textsubscript{2}O per hectare (3.66 ± 0.78 lbs. N\textsubscript{2}O per acre), or about three times as much as upland restored grassland.

Based on MPCA emission inventory totals, average annual N\textsubscript{2}O emissions from Minnesota cropland are an estimated 4.8 kg N\textsubscript{2}O per hectare (4.3 lbs. N\textsubscript{2}O 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 25. 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\textsubscript{2}O 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\textsubscript{2}O 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 13.93 kg N\textsubscript{2}O per hectare (12.43 lbs. N\textsubscript{2}O per acre) less than adjacent cropland, which is directionally consistent with our results, if also more extreme in terms of reported reductions. From table 23, we estimate annual reductions of 0.72 kg N\textsubscript{2}O per hectare (0.63 lbs. N\textsubscript{2}O per acre).
A good deal more empirical research need to be developed, particularly directed toward this latter discrepancy. Based on what admittedly is a very small group of studies, it seems possible that $\text{N}_2\text{O}$ emissions from the conversion of cropland to riparian buffers could decline a small amount or a very large amount.

Table 25. Descriptive statistics: Grassland riparian buffers - $\text{N}_2\text{O}$

<table>
<thead>
<tr>
<th></th>
<th>emissions (kg $\text{N}_2\text{O}$/hectare/yr) a</th>
<th>number of studies b</th>
<th>ratio, positive to negative results: number of studies</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>all studies</td>
<td>4.10</td>
<td>15</td>
<td>15/0</td>
<td>0.88</td>
<td>2.38</td>
<td>5.82</td>
</tr>
<tr>
<td>empirical site studies</td>
<td>4.32</td>
<td>14</td>
<td>14/0</td>
<td>0.91</td>
<td>2.53</td>
<td>6.10</td>
</tr>
<tr>
<td>modeling studies</td>
<td>2.63</td>
<td>1</td>
<td>1/0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>annual flux monitoring/modeling</td>
<td>3.49</td>
<td>11</td>
<td>11/0</td>
<td>0.68</td>
<td>2.17</td>
<td>4.82</td>
</tr>
<tr>
<td>growing season and subgrowing season flux monitoring/modeling</td>
<td>7.33</td>
<td>3</td>
<td>3/0</td>
<td>3.33</td>
<td>0.80</td>
<td>13.86</td>
</tr>
<tr>
<td>1 year or less of observations or simulations</td>
<td>4.91</td>
<td>10</td>
<td>10/0</td>
<td>1.23</td>
<td>2.50</td>
<td>7.32</td>
</tr>
<tr>
<td>&gt; 1 year of observations or simulations</td>
<td>2.43</td>
<td>4</td>
<td>4/0</td>
<td>0.69</td>
<td>1.09</td>
<td>3.77</td>
</tr>
<tr>
<td>grassland riparian buffers against counterfactuals cropland</td>
<td>(13.92)</td>
<td>7</td>
<td>3/4</td>
<td>7.41</td>
<td>(28.44)</td>
<td>0.60</td>
</tr>
</tbody>
</table>

a negative emissions = removal from atmosphere and destruction in soils
b 15 study results, 15 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 $\text{CH}_4$ 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, $\text{CH}_4$ is taken up by soils and oxidized by methanotrophic bacteria and, as just noted, under near-saturated conditions, $\text{CH}_4$ is produced by methanogenic bacteria. On an annual basis, the balance between these processes of methane consumption (methanotrophy) and $\text{CH}_4$ production (methanogenesis) determines whether a riparian buffer is a net source or net sink of $\text{CH}_4$. (Jacinthe and Vidon, 2017)

In this report, net $\text{CH}_4$ 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 $\text{CH}_4$ uptake and oxidation in temperate croplands, developed from the average rates of cropland $\text{CH}_4$ oxidation given in Aronson and Helliker (2010), and estimated emissions from grassland riparian buffers.

In developing a $\text{CH}_4$ 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 $\text{CH}_4$ emissions from riparian buffers, while two reported net $\text{CH}_4$ uptake. The mean value for $\text{CH}_4$ emission for these eleven studies was 22.52 kg $\text{CH}_4$ per hectare per year (20.09 lbs. $\text{CH}_4$ per acre per year).

Care should be taken with this mean $\text{CH}_4$ 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 $\text{CH}_4$ 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 26). 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 26. Descriptive statistics: Grassland riparian buffers - CH$_4$

<table>
<thead>
<tr>
<th>Source of Emission Avoidance</th>
<th>Emissions (kg CH$_4$/hectare/yr)</th>
<th>Number of Studies</th>
<th>Ratio, Positive to Negative Results: Study Numbers</th>
<th>Standard Error of Mean (±)</th>
<th>Lower 95% Confidence Interval</th>
<th>Upper 95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Studies</td>
<td>22.52</td>
<td>11</td>
<td>9:2</td>
<td>12.36</td>
<td>(1.71)</td>
<td>46.75</td>
</tr>
<tr>
<td>Empirical Site Studies</td>
<td>22.52</td>
<td>11</td>
<td>9:2</td>
<td>12.36</td>
<td>(1.71)</td>
<td>46.75</td>
</tr>
<tr>
<td>Annual Flux Monitoring/Modeling</td>
<td>3.24</td>
<td>6</td>
<td>4:2</td>
<td>2.24</td>
<td>(1.15)</td>
<td>7.64</td>
</tr>
<tr>
<td>Growing Season and Subgrowing Season Flux Monitoring/Modeling</td>
<td>45.35</td>
<td>5</td>
<td>4:1</td>
<td>24.38</td>
<td>(2.43)</td>
<td>93.13</td>
</tr>
<tr>
<td>1 Year of Observations or Simulations</td>
<td>21.53</td>
<td>7</td>
<td>6:1</td>
<td>16.41</td>
<td>(10.63)</td>
<td>53.68</td>
</tr>
<tr>
<td>&gt; 1 Year of Observations or Simulations</td>
<td>17.54</td>
<td>5</td>
<td>3:2</td>
<td>17.62</td>
<td>(16.99)</td>
<td>52.07</td>
</tr>
</tbody>
</table>

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 203,000 CO$_2$-equivalent short tons of emissions that would otherwise have occurred are avoided (see Table 27 below). For croplands converted to forested buffers, this is roughly two and one-half times what is avoided by grassland-type riparian buffers, but only 80 percent that of upland afforested lands.

Forested and multispecies riparian buffers are emission sources of both CH$_4$ and N$_2$O, although in the case of N$_2$O, 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 Gb, the large amounts of nutrients that, by design, are intercepted in buffers sustain high levels of N$_2$O production in riparian soils. Soil wetness also contributes to relatively high rates of N$_2$O emission from these soils.

Avoided-emissions from forested and multispecies buffers on former cropland are shown in Table 27 by source of emission-avoidance. Most avoided-emissions from the retirement of cropland to forested riparian buffers or multispecies buffers occur in state, about 90 percent. The rest is associated with the out-of-state avoided manufacture of fertilizer, fuel and agricultural chemicals no longer used in crop production.
Biogenic carbon sequestration from forested buffer establishment on idled soils is discussed immediately below. Avoided direct emissions of N₂O from soils and the effects of forested riparian buffer creation on soil CH₄ oxidation are discussed in the subsequent two subsections. 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 are 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 CO₂. 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 203,000 CO₂-equivalent 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 401,000 CO₂-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 995,000 CO₂-equivalent short tons (see Table 27). The approach that we use in converting observed rates 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,

---

**Table 27. Forested and multispecies riparian buffers: Emissions-avoided**

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Emission Source or Sink</th>
<th>Emission (CO₂-e short tons per 100,000 acres per year)</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂O-direct</td>
<td>soils</td>
<td>7,033</td>
<td>crop production</td>
</tr>
<tr>
<td>N₂O-indirect</td>
<td>indirect emission-Nitrogen volatilization, deposition</td>
<td>(2,148)</td>
<td>crop production</td>
</tr>
<tr>
<td>CH₄</td>
<td>soils</td>
<td>33,466</td>
<td>crop production</td>
</tr>
<tr>
<td>CO₂⁺</td>
<td>carbon accumulation in soils and biomass</td>
<td>(198,058)</td>
<td>crop production</td>
</tr>
<tr>
<td>CO₂</td>
<td>cultivated soils from lime or urea use</td>
<td>(2,808)</td>
<td>crop production</td>
</tr>
<tr>
<td>GHGs-energy</td>
<td>fossil fuel and electricity use in crop production</td>
<td>(6,892)</td>
<td>crop production</td>
</tr>
<tr>
<td>Out-of-State GHGs</td>
<td>upstream agricultural chemicals and fossil fuel production</td>
<td>(20,190)</td>
<td>crop production</td>
</tr>
</tbody>
</table>

**Total**

(203,251)

<table>
<thead>
<tr>
<th>Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 year storage</td>
</tr>
<tr>
<td>all sources and sinks</td>
</tr>
<tr>
<td>crop production</td>
</tr>
<tr>
<td>100 year storage</td>
</tr>
<tr>
<td>all sources and sinks</td>
</tr>
<tr>
<td>crop production</td>
</tr>
</tbody>
</table>

*positive = emissions increase, negative = emissions reduction  
⁺carbon accumulation in soil and biomass = net removal of CO₂ from the atmosphere = net emission reduction  
⁺⁺assumes 20 years of sustained storage of newly sequestered organic carbon in soils and biomass
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. 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 macroaggregates 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 27, we estimate that, on 100,000 afforested acres, riparian buffers on former cropland will sequester 198,000 short tons of carbon as CO₂, or 54,000 nominal 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 CO₂-equivalent tons for inclusion in the summary Table 27. During afforestation, CO₂ is removed from the atmosphere and incorporated into tree biomass and, eventually, into woody detritus and soils. This acts to offset emissions of CO₂ from elsewhere in the economy.

The average per acre sequestration rate for forests in riparian areas was developed from 15 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. Using the total ecosystem carbon approach, forested and multi-species buffers are estimated annually to sequester 3.15 ± 0.69 metric tons of carbon per hectare (1.41 ± 0.31 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, 27 studies of carbon sequestration in forested and multi-species buffers were reviewed. None reported carbon losses. Only one meta-analysis was available, but yielded an estimate of annual sequestration reasonably close to that of the mean for the 15 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 28. 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 remarkably similar to those reported for the larger set of studies reporting changes in total ecosystem carbon. Pooled, the sequestration estimates range from 1.57 to 5.58 metric tons of carbon per hectare per year (0.70 to 2.49 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-one 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 substantially higher during the first 15 years after buffer establishment than afterwards and as much as 40 percent 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.

Table 28. Descriptive statistics: Forested riparian buffers and multispecies buffers - carbon sequestration in soils and biomass

<table>
<thead>
<tr>
<th>Study Type</th>
<th>Biogenic Carbon Sequestration (Mg C/ha/yr)</th>
<th>Number of Studies</th>
<th>Ratio of Sequestration to Emission: Study Numbers</th>
<th>Standard Error of Mean (+/-)</th>
<th>Lower 95% Confidence Interval</th>
<th>Upper 95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total ecosystem carbon (soil organic carbon [SOC], above and belowground biomass)</td>
<td>3.15</td>
<td>15/0</td>
<td>0.69</td>
<td>1.79</td>
<td>4.51</td>
<td></td>
</tr>
<tr>
<td>Soil organic carbon-only</td>
<td>1.57</td>
<td>5/0</td>
<td>0.57</td>
<td>0.46</td>
<td>2.68</td>
<td></td>
</tr>
<tr>
<td>Above and belowground biomass</td>
<td>3.16</td>
<td>5/0</td>
<td>0.80</td>
<td>1.58</td>
<td>4.73</td>
<td></td>
</tr>
<tr>
<td>Empirical site study- eddy covariance (NECB/NBP)</td>
<td>2.92</td>
<td>3/0</td>
<td>0.30</td>
<td>2.33</td>
<td>3.52</td>
<td></td>
</tr>
<tr>
<td>Empirical site study-SOC soil sampling</td>
<td>1.93</td>
<td>3/0</td>
<td>0.81</td>
<td>0.34</td>
<td>3.52</td>
<td></td>
</tr>
<tr>
<td>Empirical site study-soil sampling, bole measurements, destructive biomass sampling, allometric relationships</td>
<td>5.58</td>
<td>4/0</td>
<td>1.95</td>
<td>1.75</td>
<td>9.41</td>
<td></td>
</tr>
<tr>
<td>Meta-analyses</td>
<td>2.60</td>
<td>1/0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Other derivative statistical analyses or statistical summaries</td>
<td>3.00</td>
<td>1/0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>Modeling study</td>
<td>2.18</td>
<td>4/0</td>
<td>0.30</td>
<td>1.60</td>
<td>2.77</td>
<td></td>
</tr>
<tr>
<td>Expert judgment/literature review</td>
<td>2.33</td>
<td>6/0</td>
<td>1.06</td>
<td>0.26</td>
<td>4.40</td>
<td></td>
</tr>
<tr>
<td>15 to 25 year annual rate of sequestration</td>
<td>3.86</td>
<td>8/0</td>
<td>1.29</td>
<td>1.33</td>
<td>6.40</td>
<td></td>
</tr>
<tr>
<td>0 to 15 year annual rate of sequestration</td>
<td>4.72</td>
<td>7/0</td>
<td>1.25</td>
<td>2.28</td>
<td>7.17</td>
<td></td>
</tr>
<tr>
<td>&gt;25 year annual rate of sequestration</td>
<td>3.91</td>
<td>6/0</td>
<td>1.44</td>
<td>1.09</td>
<td>6.72</td>
<td></td>
</tr>
</tbody>
</table>

a All estimates developed against cropland counterfactuals except other derivative statistical analyses or statistical summaries, empirical site studies- eddy covariance studies (NECB/NBP), and modeling studies.

b Statistical summaries or derivative statistical analyses other than meta-analyses.

c Ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions.

d 27 study results; 27 studies.

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 3.2 metric tons per hectare per year.
b. Nitrous oxide

The microbial processes and environmental conditions that, in riparian buffers, give rise to \( \text{N}_2\text{O} \) emission were discussed above in Section IV, Subsection Eb. 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 \( \text{N}_2\text{O} \) emissions from Minnesota cropland. \( \text{N}_2\text{O} \) emissions from Minnesota cropland are taken from the MPCA Greenhouse Gas Inventory. \( \text{N}_2\text{O} \) emissions from forested riparian buffers are estimated using emission rates developed on a per hectare basis from the scientific literature and converted to lbs. \( \text{N}_2\text{O} \) per acre for use in the calculation. To estimate \( \text{N}_2\text{O} \) emissions from forested and multi-species buffers, 28 studies with 33 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 29 studies (5.33 kilograms \( \text{N}_2\text{O} \) per hectare per year [4.76 lbs. \( \text{N}_2\text{O} \) per acre per year]) as the best estimate of mean annual \( \text{N}_2\text{O} \) emissions from forested riparian buffers.

No meta-analyses were available to support the calculation. The same is true of other classes of derivative statistical analyses. Likewise, results from literature reviews and from studies that report results based on expert judgment were not available.

Finally, eight studies were found in the scientific literature that, in side-by-side experiments compare \( \text{N}_2\text{O} \) 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 \( \text{N}_2\text{O} \) per hectare per year (5.9 lbs. \( \text{N}_2\text{O} \) per acre per year), favoring croplands as by far the higher emitting source. These results contrast substantially with the results we present in Table 27, which suggests that uncertainty still shrouds these issues. Based on the side-by-side studies, few as they are, it seems possible that \( \text{N}_2\text{O} \) emissions from cropland converted to riparian forestland could decline. Clearly, more research is needed on this question.

The descriptive statistics for the studies that were reviewed are shown in Table 29.

**Table 29. Descriptive statistics: Forested and multispecies riparian buffers - \( \text{N}_2\text{O} \)**

<table>
<thead>
<tr>
<th></th>
<th>emissions (kg ( \text{N}_2\text{O}/ )hectare/yr)</th>
<th>number of study results</th>
<th>ratio, positive to negative results: number of study results</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>all studies</td>
<td>5.33</td>
<td>33</td>
<td>32/1</td>
<td>1.94</td>
<td>1.53</td>
<td>9.14</td>
</tr>
<tr>
<td>empirical site studies</td>
<td>5.22</td>
<td>32</td>
<td>31/1</td>
<td>2.00</td>
<td>1.29</td>
<td>9.14</td>
</tr>
<tr>
<td>derivative statistical analyses or statistical summaries $^b$</td>
<td>9.10</td>
<td>1</td>
<td>1/0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>annual flux monitoring/modeling</td>
<td>6.76</td>
<td>24</td>
<td>23/1</td>
<td>2.62</td>
<td>1.63</td>
<td>11.90</td>
</tr>
<tr>
<td>growing season and subgrowing season flux monitoring/modeling</td>
<td>1.49</td>
<td>9</td>
<td>9/0</td>
<td>0.47</td>
<td>0.56</td>
<td>2.42</td>
</tr>
<tr>
<td>&gt; 1 year of observations or simulations</td>
<td>6.79</td>
<td>20</td>
<td>19/1</td>
<td>2.67</td>
<td>1.56</td>
<td>12.01</td>
</tr>
<tr>
<td>&gt; 1 year of observations or simulations</td>
<td>3.76</td>
<td>21</td>
<td>21/0</td>
<td>1.75</td>
<td>0.32</td>
<td>7.19</td>
</tr>
<tr>
<td>forested riparian buffers against cropland or pastureland counterfactuals</td>
<td>(6.61)</td>
<td>8</td>
<td>3/5</td>
<td>4.29</td>
<td>(15.01)</td>
<td>1.80</td>
</tr>
</tbody>
</table>

$^a$ negative emissions = removal from atmosphere and destruction in soils  
$^b$ statistical summaries or derivative statistical analyses other than meta-analyses  
$^c$ 33 study results, 28 studies (1 derivative statistical analysis, 27 empirical site studies)  
$^d$ 4 studies report multiple results by buffer type (forested, mixed) or vegetation type
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 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 27.

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 buffer 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 30.

Table 30. Descriptive statistics: Forested and multispecies riparian buffers - CH$_4$
G. 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 al., 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.

Table 31 shows the estimated net annual greenhouse gas balance from the use of cover crops on 100,000 acres of cropland. For each 100,000 acres of cropland in winter cover crops, an estimated 20,000 CO2-equivalent short tons of GHGs are avoided annually. Of this, most derives from biogenic carbon sequestration in cover crop soils. Also important are reduced N2O emissions from surface water and groundwater resulting from reduced leaching. Emissions of N2O from cropped soils increase under cover crops, offsetting some of otherwise avoided-emissions through reduced nitrate leaching and soil carbon sequestration. About 95 percent of emissions-avoided are from in-state sources, and the remainder is from the avoided out-of-state manufacture of fertilizer, other agricultural chemicals and fuels.

As elsewhere in this report, in developing the estimates shown in Table 31, 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 20,000 CO\textsubscript{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 41,000 CO\textsubscript{2}-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 101,000 CO\textsubscript{2}-equivalent short tons (see Table 31). 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 31. Winter cover crops/Catch crops: Emissions-avoided

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Emission Source or Sink</th>
<th>Emission (CO\textsubscript{2}-e short tons per 100,000 acres per year) \textsuperscript{a}</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>N\textsubscript{2}O-direct</td>
<td>soils</td>
<td>7,511</td>
<td>no cover crop</td>
</tr>
<tr>
<td>N\textsubscript{2}O-indirect volatilization</td>
<td>indirect emission-Nitrogen volatilization, redeposition</td>
<td>not known</td>
<td>no cover crop</td>
</tr>
<tr>
<td>N\textsubscript{2}O-indirect leaching</td>
<td>indirect emission-Nitrogen leaching or runoff</td>
<td>(7,329)</td>
<td>no cover crop</td>
</tr>
<tr>
<td>CH\textsubscript{4} \textsuperscript{b}</td>
<td>soils</td>
<td>131</td>
<td>no cover crop</td>
</tr>
<tr>
<td>CO\textsubscript{2} \textsuperscript{c,d}</td>
<td>carbon accumulation in soils</td>
<td>(20,118)</td>
<td>no cover crop</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>cultivated soils from lime or urea use</td>
<td>-</td>
<td>no cover crop</td>
</tr>
<tr>
<td>GHGs-energy</td>
<td>fossil fuel and electricity use in crop production</td>
<td>519</td>
<td>no cover crop</td>
</tr>
<tr>
<td>Out-of-State Upstream GHGs</td>
<td>upstream agricultural chemicals and fossil fuel production</td>
<td>(1,187)</td>
<td>no cover crop</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>(20,474)</td>
<td></td>
</tr>
</tbody>
</table>

Emissions with leguminous cover crops-only:

| GHGS | all sources and sinks | (9,022) | no cover crop |

Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass

| 40 year storage | all sources and sinks | (40,592) | no cover crop |
| 100 year storage | all sources and sinks | (100,946) | no cover crop |

\textsuperscript{a} positive = emissions increase, negative = emissions reduction
\textsuperscript{b} a reduction in soil CH\textsubscript{4} oxidation = a relative increase in CH\textsubscript{4} emissions
\textsuperscript{c} carbon accumulation in soils = a net removal of CO\textsubscript{2} from the atmosphere = net emission reduction
\textsuperscript{d} assumes 20 years of sustained storage of newly sequestered organic carbon in soils and biomass

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 9,000 CO\textsubscript{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\textsubscript{2}O emissions from cropland soils, more than offsetting any emission reduction resulting from reduced use and manufacture of synthetic fertilizer.

A small 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 32. Taken together, these studies report an average annual rate of avoidance of 0.60 CO\textsubscript{2}-equivalent short tons per acre (1.35 CO\textsubscript{2}-equivalent metric tons per hectare).
Table 32. Published estimates of greenhouse gas-avoidance from cover crop use a

<table>
<thead>
<tr>
<th>Study</th>
<th>Type of study</th>
<th>CO₂-eq. short tons per acre per year</th>
<th>CO₂-eq. short tons per 100,000 acres per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gelfand and Robertson (2015)</td>
<td>site study</td>
<td>0.50</td>
<td>49,953</td>
</tr>
<tr>
<td>Robertson et al. (2000)</td>
<td>site study</td>
<td>0.23</td>
<td>22,747</td>
</tr>
<tr>
<td>DeGryze et al. (2010)</td>
<td>modeling study</td>
<td>0.60</td>
<td>59,840</td>
</tr>
<tr>
<td>DeGryze et al. (2011)</td>
<td>modeling study</td>
<td>0.53</td>
<td>53,465</td>
</tr>
<tr>
<td>Kaye and Quemada (2017)</td>
<td>literature review/expert judgment</td>
<td>0.67</td>
<td>67,125</td>
</tr>
<tr>
<td>Swan et al. (2015) b</td>
<td>literature review/expert judgment</td>
<td>0.41</td>
<td>40,778</td>
</tr>
<tr>
<td>Abdalla et al. (2019)</td>
<td>derivative statistical analysis</td>
<td>0.92</td>
<td>91,878</td>
</tr>
<tr>
<td>Eagle et al. (2012)</td>
<td>derivative statistical analysis</td>
<td>0.86</td>
<td>85,634</td>
</tr>
<tr>
<td>This report</td>
<td>literature review</td>
<td>0.20</td>
<td>20,474</td>
</tr>
</tbody>
</table>

a results as reported without adjustments
b partial difference, accounting for direct soils emissions and soil carbon sequestration-only

Terrestrial carbon sequestration resulting from the use of winter cover crops is discussed below, as are avoided direct emissions of N₂O and the effects of winter cover crops 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 above 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. 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.

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). 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 31 for winter cover crops on 100,000 acres were developed using meta-analysis estimates of average annual sequestration rates, discounted to account for an assumed 20-year persistence of newly sequestered organic carbon in soil. We reviewed 75 studies with 114 study results, including one meta-analysis, seven other derivative statistical summaries or analyses, 37 empirical site studies (67 study results), 19 modeling studies (25 study results), and eleven literature reviews or studies that report results developed on the basis of expert judgment (twelve 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-analysis, the introduction of cover crops to 100,000 acres of cropland would result in 20,000 CO₂-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 meta-analysis estimate, winter cover crops are estimated to annually sequester 0.32 metric tons of carbon per hectare (0.52 short tons of CO₂). This is the estimated rate prior to truncation to accommodate 20-year assumed persistence of carbon in cropland soils.

The descriptive statistics for the 75 studies that were reviewed are shown in Table 33. These are given in metric tons of carbon, but converted to short CO₂-equivalent tons for inclusion in the summary Table 31. The average of all studies reviewed (0.33 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 0.19 to 0.46 metric tons per hectare per year (0.31 to 0.76 short tons of CO₂ per acre). Estimated annual sequestration from the 37 empirical site studies is some 0.36 ± 0.06 metric tons per hectare (0.59 ± 0.1 short tons of CO₂ per acre), or quite similar to the meta-analysis estimate. Excluding the estimates drawn from the modeling studies, the estimates cluster in a tight range of 0.32 to 0.46 metric tons of carbon per hectare per year.

Overall, in roughly nine out of ten study results, cropland soil accumulated organic carbon under cover crops. The rate was slightly lower in empirical site studies, 8.5 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 leguminous cover crops was slightly higher than that for nonleguminous cover crops or a mix of legumes and nonleguminous cover crops. The differences were not substantial. Soil sampling depth did not play a role in the results; sequestration rates for soil depths of 4 to 12 inches (10 to 30 centimeters) and 16 inches (40 centimeters) and deeper were virtually identical. In the scientific literature, sequestration rates often are said to peak in the first decade after the change in practice, declining thereafter. (Nepchalova et al., 2018) This is borne out by sequestration rates reported in Table 33 by decade after initiation of cover crop practices.

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 30 to 40 percent by simultaneously adopting less intensive tillage practices and cover cropping (see Table 33).

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 0.3 metric tons of carbon per hectare per year (0.13 short tons of carbon per acre per year).

Table 33. Descriptive statistics: Winter cover crops/Catch crops - carbon sequestration in soils

<table>
<thead>
<tr>
<th></th>
<th>biogenic carbon sequestration (Mg C/ha/yr)</th>
<th>number of study results</th>
<th>ratio of sequestration to emission: number of study results</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>meta-analyses</td>
<td>0.32</td>
<td>1</td>
<td>1/0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>all studies</td>
<td>0.33</td>
<td>114</td>
<td>102/12</td>
<td>0.04</td>
<td>0.25</td>
<td>0.41</td>
</tr>
<tr>
<td>derivative statistical analyses or statistical summaries a</td>
<td>0.46</td>
<td>9</td>
<td>9/0</td>
<td>0.12</td>
<td>0.22</td>
<td>0.71</td>
</tr>
<tr>
<td>site-empirical studies</td>
<td>0.36</td>
<td>67</td>
<td>57/10</td>
<td>0.06</td>
<td>0.23</td>
<td>0.49</td>
</tr>
<tr>
<td>modeling studies</td>
<td>0.19</td>
<td>25</td>
<td>23/2</td>
<td>0.04</td>
<td>0.11</td>
<td>0.27</td>
</tr>
<tr>
<td>expert judgment/literature reviews</td>
<td>0.36</td>
<td>12</td>
<td>12/0</td>
<td>0.10</td>
<td>0.17</td>
<td>0.55</td>
</tr>
<tr>
<td>nonleguminous cover crop</td>
<td>0.36</td>
<td>39</td>
<td>35/4</td>
<td>0.09</td>
<td>0.19</td>
<td>0.53</td>
</tr>
<tr>
<td>leguminous cover crop</td>
<td>0.37</td>
<td>31</td>
<td>26/5</td>
<td>0.08</td>
<td>0.21</td>
<td>0.52</td>
</tr>
<tr>
<td>mixed leguminous/nonleguminous cover crop or undifferentiated by cover crop type</td>
<td>0.31</td>
<td>45</td>
<td>42/3</td>
<td>0.05</td>
<td>0.21</td>
<td>0.41</td>
</tr>
<tr>
<td>conventional tillage</td>
<td>0.30</td>
<td>15</td>
<td>15/0</td>
<td>0.09</td>
<td>0.12</td>
<td>0.48</td>
</tr>
<tr>
<td>reduced tillage</td>
<td>0.25</td>
<td>18</td>
<td>15/3</td>
<td>0.09</td>
<td>0.08</td>
<td>0.43</td>
</tr>
<tr>
<td>no-till tillage</td>
<td>0.41</td>
<td>38</td>
<td>32/6</td>
<td>0.10</td>
<td>0.22</td>
<td>0.60</td>
</tr>
<tr>
<td>10 to 30 cm soil sampling/modeling depth b</td>
<td>0.39</td>
<td>56</td>
<td>49/7</td>
<td>0.06</td>
<td>0.27</td>
<td>0.51</td>
</tr>
<tr>
<td>&gt; 40 cm soil sampling/modeling depth b</td>
<td>0.36</td>
<td>26</td>
<td>23/3</td>
<td>0.11</td>
<td>0.14</td>
<td>0.59</td>
</tr>
<tr>
<td>0 to 9 year annual sequestration rate</td>
<td>0.48</td>
<td>47</td>
<td>38/9</td>
<td>0.09</td>
<td>0.31</td>
<td>0.66</td>
</tr>
<tr>
<td>10 year or more annual sequestration rate</td>
<td>0.22</td>
<td>46</td>
<td>44/2</td>
<td>0.03</td>
<td>0.15</td>
<td>0.28</td>
</tr>
</tbody>
</table>

a statistical summaries or derivative statistical analyses other than meta-analyses
b results for lowest reported sampling depth
c 114 study results, 75 studies (1 meta-analysis, 7 other derivative statistical analysis, 19 modeling studies, 37 empirical site studies, 11 expert reviews)
d 22 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
b. Nitrous oxide

$\text{N}_2\text{O}$ is produced in cropland by nitrification and denitrification processes. $\text{N}_2\text{O}$ 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 $\text{N}_2\text{O}$ 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. $\text{N}_2\text{O}$ is produced in these anaerobic microsites by denitrifying bacteria. (Mitchell et al., 2013; Petersen et al., 2011; Sardokie-Addio et al., 2003) Large $\text{N}_2\text{O}$ 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 $\text{N}_2\text{O}$ 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 $\text{N}_2\text{O}$ emissions. Average Minnesota cropland $\text{N}_2\text{O}$ emissions are taken from the MPCA Greenhouse Gas Inventory. To estimate the percentage change in $\text{N}_2\text{O}$ emissions under cover crops we reviewed 34 studies with 57 study results across cover crop type and tillage practice. Of these, 24 studies (34 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), four were modeling studies (8 study results), 16 were empirical site studies (22 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 $\text{N}_2\text{O}$ emission with cover crops. Using the meta-analysis mean estimate, the use of winter cover crops is estimated to increase $\text{N}_2\text{O}$ emissions by $12 \pm 1$ percent, a relatively minor change. By study type, the estimate percentage change ranged from $+12$ to $+81$ percent. The mean value for all 24 full-year studies that were reviewed was $+26 \pm 8$ percent, the same as for the 16 empirical site studies that were reviewed.

Of the 24 full-year studies that were reviewed, one-third reported emission reductions, while two-thirds reported increases. In the empirical site studies, 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 $\text{N}_2\text{O}$ emissions will prove muted.

By cover crop type, the increase in full-year $\text{N}_2\text{O}$ emissions ranged from 8 percent, in the case of nonleguminous cover crops, to 39 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, emissions under no-till tillage increased substantially more than did $\text{N}_2\text{O}$ 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 N₂O 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 15 percent.

The mean percentage change in the rate of N₂O 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 N₂O emissions that often occurs during cover crop residue decomposition.

The descriptive statistics for the studies that were reviewed are shown in Table 34.

The general sense of the analysis presented here, and of the large scientific literature, is that the effects of cover crops on N₂O soil emissions are likely to be muted. Best available evidence suggests a slight increase in emissions from the introduction of this practice.

### Table 34. Descriptive statistics: Winter cover crops/Catch crops - N₂O

<table>
<thead>
<tr>
<th>Category</th>
<th>Emissions: % change in emissions per hectare</th>
<th>Number of study results</th>
<th>Change in emissions, ratio positive-to-negative: numbers of study results</th>
<th>Standard error of mean (±)</th>
<th>Lower 95% confidence interval</th>
<th>Upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Full crop studies:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meta-analyses</td>
<td>12%</td>
<td>2</td>
<td>2/0</td>
<td>1%</td>
<td>9%</td>
<td>14%</td>
</tr>
<tr>
<td>All studies</td>
<td>26%</td>
<td>34</td>
<td>23/11</td>
<td>8%</td>
<td>10%</td>
<td>42%</td>
</tr>
<tr>
<td>Empirical site studies</td>
<td>27%</td>
<td>22</td>
<td>11/11</td>
<td>11%</td>
<td>5%</td>
<td>49%</td>
</tr>
<tr>
<td>Modeling studies</td>
<td>14%</td>
<td>8</td>
<td>8/0</td>
<td>6%</td>
<td>1%</td>
<td>26%</td>
</tr>
<tr>
<td>Expert judgment/literature reviews</td>
<td>81%</td>
<td>2</td>
<td>2/0</td>
<td>44%</td>
<td>-6%</td>
<td>168%</td>
</tr>
<tr>
<td>Nongenious cover crop</td>
<td>8%</td>
<td>16</td>
<td>9/7</td>
<td>8%</td>
<td>-8%</td>
<td>23%</td>
</tr>
<tr>
<td>Leguminous and mixed leguminous/nonleguminous cover crop</td>
<td>39%</td>
<td>16</td>
<td>15/4</td>
<td>13%</td>
<td>14%</td>
<td>64%</td>
</tr>
<tr>
<td>No-till tillage</td>
<td>46%</td>
<td>11</td>
<td>9/2</td>
<td>18%</td>
<td>11%</td>
<td>82%</td>
</tr>
<tr>
<td>Reduced tillage</td>
<td>25%</td>
<td>4</td>
<td>1/3</td>
<td>31%</td>
<td>-36%</td>
<td>86%</td>
</tr>
<tr>
<td>Conventional tillage</td>
<td>5%</td>
<td>4</td>
<td>3/1</td>
<td>3%</td>
<td>-1%</td>
<td>11%</td>
</tr>
<tr>
<td>1-2 years of observations or simulations</td>
<td>36%</td>
<td>12</td>
<td>7/5</td>
<td>12%</td>
<td>11%</td>
<td>60%</td>
</tr>
<tr>
<td>3 years or more of observations or simulations</td>
<td>15%</td>
<td>18</td>
<td>12/6</td>
<td>11%</td>
<td>-7%</td>
<td>38%</td>
</tr>
<tr>
<td><strong>Partial and full crop-year studies:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meta-analyses</td>
<td>76%</td>
<td>9</td>
<td>8/1</td>
<td>54%</td>
<td>-31%</td>
<td>183%</td>
</tr>
<tr>
<td>All studies</td>
<td>37%</td>
<td>57</td>
<td>42/15</td>
<td>10%</td>
<td>17%</td>
<td>58%</td>
</tr>
</tbody>
</table>

*34 study results, 24 studies (2 meta-analysis, 4 modeling studies, 16 empirical site studies, 2 expert reviews)*

**3 studies report multiple results by cover crop type (leguminous, nonleguminous), crop cover treatment (residues incorporated, nonincorporated), and/or tillage (no-till, reduced tillage, conventional tillage)

### c. Methane

The estimated change in methane soil oxidation resulting from the use of winter cover crops on 100,000 acres is miniscule, 131 CO₂-equivalent tons annually. The calculation of net greenhouse gas-avoidance from the use of winter cover crops is largely unaffected by changes in CH₄ 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 CH₄
is emitted from soils on a net basis or is consumed and whether a change in CH₄ from cropland, described in terms of CH₄ oxidation, enhances or reduces CH₄ oxidation.

In evaluating the effect of winter cover crops on CH₄ soil oxidation, we reviewed seven studies with 13 discrete observations, including five empirical site studies (eight study results) and one modelling study (four study results). Using the average value from all 13 studies, we estimate that the use of winter cover crops will reduce CH₄ soil oxidation by 6 percent, which applied on 100,000 acres, results in the reported 131 CO₂-equivalent tons of reduction in cropland CH₄ 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 13 studies, 40 percent favor an increase in CH₄ soil oxidation with cover cropping, 60 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 CH₄ soil oxidation to a 39 percent decrease.

The descriptive statistics for the studies that were reviewed are shown in Table 35, including standard errors and 95 percent confidence intervals.

**H. 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.

### Table 35. Descriptive statistics: Winter cover crops/Catch crops - CH₄

<table>
<thead>
<tr>
<th></th>
<th>oxidation: % change in oxidation</th>
<th>number of study results</th>
<th>change in oxidation, ratio positive-to-negative: numbers of study results</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>full crop studies: a,b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>all studies</td>
<td>-6%</td>
<td>13</td>
<td>5/8</td>
<td>17%</td>
<td>-39%</td>
<td>26%</td>
</tr>
<tr>
<td>empirical site studies</td>
<td>-6%</td>
<td>8</td>
<td>3/5</td>
<td>28%</td>
<td>-60%</td>
<td>49%</td>
</tr>
<tr>
<td>modeling studies</td>
<td>-10%</td>
<td>4</td>
<td>2/2</td>
<td>7%</td>
<td>-24%</td>
<td>5%</td>
</tr>
<tr>
<td>legume cover crop</td>
<td>31%</td>
<td>6</td>
<td>4/2</td>
<td>20%</td>
<td>-8%</td>
<td>69%</td>
</tr>
<tr>
<td>nonleguminous cover crop</td>
<td>-38%</td>
<td>7</td>
<td>1/6</td>
<td>20%</td>
<td>-77%</td>
<td>1%</td>
</tr>
<tr>
<td>1 year of observations or simulations</td>
<td>16%</td>
<td>5</td>
<td>2/3</td>
<td>30%</td>
<td>-43%</td>
<td>76%</td>
</tr>
<tr>
<td>4 years or more of observations or simulations</td>
<td>-24%</td>
<td>7</td>
<td>3/4</td>
<td>22%</td>
<td>-67%</td>
<td>20%</td>
</tr>
<tr>
<td>partial and full crop-year studies:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>all studies</td>
<td>-9%</td>
<td>14</td>
<td>5/9</td>
<td>16%</td>
<td>-40%</td>
<td>22%</td>
</tr>
</tbody>
</table>

*13 study results, 7 studies (1 modeling study, 5 empirical site studies, 1 expert review)

*b 2 studies report multiple results by cover crop type (leguminous, nonleguminous), crop cover treatment (residues incorporated, nonincorporated), and/or tillage (no-till, reduced tillage, conventional tillage)
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. (Baransi 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 N₂O 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 CO₂ from fossil fuel use in crop production.

A budget of avoided greenhouse gas emissions from no-till cultivation is given in Table 36. For each 100,000 acres of cropland converted from full inversion tillage to no-till practice, an estimated 14,000 CO₂-equivalent short tons of emissions are avoided. All of this, plus some, is accounted for by enhanced soil organic carbon sequestration in soils. Increased soil emissions of N₂O act to offset about one-quarter of the sequestration effects. About 95 percent of emissions-avoided are 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 CO₂. This is the longest period over which, in our opinion, sustained storage safely can be assumed. Under this assumption, avoided-emissions are estimated 14,000 CO₂-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 28,000 CO₂-equivalent short tons. Had 100-years of assured storage been assumed, avoided-emissions would have totaled 72,000 CO₂-equivalent short tons (see Table 36).

The amount of time in storage determines the degree to which, for any particular project, sequestered carbon offsets CO₂ 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 37, all support a positive emissions effect of conventional tillage to no-till conversions, with reductions per 100,000 acres of conversions ranging 18,000 to 121,000 CO₂-equivalent short tons.
Table 36. No-till tillage: Emissions-avoided

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Emission Source or Sink</th>
<th>Emission (CO₂-e short tons per 100,000 acres per year)</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂O-direct</td>
<td>soils</td>
<td>3,815</td>
<td>conventional tillage</td>
</tr>
<tr>
<td>N₂O-indirect leaching</td>
<td>indirect emission-Nitrogen leaching or runoff</td>
<td>-</td>
<td>conventional tillage</td>
</tr>
<tr>
<td>CH₄ c</td>
<td>soils</td>
<td>(283)</td>
<td>conventional tillage</td>
</tr>
<tr>
<td>CO₂ d,e</td>
<td>carbon accumulation in soils</td>
<td>(14,589)</td>
<td>conventional tillage</td>
</tr>
<tr>
<td>GHGs-energy</td>
<td>fossil fuel and electricity use in crop production</td>
<td>(2,704)</td>
<td>conventional tillage</td>
</tr>
<tr>
<td>Out-of-State Upstream GHGs</td>
<td>upstream agricultural chemicals and fossil fuel production</td>
<td>(599)</td>
<td>conventional tillage</td>
</tr>
</tbody>
</table>

Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils

<table>
<thead>
<tr>
<th>Year Storage</th>
<th>Total Source and Sinks (short tons per 100,000 acres per year)</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 year storage</td>
<td>(28,396)</td>
<td>conventional tillage</td>
</tr>
<tr>
<td>100 year storage</td>
<td>(72,162)</td>
<td>conventional tillage</td>
</tr>
</tbody>
</table>

Biogenic carbon sequestration from the use of no-till on cropland soils is discussed below, as are avoided direct emissions of N₂O from soils and the effects of no-till 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 above in Section II, Subsection E.

a. Carbon sequestration in soils

No-till is a crop production practice in which cropland soils are left untillled. 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 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.

Table 37. Published studies of the integrated impacts of no-till practice on greenhouse gases from all sources of emissions-avoidance a

<table>
<thead>
<tr>
<th>Study</th>
<th>Type of study</th>
<th>CO2-eq. short tons per acre per year</th>
<th>CO2-eq. short tons per 100,000 acres per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Archer and Halvorson (2010)</td>
<td>site study</td>
<td>0.89</td>
<td>88,711</td>
</tr>
<tr>
<td>Gelford and Robertson (2015)</td>
<td>site study</td>
<td>0.51</td>
<td>51,291</td>
</tr>
<tr>
<td>Krauss et al. (2017)</td>
<td>site study</td>
<td>0.79</td>
<td>78,632</td>
</tr>
<tr>
<td>Mosier et al. (2005)</td>
<td>site study</td>
<td>0.71</td>
<td>71,495</td>
</tr>
<tr>
<td>Mosier et al. (2006)</td>
<td>site study</td>
<td>1.21</td>
<td>120,958</td>
</tr>
<tr>
<td>Robertson et al. (2000)</td>
<td>site study</td>
<td>0.45</td>
<td>44,601</td>
</tr>
<tr>
<td>Sainju et al. (2014)</td>
<td>site study</td>
<td>0.18</td>
<td>17,796</td>
</tr>
<tr>
<td>Tellez et al. (2017)</td>
<td>site study</td>
<td>0.64</td>
<td>63,811</td>
</tr>
<tr>
<td>Del Grosso et al. (2005)</td>
<td>modeling study</td>
<td>0.78</td>
<td>78,052</td>
</tr>
<tr>
<td>Grant et al. (2004)</td>
<td>modeling study</td>
<td>0.27</td>
<td>27,207</td>
</tr>
<tr>
<td>Eagle et al. (2012)</td>
<td>other derivative statistical analysis c</td>
<td>0.66</td>
<td>65,563</td>
</tr>
<tr>
<td>Six et al. (2004)</td>
<td>other derivative statistical analysis c</td>
<td>0.31</td>
<td>30,772</td>
</tr>
<tr>
<td>Swan et al. (2015) b</td>
<td>literature review/expert judgment</td>
<td>0.34</td>
<td>34,166</td>
</tr>
<tr>
<td>Sainju et al. (2016)</td>
<td>meta-analysis</td>
<td>0.69</td>
<td>69,265</td>
</tr>
<tr>
<td>This report</td>
<td>literature review</td>
<td>0.14</td>
<td>13,807</td>
</tr>
</tbody>
</table>

a results as reported without adjustments
b change in soil N2O and soil organic carbon only
c other than formal meta-analysis

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 CO2, 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 CO2. Inland waters are known to be larger emitters of CO2. (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. (Angers and Eriksen-Hamel, 2008; Bai et al., 2018; Congreves et al., 2014; Du et al., 2017; Luo et al., 2010; Ogle et al., 2005; Ogle et al., 2010; Puget and Lal, 2005; Six et al., 2002a; Virto et al., 2012; West and Post, 2002)

Soils under no-till practice have a finite carbon storage capacity. 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 CO₂-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. Empirical site studies have found limited or no effect on soil carbon. (Yang et al., 2008; Wortman et al., 2010; Dimassi et al., 2013) In a modeling study, Conant et al. (2007) found substantial impacts of periodic tillage on SOC on a 100-year time frame.

In Table 36, we estimate that conversion to no-till from conventional tillage on 100,000 acres would result in 15,000 CO₂-equivalent short tons (4,000 short tons of carbon) of sequestration. The results shown in Table 36 were developed using sequestration estimates for conventional tillage to no-till conversion from seven 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 0.23 ±0.06 metric tons of carbon per hectare (0.38 ± 0.1 CO₂-equivalent short tons). Meta-analysis is a powerful statistical tool for aggregating estimates across studies with different designs. The estimate just given – 0.23 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, 117 studies of no-till were reviewed with 122 reported study results. The average annual rate of soil carbon sequestration from the seven meta-analyses is in fairly good agreement with the estimate developed for other study types. We reviewed eight statistical summaries or derivative analyses other than formal meta-analyses, 19 modeling studies, 69 empirical site studies, and 11 literature reviews or studies that develop analyses based on expert judgment. Using a simple arithmetic average, sequestration rates for the conversion of conventional tillage to no-till practice were, for other derivative statistical analyses or summaries, modeling studies, empirical site studies and literature reviews, 0.27 ±0.06, 0.20 ±0.06, 0.41 ±0.08 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 38 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 38 are in metric tons of carbon per hectare, and subsequently are converted to CO₂-equivalent short tons for use in summary Table 36.

Table 38. Descriptive statistics: No-till tillage–carbon sequestration in soils

<table>
<thead>
<tr>
<th>Category</th>
<th>Biogenic Carbon Sequestration (Mg C/ha/yr)</th>
<th>Number of Study Results</th>
<th>Ratio of Sequestration to Emission: Number of Study Results</th>
<th>Standard Error of Mean (+/-)</th>
<th>Lower 95% Confidence Interval</th>
<th>Upper 95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meta-analyses</td>
<td>0.23</td>
<td>7</td>
<td>7/0</td>
<td>0.06</td>
<td>0.11</td>
<td>0.35</td>
</tr>
<tr>
<td>Other Derivative Statistical Analyses or Statistical Summaries</td>
<td>0.27</td>
<td>8</td>
<td>7/1</td>
<td>0.06</td>
<td>0.15</td>
<td>0.39</td>
</tr>
<tr>
<td>Empirical Site Studies</td>
<td>0.41</td>
<td>76</td>
<td>62/14</td>
<td>0.08</td>
<td>0.25</td>
<td>0.56</td>
</tr>
<tr>
<td>Modeling Studies</td>
<td>0.20</td>
<td>20</td>
<td>20/1</td>
<td>0.06</td>
<td>0.08</td>
<td>0.32</td>
</tr>
<tr>
<td>Expert Judgment/Literature Reviews</td>
<td>0.29</td>
<td>11</td>
<td>11/0</td>
<td>0.03</td>
<td>0.23</td>
<td>0.36</td>
</tr>
<tr>
<td>40 cm-plus Soil Sampling/Modeling Depth</td>
<td>0.35</td>
<td>39</td>
<td>29/10</td>
<td>0.11</td>
<td>0.14</td>
<td>0.57</td>
</tr>
<tr>
<td>10 to 30 cm Soil Sampling/Modeling Depth</td>
<td>0.34</td>
<td>65</td>
<td>59/6</td>
<td>0.07</td>
<td>0.21</td>
<td>0.48</td>
</tr>
<tr>
<td>10 to 20 Year Annual Sequestration Rate</td>
<td>0.32</td>
<td>60</td>
<td>52/8</td>
<td>0.07</td>
<td>0.19</td>
<td>0.45</td>
</tr>
<tr>
<td>20 to 30 Year Annual Sequestration Rate</td>
<td>0.24</td>
<td>24</td>
<td>21/3</td>
<td>0.06</td>
<td>0.12</td>
<td>0.35</td>
</tr>
<tr>
<td>0 to 10 Year Annual Sequestration Rate</td>
<td>0.49</td>
<td>26</td>
<td>21/5</td>
<td>0.17</td>
<td>0.15</td>
<td>0.83</td>
</tr>
<tr>
<td>No-till with Cover Crop</td>
<td>0.40</td>
<td>9</td>
<td>9/0</td>
<td>0.10</td>
<td>0.21</td>
<td>0.60</td>
</tr>
<tr>
<td>No-till on Former Conventional Till/Reduced Till Acres: Meta-analyses</td>
<td>0.24</td>
<td>8</td>
<td>8/0</td>
<td>0.05</td>
<td>0.14</td>
<td>0.35</td>
</tr>
</tbody>
</table>

As noted above, results from the different study types are generally supportive of the mean estimate drawn from the seven meta-analyses, although estimates from the empirical site studies might support a higher value. Soil sampling depth does not appear to be a factor. Thirty-six studies with sampling depths at or below 16 inches (40 centimeters) were reviewed. These yielded average annual sequestration rates, averaged across the 36 studies, of 0.35 metric tons of carbon (0.58 CO₂-equivalent short tons), or the same as the mean rate for studies with sampling depths of 4 to 12 inches (10 to 30 centimeters).

Seven studies 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 higher than the mean estimate for the seven meta-analyses, but based on only a handful of studies.

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 half 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 0.2 to 0.4 metric tons of carbon per hectare per year (0.09 to 0.18 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$_2$O 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$_2$O 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$_2$O production through denitrification. Generally, denitrification is the dominant source of N$_2$O 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$_2$O once WFPS passes 60 to 65 percent. (Liu et al., 2007; Metivier et al., 2009) Rates of N$_2$O formation through denitrification generally increase exponentially as soil water filled pore space increases beyond 60 percent. (David et al., 2009) Maximum N$_2$O 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$_2$O 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$_2$O 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$_2$O 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 topsoils also are lower than in soils under conventional tillage, reducing the supply of nitrate available for denitrification, and presumably N$_2$O 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 N₂O 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 N₂O 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 N₂O 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 N₂O 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 both 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 N₂O 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 N₂O emissions from tillage change are complex. Simple relationships between, on the one hand, N₂O 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 N₂O 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 N₂O 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 36, we provided an estimate of emissions-avoided from a change in tillage practice from conventional to no-till on 100,000 acres of some -4,000 CO₂-equivalent short tons (4,000 CO₂-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 nine published meta-analyses. The mean response rate of N₂O emissions to a change to no-till was positive in six of these nine meta-analyses, and negative in the remaining three. The specific emissions-avoidance value given in Table 36 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 N₂O emissions on 100,000 acres. Average annual Minnesota cropland N₂O 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 drawn overall conclusions at broad spatial scales.

Using the meta-analyses mean estimates, the conversion to no-till practice from conventional tillage is estimated to increase N₂O emissions by 6.0 ± 4.9 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.

Overall, we reviewed 82 studies with 88 study results. Of these, nine were meta-analyses, four were other derivative statistical summaries or analyses, 11 were modeling studies, 56 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 44 of the 88 observations of the larger database, and decreased in 44, 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, 53 percent reported reduced N$_2$O emissions with tillage change, while 47 percent reported increasing N$_2$O emissions.

The descriptive statistics for the studies that were reviewed are shown in Table 39. 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 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$_2$O emissions were 4.2 percent higher than paired soils in conventional tillage. For soils in no-till practice 10 or more years, N$_2$O emissions were 0.7 percent higher than paired soils in conventional tillage, based on the results from 60 studies. N$_2$O emissions generally declined 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. A change to no-till practice from conventional tillage generally yielded much larger percentage reductions when conducted in conjunction with cover crops than without cover crops—about 15 percent lower emissions—but based on relatively few observations.

**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 CH₄ oxidation resulting from the use of no-till practice is small, an increase of 283 CO₂-equivalent short tons (see Table 36). This was calculated using the average percent change in soil CH₄ 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 CH₄ 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 40, 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 CH₄ 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 CH₄ uptake and oxidation would be expected to decline 6 and 83 percent, respectively, but based on only a relatively few studies.

The contribution of CH₄ oxidation to overall GHG-avoidance from tillage change is small, with little effect on the larger budget totals developed in Table 36.
I. 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 CO₂. Under reduced tillage, soils that have suffered large losses of soil organic carbon, 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 41 shows the estimated emissions-avoidance effects of the conversion of 100,000 acres of cropland from full inversion tillage to reduced tillage. For each 100,000 acres of cropland converted from full inversion tillage to reduced tillage, an estimated 15,000 CO₂-equivalent short tons of GHGs are 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 CO₂ 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 15,000 CO₂-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 28,000 CO₂-equivalent short tons. Had we assumed a 100-year timespan for sustained storage, estimated avoidance would have totaled 67,000 CO₂-equivalent short tons (see Table 41). 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 CO₂, is incorporated into plant biomass and, eventually, soils.

Table 40. Descriptive statistics: No-till - CH₄

<table>
<thead>
<tr>
<th></th>
<th>% change in oxidation per hectare or acre</th>
<th>number of study results</th>
<th>change in oxidation, ratio positive-to-negative: number of study results</th>
<th>standard error of mean (±)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>meta-analyses</td>
<td>13.7%</td>
<td>4</td>
<td>3/1</td>
<td>5.5%</td>
<td>3%</td>
<td>24%</td>
</tr>
<tr>
<td>empirical site studies</td>
<td>-83.4%</td>
<td>18</td>
<td>5/13</td>
<td>36.6%</td>
<td>-155%</td>
<td>-12%</td>
</tr>
<tr>
<td>modeling studies</td>
<td>-6.5%</td>
<td>4</td>
<td>2/2</td>
<td>15.7%</td>
<td>-37%</td>
<td>24%</td>
</tr>
</tbody>
</table>

a conventional tillage counterfactual
b 26 study results, 25 studies (4 meta-analyses, 3 modeling studies, 18 empirical site studies)
c 1 study reports multiple results by cover crop treatment
Table 41. Reduced tillage: Emissions-avoided *

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Emission Source or Sink</th>
<th>Emission (CO$_2$-e short tons per 100,000 acres per year)</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>N$_2$O-direct</td>
<td>soils</td>
<td>(102)</td>
<td>conventional tillage</td>
</tr>
<tr>
<td>N$_2$O-indirect leaching</td>
<td>indirect emission-Nitrogen leaching or runoff</td>
<td>-</td>
<td>conventional tillage</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>soils</td>
<td>52</td>
<td>conventional tillage</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>carbon accumulation in soils</td>
<td>(13,026)</td>
<td>conventional tillage</td>
</tr>
<tr>
<td>GHGs-energy</td>
<td>fossil fuel and electricity use in crop production</td>
<td>(1,653)</td>
<td>conventional tillage</td>
</tr>
<tr>
<td>Out-of-State Upstream GHGs</td>
<td>upstream agricultural chemicals and fossil fuel production</td>
<td>(366)</td>
<td>conventional tillage</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>(14,543)</td>
<td></td>
</tr>
</tbody>
</table>

Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils

<table>
<thead>
<tr>
<th>Years of Assumed Storage</th>
<th>All Sources and Sinks</th>
<th>Emissions (CO$_2$-e short tons per 100,000 acres per year)</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 year storage</td>
<td>all sources and sinks</td>
<td>(27,568)</td>
<td>conventional tillage</td>
</tr>
<tr>
<td>100 year storage</td>
<td>all sources and sinks</td>
<td>(66,645)</td>
<td>conventional tillage</td>
</tr>
</tbody>
</table>

* 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

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 that are quite similar, if somewhat 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$_2$O from soils and the effects of reduced tillage on soil CH$_4$ oxidation. The methods and sources used to estimate avoided indirect N$_2$O 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

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 H). 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 41, reduced tillage on 100,000 acres is estimated to result in 13,000 CO₂-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 41 were developed using two 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 0.21 ±0.01 metric tons of carbon per hectare (0.09 ± 0.004 short tons of carbon per acre).

In developing this estimate, 69 studies of reduced tillage were reviewed with 74 study results, including 44 empirical site studies, twelve modeling studies, six literature reviews or studies that develop analyses based on expert judgment, two statistical summaries or statistical analyses other than formal meta-analysis, and the two formal meta-analyses. One study gave results for two different study types, both of which are represented in the database. The results from the meta-analyses were selected in deference to the place meta-analyses increasingly has assumed in determinations of response rates for ecological process in the scientific literature. Estimated mean sequestration rates for the 69 studies reviewed range from 0.11 to 0.23 metric tons of carbon per hectare per year (0.05 to 0.1 short ton of carbon per acre per year).

The descriptive statistics for the studies that were reviewed are shown in Table 42 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 CO₂-equivalent short tons for use in summary Table 41. The estimates in Table 42 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 42 are roughly similar in width to those reported in Table 38 for no-till. Of study types, the results from the empirical site studies and the literature reviews are in good agreement with the average developed from the results from the meta-analyses, the results from the modeling studies and statistical summaries and other derivative statistical analyses 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 one-third, up from about 20 percent under no-till. More troubling are the results at the 40 centimeter and below soil sampling depth, where the numbers of studies showing a negative SOC response to reduced tillage is the same as those showing a positive response. The mean rate of sequestration at these depths is 60 percent of the rate reported for the 10 to 30 centimeter soil layer, raising the possibility that, to some degree, the positive 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 42. A good deal 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 42. Descriptive statistics: Reduced tillage - carbon sequestration in soils

<table>
<thead>
<tr>
<th></th>
<th>biogenic carbon sequestration (Mg C/ha/yr)</th>
<th>number of study results</th>
<th>ratio of sequestration to emission: number of study results</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>meta-analyses</td>
<td>0.21</td>
<td>2</td>
<td>2/0</td>
<td>0.10</td>
<td>0.00</td>
<td>0.41</td>
</tr>
<tr>
<td>other derivative statistical analyses or summaries</td>
<td>0.11</td>
<td>2</td>
<td>2/0</td>
<td>0.01</td>
<td>0.09</td>
<td>0.13</td>
</tr>
<tr>
<td>empirical site studies</td>
<td>0.18</td>
<td>49</td>
<td>32/16/1</td>
<td>0.08</td>
<td>0.03</td>
<td>0.34</td>
</tr>
<tr>
<td>modeling studies</td>
<td>0.12</td>
<td>12</td>
<td>11/0</td>
<td>0.05</td>
<td>0.03</td>
<td>0.21</td>
</tr>
<tr>
<td>expert judgment/literature reviews</td>
<td>0.23</td>
<td>6</td>
<td>6/0</td>
<td>0.07</td>
<td>0.09</td>
<td>0.37</td>
</tr>
<tr>
<td>40 cm-plus soil sampling/modeling depth b</td>
<td>0.12</td>
<td>25</td>
<td>12/12/1</td>
<td>0.15</td>
<td>(0.17)</td>
<td>0.41</td>
</tr>
<tr>
<td>10 to 30 cm soil sampling/modeling depth b</td>
<td>0.20</td>
<td>37</td>
<td>32/5</td>
<td>0.04</td>
<td>0.12</td>
<td>0.29</td>
</tr>
<tr>
<td>10 to 20 year annual sequestration rate</td>
<td>0.28</td>
<td>34</td>
<td>29/5</td>
<td>0.08</td>
<td>0.12</td>
<td>0.43</td>
</tr>
<tr>
<td>20 to 30 year annual sequestration rate</td>
<td>(0.06)</td>
<td>14</td>
<td>9/5</td>
<td>0.09</td>
<td>(0.23)</td>
<td>0.11</td>
</tr>
<tr>
<td>0 to 10 year annual sequestration rate</td>
<td>0.18</td>
<td>12</td>
<td>7/5</td>
<td>0.21</td>
<td>(0.23)</td>
<td>0.59</td>
</tr>
</tbody>
</table>

* conventional tillage counterfactual
b results for lowest reported sampling depth
174 study results, 69 studies (2 meta-analyses, 2 statistical summaries or other derivative statistical analyses, 12 modeling studies, 3 IPCC-inventory studies, 44 empirical site studies, 6 expert reviews)
5 studies report multiple results by cover crop treatment
* ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

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 N₂O emissions, again on 100,000 acres. As discussed in the Methodology section of this report, average Minnesota cropland N₂O emissions are from the MPCA Greenhouse Gas Inventory. To estimate the percentage change in N₂O emissions under reduced-till on cropland formerly in conventional tillage, we reviewed 42 studies with 43 study results. These include five meta-analyses, one other derivative statistical analysis, nine modeling studies and 27 empirical site studies.

We used the mean estimate from the five meta-analyses as the best estimate of the percentage change in N₂O emission with reduced tillage practice on croplands formerly under conventional tillage practice. Of the five meta-analyses, three reported N₂O emission increases with reduced tillage in place of conventional, while two reported reductions. Using the mean estimate for the five meta-analyses, the use of reduced tillage practice on cropland formerly under conventional tillage practice is estimated to reduce N₂O emissions by 0.2 ± 4.9 percent. As in the case of no-till on cropland formerly under conventional tillage, the estimated percentage N₂O 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 N₂O response to tillage change to be developed.

Descriptive statistics are shown in Table 43 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 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 N₂O fluxes, do so on an annual basis is negative, but again the confidence intervals are wide.

Of the 27 empirical site studies reviewed, N₂O emissions increased in 14 and decreased in 13, 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 N₂O emissions, net greenhouse gas effects of reduced tillage in place of conventional tillage would remain almost unchanged from those shown in Table 41, about 15,000 CO₂-equivalent tons.

Table 43. Descriptive statistics: Reduced tillage - N₂O *

<table>
<thead>
<tr>
<th></th>
<th>emissions: % change in emissions per hectare</th>
<th>number of study results</th>
<th>change in emissions, ratio positive-to-negative: number of study results</th>
<th>standard error of mean (±%)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>meta-analyses</td>
<td>-0.2%</td>
<td>5</td>
<td>3/2</td>
<td>4.9%</td>
<td>-9.8%</td>
<td>9.5%</td>
</tr>
<tr>
<td>other derivative statistical analyses or summaries</td>
<td>-15.3%</td>
<td>1</td>
<td>0/1</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>modeling studies</td>
<td>-14.6%</td>
<td>9</td>
<td>1/8</td>
<td>6.3%</td>
<td>-27.0%</td>
<td>-2.3%</td>
</tr>
<tr>
<td>empirical site studies</td>
<td>7.8%</td>
<td>28</td>
<td>14/14</td>
<td>9.6%</td>
<td>-10.9%</td>
<td>26.4%</td>
</tr>
<tr>
<td>annual flux monitoring/modeling</td>
<td>-7.1%</td>
<td>27</td>
<td>9/18</td>
<td>4.3%</td>
<td>-15.4%</td>
<td>1.3%</td>
</tr>
<tr>
<td>growing season and subgrowing season flux monitoring/modeling</td>
<td>17.4%</td>
<td>16</td>
<td>9/7</td>
<td>15.4%</td>
<td>-12.9%</td>
<td>47.6%</td>
</tr>
<tr>
<td>1 year of observations or simulations</td>
<td>21.8%</td>
<td>10</td>
<td>5/5</td>
<td>23.4%</td>
<td>-24.1%</td>
<td>67.8%</td>
</tr>
<tr>
<td>2 to 3 years of observations or simulations</td>
<td>-4.9%</td>
<td>24</td>
<td>9/15</td>
<td>6.1%</td>
<td>-16.9%</td>
<td>7.0%</td>
</tr>
<tr>
<td>3 yrs-plus of observations or simulations</td>
<td>2.4%</td>
<td>2</td>
<td>1/1</td>
<td>5.8%</td>
<td>-8.8%</td>
<td>13.7%</td>
</tr>
</tbody>
</table>

* conventional tillage counterfactual

** 43 study results, 42 studies (5 meta-analyses, 1 statistical summary or other derivative statistical analysis, 9 modeling studies, 27 empirical site studies)

*** 1 study reports multiple results by cover crop treatment

### c. Methane

Tillage acts to disrupt methanotrophic communities that oxidize CH₄ to CO₂. 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 CH₄ 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 CH₄ oxidizing capacity might take up to several hundred years after disruptions cease. (Allen et al., 2009)

The estimated annual change in soil CH₄ oxidation resulting from the use of reduced tillage practice in is small, a 52 CO₂-equivalent short ton decrease in oxidation (see Table 41). This was calculated using the average percent change in soil CH₄ oxidation from a single available meta-analysis with a change in upland soils from conventional tillage to reduced tillage. Formal meta-analysis is probably the most powerful tool now available for aggregating estimates across study types with differing designs. Baseline CH₄ 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 CH₄ oxidation slightly, by 2.5 percent (see Table 44). In perusing the scientific literature, we also reviewed ten empirical site studies. Using the results from the empirical site studies, soil CH₄ uptake and oxidation...
might be expected to increase by 49 percent, but based on a very few number of studies showing widely scattered results (+217 to -50 percent change in soil CH\textsubscript{4} oxidation).

Table 44. Descriptive statistics: Reduced tillage - CH\textsubscript{4} \textsuperscript{a}

<table>
<thead>
<tr>
<th></th>
<th>% change in oxidation per hectare</th>
<th>number of studies \textsuperscript{b}</th>
<th>change in emissions, ratio positive-to-negative: study numbers</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>meta-analyses</td>
<td>-2.5%</td>
<td>1</td>
<td>0/1</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>empirical site studies</td>
<td>49.2%</td>
<td>10</td>
<td>6/3/1</td>
<td>30%</td>
<td>-10%</td>
<td>109%</td>
</tr>
</tbody>
</table>

\textsuperscript{a} conventional tillage counterfactual
\textsuperscript{b} 11 study results, 11 studies

J. No till: Reduced tillage counterfactual

No-till practice can be introduced to cropland already in reduced tillage. As noted above in Section IV, Subsection H, 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 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 Ha). That discussion will not be repeated. The same is true for changes in N\textsubscript{2}O emissions from tillage change. No estimate is available for CH\textsubscript{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 45. From Table 45, an estimated 23,000 CO\textsubscript{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\textsubscript{2}O 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\textsubscript{2}. This is the longest period over which, in our opinion, sustained storage safely can be assumed. Under this assumption, avoided-emissions are estimated 23,000 CO\textsubscript{2}-equivalent short tons (see Table 45). 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 36,000 CO\textsubscript{2}-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 77,000 CO\textsubscript{2}-equivalent short tons (again see Table 45).
The amount of time in storage determines the degree to which, for any particular project, sequestered carbon offsets CO₂ 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 45, an estimate for annual carbon sequestration in cropland formerly under reduced tillage and converted to no-till of 14,000 short tons of CO₂ or 3,705 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, CO₂ 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 CO₂ from fossil fuel combustion.

In estimating the average annual sequestration rate in no-till soils converted from reduced tillage practice, we reviewed 93 studies with 103 study results. These included 80 empirical site studies, 10 modeling studies, and 3 statistical summaries or derivative statistical analyses. Of the 93 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 0.22 ± 0.07 metric tons of carbon per hectare (0.10 ± 0.03 short tons of carbon per acre). 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 0.11 to 0.33 metric tons of carbon per hectare (0.05 to 0.15 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 exceedingly small. Soil organic carbon declined in about one-quarter of all the studies reviewed, increasing in about 75 percent, which is consistent with substantial site-to-site variability reported across all tillage studies.

The descriptive statistics for the various studies that were reviewed are shown in Table 46. About one-third more 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) than 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 excluded, particularly below the 16-inch (40 centimeter) sampling depth. By duration of experiment, studies that report on no-till soils formerly in reduced tillage practice in experiments lasting 10 to 20 years show little net sequestration in no-till soils. If the timeframe is lengthened to 20 to 30 years, this reverses and no-till soils sequester substantial amounts of carbon.

Table 46. Descriptive statistics: No-till tillage - carbon sequestration in soils a

<table>
<thead>
<tr>
<th>Study Type</th>
<th>Biogenic carbon sequestration (Mg C/ha/yr)</th>
<th>Number of study results</th>
<th>Ratio of sequestration to emission: number of study results</th>
<th>Standard error of mean (+/-)</th>
<th>Lower 95% confidence interval</th>
<th>Upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>All studies</td>
<td>0.22 ± 0.07</td>
<td>103</td>
<td>79/23/1</td>
<td>0.07</td>
<td>0.09</td>
<td>0.35</td>
</tr>
<tr>
<td>Empirical site studies</td>
<td>0.22 ± 0.07</td>
<td>89</td>
<td>68/20/1</td>
<td>0.08</td>
<td>0.07</td>
<td>0.37</td>
</tr>
<tr>
<td>Modeling studies</td>
<td>0.11 ± 0.04</td>
<td>10</td>
<td>8/2</td>
<td>0.04</td>
<td>0.03</td>
<td>0.19</td>
</tr>
<tr>
<td>Derivative statistical analyses or summaries</td>
<td>0.22 ± 0.07</td>
<td>30</td>
<td>3/0</td>
<td>0.07</td>
<td>0.20</td>
<td>0.47</td>
</tr>
<tr>
<td>40 cm-plus soil sampling/modeling depth b</td>
<td>0.15 ± 0.15</td>
<td>33</td>
<td>23/9/1</td>
<td>0.15</td>
<td>(0.14)</td>
<td>0.44</td>
</tr>
<tr>
<td>10 to 30 cm soil sampling/modeling depth b</td>
<td>0.22 ± 0.44</td>
<td>58</td>
<td>44/14</td>
<td>0.08</td>
<td>0.06</td>
<td>0.37</td>
</tr>
<tr>
<td>10 to 20 year annual sequestration rate</td>
<td>0.09 ± 0.10</td>
<td>40</td>
<td>32/8</td>
<td>0.10</td>
<td>(0.10)</td>
<td>0.28</td>
</tr>
<tr>
<td>20 to 30 year annual sequestration rate</td>
<td>0.26 ± 0.13</td>
<td>14</td>
<td>10/3</td>
<td>0.13</td>
<td>0.01</td>
<td>0.51</td>
</tr>
<tr>
<td>0 to 10 year annual sequestration rate</td>
<td>0.31 ± 0.13</td>
<td>39</td>
<td>27/12</td>
<td>0.13</td>
<td>0.05</td>
<td>0.56</td>
</tr>
</tbody>
</table>

a reduced tillage counterfactual
b results for lowest reported sampling depth
c 103 study results, 93 studies (3 statistical summaries or derivative statistical analyses, 10 modeling studies, 80 empirical site studies)
d 10 studies report multiple results by cover crop treatment

Greenhouse gas reduction potential of agricultural best management practices  •  October 2019  Minnesota Pollution Control Agency

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The study results by soil sampling depth and experiment duration suggest that caution be exercised with the numbers. Regarding experiment duration, the calculated confidence intervals for experiments lasting 10 to 20 years are quite broad. One or two very negative study results seem largely to account for the lack of sequestration in experiments with this length of study. A good deal more research may be needed to understand how experiment duration influences soil organic carbon changes in soils converting from reduced tillage to no-till practice.

The weight of the evidence now supports a positive response rate for no tillage on soils formerly in reduced tillage, but with the caveat that oddities in the data persist and that more experimental data could alter this judgment going forward.

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$_2$O emissions. Average Minnesota cropland N$_2$O emissions are from the MPCA Greenhouse Gas Inventory. To estimate the percentage change in N$_2$O emissions under no-till on cropland formerly in reduced tillage, we reviewed 49 studies with 50 study results. These included 4 modeling studies and 45 empirical site studies.

We used the mean estimate from all studies reviewed as the best estimate of the percentage change in N$_2$O emission with no-till practice on croplands formerly under reduced tillage practice. No meta-analyses were available to support a calculation. Using the mean estimate for all reviewed studies, the use of no-till practice on cropland formerly under reduced tillage practice is estimated to reduce N$_2$O emissions by 12.9 ± 4.9 percent. By study type, the estimate percentage change ranges from -10.9 to -35.9 percent.

Of the 49 studies reviewed, 14 reported increased N$_2$O emissions with no-till on former reduced tillage cropland, 34 reported reductions, and one reported no change. The descriptive statistics for the reviewed studies are shown in Table 47, with standard errors and upper and lower 95 percent confidence intervals. The confidence interval for the percentage change for all studies is fairly broad, though solidly in negative territory. The change in mean N$_2$O fluxes from the studies that report emissions on an annual, as opposed to growing season, basis is somewhat larger than the mean change in growing season-only fluxes, though not substantially. There is no evident pattern in the results by number of study years.

K. 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$_2$O to the atmosphere. Fewer upstream emissions from the out-of-state manufacture of synthetic fertilizer also result.
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. 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 below ground 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 48 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 removed to 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 48 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 294,000 $CO_2$-equivalent tons (see Table 48).

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 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 49 in $CO_2$-equivalent short tons per 100,000 acres. They support a range of emissions reductions of 37,000 to 298,000 short $CO_2$-equivalent tons for each 100,000 acres of conversions.

Table 47. Descriptive statistics: No-tillage - $N_2O$ *

<table>
<thead>
<tr>
<th></th>
<th>emissions: % change in emissions per hectare</th>
<th>number of study results</th>
<th>change in emissions, ratio positive-to-negative: number of study results</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>all studies</td>
<td>-12.9%</td>
<td>50</td>
<td>14/35/1</td>
<td>4.9%</td>
<td>-22.6%</td>
<td>-3.2%</td>
</tr>
<tr>
<td>modeling studies</td>
<td>-35.9%</td>
<td>4</td>
<td>0/4</td>
<td>11.4%</td>
<td>-58.2%</td>
<td>-13.6%</td>
</tr>
<tr>
<td>empirical site studies</td>
<td>-10.9%</td>
<td>46</td>
<td>13/32/1</td>
<td>5.1%</td>
<td>-29.9%</td>
<td>-0.9%</td>
</tr>
<tr>
<td>annual flux monitoring/modeling</td>
<td>-12.6%</td>
<td>23</td>
<td>6/16/1</td>
<td>8.0%</td>
<td>-28.3%</td>
<td>3.2%</td>
</tr>
<tr>
<td>growing season and subgrowing season flux monitoring/modeling</td>
<td>-10.7%</td>
<td>23</td>
<td>7/16</td>
<td>6.8%</td>
<td>-24.0%</td>
<td>2.6%</td>
</tr>
<tr>
<td>1 year of observations or simulations</td>
<td>-31.3%</td>
<td>15</td>
<td>2/13</td>
<td>6.2%</td>
<td>-43.5%</td>
<td>-19.0%</td>
</tr>
<tr>
<td>2 to 3 years of observations or simulations</td>
<td>1.2%</td>
<td>28</td>
<td>11/16/1</td>
<td>6.8%</td>
<td>-12.1%</td>
<td>14.5%</td>
</tr>
<tr>
<td>3 yrs-plus of observations or simulations</td>
<td>-31.2%</td>
<td>6</td>
<td>0/6</td>
<td>8.2%</td>
<td>-47.3%</td>
<td>-15.0%</td>
</tr>
</tbody>
</table>

* reduced tillage counterfactual
b 50 study results, 49 studies (4 modeling studies, 45 empirical site studies)
c 1 study reports multiple results by cover crop treatment
Biogenic carbon sequestration in soils from the conversion of cropland to hayland is discussed below, as are avoided direct emissions of N$_2$O 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$_2$O emissions from nitrate leaching and ammonia.

---

**Table 48. Cropland to hayland: Emissions-avoided**

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Emission Source or Sink</th>
<th>Emission (CO$_2$-eq. short tons per 100,000 acres per year)</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>N$_2$O-direct</td>
<td>soils</td>
<td>(52,012)</td>
<td>crop production</td>
</tr>
<tr>
<td>N$_2$O-indirect volatilization</td>
<td>indirect emission-Nitrogen volatilization, redeposition</td>
<td>(2,107)</td>
<td>crop production</td>
</tr>
<tr>
<td>N$_2$O-indirect leaching</td>
<td>indirect emission-Nitrogen leaching or runoff</td>
<td>(11,703)</td>
<td>crop production</td>
</tr>
<tr>
<td>CH$_4$ $^b$</td>
<td>soils</td>
<td>not known</td>
<td>crop production</td>
</tr>
<tr>
<td>CO$_2$ $^{c,d}$</td>
<td>carbon accumulation in soils and biomass</td>
<td>(43,040)</td>
<td>crop production</td>
</tr>
<tr>
<td>CO$_2$ $^d$</td>
<td>cultivated soils from lime or urea use</td>
<td>(2,786)</td>
<td>crop production</td>
</tr>
<tr>
<td>GHGs-energy</td>
<td>fossil fuel and electricity use in crop production</td>
<td>3,681</td>
<td>crop production</td>
</tr>
<tr>
<td>Out-of-State Upstream GHGs</td>
<td>upstream agricultural chemicals and fossil fuel production</td>
<td>(13,373)</td>
<td>crop production</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>(121,339)</td>
<td></td>
</tr>
</tbody>
</table>

Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass

<table>
<thead>
<tr>
<th></th>
<th>all sources and sinks</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>40 year storage</td>
<td></td>
<td>(164,379)</td>
<td>crop production</td>
</tr>
<tr>
<td>100 year storage</td>
<td></td>
<td>(293,501)</td>
<td>crop production</td>
</tr>
</tbody>
</table>

$^a$ positive = emissions increase, negative = emissions reduction
$^b$ reduction in soil CH$_4$ oxidation = relative increase in 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

**Table 49. Change in total greenhouse gases from conversion of cropland to hayland rotation $^a$**

<table>
<thead>
<tr>
<th>Study</th>
<th>Type of study</th>
<th>CO$_2$-eq. short tons per acre per year</th>
<th>CO$_2$-eq. short tons per 100,000 acres per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barsottti et al. (2012)</td>
<td>site study</td>
<td>2.04</td>
<td>203,960</td>
</tr>
<tr>
<td>Gelford and Robertson (2015)</td>
<td>site study</td>
<td>0.37</td>
<td>36,796</td>
</tr>
<tr>
<td>Meyer-Aurich, et al. (2006)</td>
<td>site study</td>
<td>1.20</td>
<td>120,021</td>
</tr>
<tr>
<td>Robertson et al. (2000)</td>
<td>site study</td>
<td>0.37</td>
<td>37,465</td>
</tr>
<tr>
<td>Sulaiman et al. (2017) $^b$</td>
<td>site study</td>
<td>2.98</td>
<td>298,381</td>
</tr>
<tr>
<td>Shafer and Thompson (2015)</td>
<td>modeling study</td>
<td>1.38</td>
<td>138,263</td>
</tr>
<tr>
<td>Eagle et al. (2012)</td>
<td>other derivative statistical analysis $^c$</td>
<td>0.64</td>
<td>63,779</td>
</tr>
<tr>
<td>Swan et al. (2015) $^b$</td>
<td>literature review/expert judgment</td>
<td>0.41</td>
<td>40,778</td>
</tr>
<tr>
<td>Sainju et al. (2016)</td>
<td>meta-analysis</td>
<td>0.66</td>
<td>66,411</td>
</tr>
</tbody>
</table>

| This report                | literature review         | 1.21                                   | 121,339                                         |

$^a$ results as reported without adjustments
$^b$ change in soil N$_2$O and soil organic carbon only
$^c$ other than formal meta-analyses
volatilization, avoided-emissions from fuel use, and avoided-emissions from foregone agricultural chemicals and fuels manufacture were discussed above in Section II, Subsection E.

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 (see Section IV, Subsection Aa) will not be repeated.

In Table 48, an estimate of 43,000 CO₂-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 50 below) and converted to CO₂-equivalent short tons for inclusion in summary Table 48.

In developing this estimate, 35 studies were reviewed with 36 study results, including six modeling studies, 20 empirical site studies, three statistical summaries or derivative statistical analyses, one modeling/empirical site study, and five literature reviews or studies that report average sequestration rates based on expert judgment. In developing the estimate for sequestration given in Table 48 for 100,000 acres of hayland, we used a simple average of the results from all 35 studies, or 0.68 ± 0.17 metric tons of carbon per hectare per year (0.3 ± 0.08 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 35 studies are shown in Table 50. Of the 36 results that were reported in these 35 studies, 3 indicated soil carbon losses with cropland conversion to hayland and 33 net carbon sequestration. Average sequestration rates are shown in Table 50 by study type. Across study types, annual sequestration rates range from 0.43 to 1.3 metric tons of carbon per hectare (0.19 to 0.56 short tons of carbon per acre per year). No meta-analysis 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 metric tons of carbon per hectare per year (0.22 to 0.45 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 0.64 metric tons per hectare for nonalfalfa perennial grasses and 0.78 metric tons per hectare for a mix of alfalfa and nonalfalfa grasses. Eighteen studies gave results for nonalfalfa perennial grasses, eleven for alfalfa and five for a mix of alfalfa and nonalfalfa grasses. Net sequestration in studies that sampled soils below 12 inches (30 centimeters) of depth was about a quarter 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 50. Descriptive statistics: Cropland to hayland - carbon sequestration in soils

<table>
<thead>
<tr>
<th>biogenic carbon sequestration (Mg C/ha/yr)</th>
<th>number of study results</th>
<th>ratio of sequestration to emission: number of study results</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>all studies</td>
<td>0.68</td>
<td>36</td>
<td>33/3</td>
<td>0.17</td>
<td>0.35</td>
</tr>
<tr>
<td>derivative statistical analyses or statistical summaries *</td>
<td>1.30</td>
<td>3</td>
<td>3/0</td>
<td>1.08 (0.82)</td>
<td>3.42</td>
</tr>
<tr>
<td>empirical site studies</td>
<td>0.72</td>
<td>21</td>
<td>18/3</td>
<td>0.25</td>
<td>0.23</td>
</tr>
<tr>
<td>modeling studies</td>
<td>0.51</td>
<td>7</td>
<td>7/0</td>
<td>0.12</td>
<td>0.28</td>
</tr>
<tr>
<td>expert judgment/literature review</td>
<td>0.43</td>
<td>5</td>
<td>5/0</td>
<td>0.11</td>
<td>0.21</td>
</tr>
<tr>
<td>alfalfa</td>
<td>0.74</td>
<td>11</td>
<td>9/2</td>
<td>0.45 (0.14)</td>
<td>1.63</td>
</tr>
<tr>
<td>nonalfalfa perennial grasses</td>
<td>0.64</td>
<td>18</td>
<td>17/1</td>
<td>0.20</td>
<td>0.24</td>
</tr>
<tr>
<td>mix of alfalfa and nonalfalfa perennial grasses or unidentified</td>
<td>0.78</td>
<td>5</td>
<td>5/0</td>
<td>0.20</td>
<td>0.38</td>
</tr>
<tr>
<td>5 to 30 cm soil sampling/modeling depth b</td>
<td>0.63</td>
<td>15</td>
<td>13/2</td>
<td>0.24</td>
<td>0.15</td>
</tr>
<tr>
<td>&gt;30 cm soil sampling/modeling depth b</td>
<td>0.44</td>
<td>6</td>
<td>5/1</td>
<td>0.56 (0.66)</td>
<td>1.54</td>
</tr>
<tr>
<td>1 to 10 year annual sequestration rate</td>
<td>0.12</td>
<td>9</td>
<td>7/2</td>
<td>0.51</td>
<td>0.49 (0.49)</td>
</tr>
<tr>
<td>10 to 20 year annual sequestration rate</td>
<td>0.85</td>
<td>7</td>
<td>6/1</td>
<td>0.52 (0.17)</td>
<td>1.87</td>
</tr>
<tr>
<td>20 to 30 yr annual sequestration rate</td>
<td>0.64</td>
<td>10</td>
<td>10/0</td>
<td>0.14</td>
<td>0.36</td>
</tr>
</tbody>
</table>

* statistical summaries or derivative statistical analysis other than meta-analyses
b results for lowest reported sampling depth
c 36 study results, 33 studies (3 statistical summaries or derivative statistical analyses, 6 modeling studies, 20 empirical site studies, 5 expert reviews, 1 modeling/empirical site study)
d 1 study reports multiple results by study type
e ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

b. Nitrous oxide

N₂O 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 N₂O production in grasslands were discussed in the section on restored grassland (see Section IV, Subsection Ab). They are the same as occur in cropland planted to perennial grasses and alfalfa for harvest.

N₂O 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 N₂O emissions in Minnesota are, on an annual basis, an estimated 4.81 kilograms per hectare (4.29 lbs. N₂O per acre). From a 2017 meta-analysis, we estimate annual N₂O emissions of 1.89 kilograms per hectare (1.69 lbs. per acre) from soils in alfalfa or perennial grass. (See Table 51)

In developing these estimates, we reviewed 28 studies with 33 study results, including 19 empirical site studies (20 study results), 5 modeling studies (8 study results), one meta-analysis and 3 statistical summaries or derivative statistical analyses (4 study results). Four of these studies reported multiple results across forage types, which we tracked. Across all 28 studies, annual N₂O emissions from hayland averaged 2.03 kilograms per hectare (1.81 lbs. N₂O per acre), or reasonably close to the meta-analysis estimate (see Table 51). 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 51. Descriptive statistics: Cropland to hayland - N₂O

<table>
<thead>
<tr>
<th></th>
<th>emissions (kg N₂O/hectare/yr)</th>
<th>number of study results b,c</th>
<th>ratio, positive to negative results: number of study results</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>meta-analyses</td>
<td>1.89</td>
<td>1</td>
<td>1/0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>all studies</td>
<td>2.03</td>
<td>33</td>
<td>33/0</td>
<td>0.39</td>
<td>1.11</td>
<td>2.66</td>
</tr>
<tr>
<td>derivative statistical analyses or statistical summaries a</td>
<td>1.70</td>
<td>4</td>
<td>4/0</td>
<td>0.35</td>
<td>1.35</td>
<td>2.72</td>
</tr>
<tr>
<td>empirical site studies</td>
<td>1.22</td>
<td>20</td>
<td>20/0</td>
<td>0.30</td>
<td>1.12</td>
<td>2.28</td>
</tr>
<tr>
<td>modeling studies</td>
<td>3.56</td>
<td>8</td>
<td>8/0</td>
<td>1.36 (1.45)</td>
<td>3.90</td>
<td></td>
</tr>
<tr>
<td>alfalfa studies</td>
<td>1.75</td>
<td>17</td>
<td>17/0</td>
<td>0.29</td>
<td>2.99</td>
<td>4.13</td>
</tr>
<tr>
<td>other hay and grasses studies</td>
<td>2.77</td>
<td>10</td>
<td>10/0</td>
<td>1.18</td>
<td>0.82</td>
<td>5.46</td>
</tr>
<tr>
<td>fertilized grassland</td>
<td>3.14</td>
<td>10</td>
<td>10/0</td>
<td>1.12</td>
<td>(0.46)</td>
<td>3.95</td>
</tr>
<tr>
<td>annual flux monitoring/modeling</td>
<td>2.27</td>
<td>24</td>
<td>24/0</td>
<td>0.53</td>
<td>1.74</td>
<td>3.81</td>
</tr>
<tr>
<td>growing season flux monitoring/modeling</td>
<td>0.95</td>
<td>6</td>
<td>6/0</td>
<td>0.15</td>
<td>2.84</td>
<td>3.43</td>
</tr>
<tr>
<td>1-2 years of observations</td>
<td>2.40</td>
<td>13</td>
<td>13/0</td>
<td>0.93</td>
<td>0.44</td>
<td>4.10</td>
</tr>
<tr>
<td>3 years plus of observations</td>
<td>1.92</td>
<td>13</td>
<td>13/0</td>
<td>0.38</td>
<td>0.20</td>
<td>1.69</td>
</tr>
</tbody>
</table>

a Statistical summaries or derivative statistical analyses other than meta-analyses
b 33 study results, 28 studies (1 meta-analysis, 3 statistical summaries or derivative statistical analyses, 5 modeling studies, 19 empirical site studies)
c 4 studies report multiple results by forage type

By study type, in Table 51 N₂O emissions from hayland range from 1.22 to 3.56 kilograms per hectare per year, for almost a three-fold difference in mean estimates by study type. Because of this, some care should be taken in accepting without reservations the meta-analysis results. 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 (three-year or longer) basis yield results similar to, if slightly larger than, the meta-analysis results, which provides some measure of comfort.

L. 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 introduction 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 K 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 CO₂ 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 N₂O, as well as reduced downstream N₂O 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 N₂O 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 52 shows the estimated net change in greenhouse gas emissions from the lengthening of annual crop rotation by adding to annual rotations two or more years of perennial grasses or alfalfa. For each 100,000 acres with extended rotations with perennial grasses or alfalfa, an estimated 50,000 CO₂-equivalent tons of greenhouse gas emissions would be avoided annually. Of this, about two-thirds percent derives from carbon sequestration in soils. The rest results from reduced direct emissions of N₂O 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.

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Emission Source or Sink</th>
<th>Emission (CO₂-e short tons per 100,000 acres per year)</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂O-direct</td>
<td>soils</td>
<td>(2,897)</td>
<td>crop production</td>
</tr>
<tr>
<td>N₂O-indirect</td>
<td>indirect emission-Nitrogen volatilization, redeposition</td>
<td>(1,053)</td>
<td>crop production</td>
</tr>
<tr>
<td>N₂O-indirect leaching</td>
<td>indirect emission-Nitrogen leaching or runoff</td>
<td>(6,826)</td>
<td>crop production</td>
</tr>
<tr>
<td>CH₄</td>
<td>soils</td>
<td>not known</td>
<td>crop production</td>
</tr>
<tr>
<td>CO₂⁹</td>
<td>carbon accumulation in soils and biomass</td>
<td>(32,490)</td>
<td>crop production</td>
</tr>
<tr>
<td>CO₂</td>
<td>cultivated soils from lime or urea use</td>
<td>(1,393)</td>
<td>crop production</td>
</tr>
<tr>
<td>GHGs-energy</td>
<td>fossil fuel and electricity use in crop production</td>
<td>6,861</td>
<td>crop production</td>
</tr>
<tr>
<td>Out-of-State</td>
<td>upstream agricultural chemicals and fossil fuel production</td>
<td>(11,886)</td>
<td>crop production</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>(49,685)</td>
<td></td>
</tr>
</tbody>
</table>

Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass

<table>
<thead>
<tr>
<th></th>
<th>Emissions (CO₂-e short tons per 100,000 acres per year)</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 year storage</td>
<td>(82,175)</td>
<td>crop production</td>
</tr>
<tr>
<td>100 year storage</td>
<td>(179,646)</td>
<td>crop production</td>
</tr>
</tbody>
</table>

* positive = emissions increase, negative = emissions reduction

b carbon accumulation in soils = net removal of CO₂ from the atmosphere = net emission reduction
c assumes 20 years of sustained storage of newly sequestered organic carbon in soils and biomass

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 CO₂. Twenty years is the longest period that, in our judgment, sustained terrestrial storage can be assumed for purposes of its present-day valuation. If instead of 20 years, we had assumed a 40- year timespan, the annualized total of greenhouse gas-avoidance on 100,000 acres would have totaled 82,000 CO₂-equivalent tons, up from 50,000 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 180,000 CO₂-equivalent tons.

We developed these estimates using estimates from studies employing a wide variety of both 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 rotationally were included 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.

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) 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 Aa and Section IV, Subsection Ka).

In Table 52, an estimate of 32,000 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 3 and 4. 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 53 below) and converted to CO$_2$-equivalent short tons for inclusion in summary Table 52.

In developing these estimates, 28 studies were reviewed, including five modeling studies, 15 empirical site studies, four statistical summaries or derivative statistical analyses, and three literature reviews or studies that report average sequestration rates based on expert judgment. In calculating the estimate for sequestration given in Table 52 for 100,000 acres with extended rotations with alfalfa or perennial grasses, we used a simple average of the results from these 29 studies, or 0.52 ± 0.17 metric tons of carbon per hectare per year (0.23 ± 0.08 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 29 studies are shown in Table 53. Of these, 26 studies reported net carbon sequestration, while three 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 0.22 to 0.71 metric tons of carbon per hectare (0.10 to 0.31 short tons of carbon per acre per year).

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) was 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 29 studies that were reviewed.

b. Nitrous oxide

Nitrous oxide is produced microbially in soils in the presence of soil ammonium and nitrate. The processes and environmental controls on N$_2$O production in grasslands were discussed in the section on
restored grassland (see Section IV, Subsection Ab). They are the same as occur in cropland planted to perennial grasses and alfalfa for harvest in rotation with annual crops.

Table 53. Descriptive statistics: Add a perennial grass or alfalfa to crop rotation – carbon sequestration in soils

<table>
<thead>
<tr>
<th>biogenic carbon sequestration (Mg C/ha/yr)</th>
<th>number of study results</th>
<th>ratio of sequestration to emission: number of study results</th>
<th>standard error of mean (±/−)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>all studies</td>
<td>0.52</td>
<td>29/3</td>
<td>0.17</td>
<td>0.18</td>
<td>0.85</td>
</tr>
<tr>
<td>derivative statistical analyses or statistical summaries</td>
<td>0.40</td>
<td>4/0</td>
<td>0.21</td>
<td>(0.02)</td>
<td>0.81</td>
</tr>
<tr>
<td>empirical site studies</td>
<td>0.71</td>
<td>16/3</td>
<td>0.30</td>
<td>0.11</td>
<td>1.30</td>
</tr>
<tr>
<td>modeling studies</td>
<td>0.22</td>
<td>6/0</td>
<td>0.05</td>
<td>0.12</td>
<td>0.32</td>
</tr>
<tr>
<td>expert judgment/literature reviews</td>
<td>0.27</td>
<td>3/0</td>
<td>0.12</td>
<td>0.04</td>
<td>0.50</td>
</tr>
<tr>
<td>alfalfa added to rotation</td>
<td>0.59</td>
<td>10/4</td>
<td>0.29</td>
<td>0.02</td>
<td>1.16</td>
</tr>
<tr>
<td>generic perennial added to rotation</td>
<td>0.51</td>
<td>4/0</td>
<td>0.19</td>
<td>0.14</td>
<td>0.87</td>
</tr>
<tr>
<td>other hay, unidentified hay or grass leys added to rotation</td>
<td>0.20</td>
<td>12/1</td>
<td>0.03</td>
<td>0.14</td>
<td>0.27</td>
</tr>
<tr>
<td>5 to 30 cm soil sampling/modeling depths</td>
<td>0.42</td>
<td>14/3</td>
<td>0.17</td>
<td>0.09</td>
<td>0.75</td>
</tr>
<tr>
<td>&gt;30 cm soil sampling/modeling depths</td>
<td>0.42</td>
<td>8/2</td>
<td>0.26</td>
<td>(0.09)</td>
<td>0.93</td>
</tr>
<tr>
<td>1 to 10 year annual sequestration rate</td>
<td>1.93</td>
<td>3/0</td>
<td>1.22</td>
<td>(0.45)</td>
<td>4.31</td>
</tr>
<tr>
<td>10 to 30 year annual sequestration rate</td>
<td>0.53</td>
<td>12/1</td>
<td>0.24</td>
<td>0.06</td>
<td>0.99</td>
</tr>
<tr>
<td>&gt;30 year sequestration rate</td>
<td>0.19</td>
<td>9/1</td>
<td>0.05</td>
<td>0.10</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Avoided-emissions from the extension of annual rotations using several years of either perennial grasses or alfalfa are calculated as the product of the estimated percentage change in emission from extended rotations with perennials and the average Minnesota cropland emission. Estimated annual cropland emissions are from the MPCA greenhouse gas emission inventory. Using an average of the results from 15 studies with 16 study results that were reviewed, we estimate a 5 percent reduction in N\textsubscript{2}O emissions from a change from annual rotations to extended rotations including several years of perennials. In the scientific literature, this is most often attributed to substantially reduced plant needs for synthetic nitrogen under a four-year rotation comprised of at least two years of either perennial grasses or alfalfa. (Benoit \textit{et al.}, 2015; Ellert and Janzen, 2008; MacKenzie \textit{et al.}, 1997; Osterholz \textit{et al.}, 2014) While alfalfa typically is fertilized at planting, it receives no nitrogen fertilizer during subsequent years of the stand. In addition, due to the buildup of organic nitrogen in soils under alfalfa, substantially less nitrogen is needed by annual crops following alfalfa in rotation. (Bierman \textit{et al.}, 2012) Perennial grasses in rotation also are unlikely to be fertilized.

The descriptive statistics for the studies that were reviewed are shown in Table 54 by study type. Ten empirical site studies were reviewed, as were three modeling studies, one statistical summary or derivative statistical analysis, and one a literature review. No formal meta-analysis was available to support a calculation. Of the 16 results from the 15 studies, in 14 N\textsubscript{2}O emissions declined with extended rotations with perennials, while in two emissions increased. Directionally the results across studies agree, but often based on only a few studies and, as a group or set of groupings, with unsatisfactorily wide confidence intervals.
As in the case of many estimates of N₂O change in this report, this is reason for some caution in using these estimates, even as they represent best available information. Presumably, more and better experimental data would shrink the confidence intervals to more acceptable widths. It is noteworthy that, regardless of how the N₂O avoided-emission value develops, the aggregate change in greenhouse gas-avoidance is unlikely to diverge much from its estimated value. This is due to the relatively small contribution of N₂O to the overall greenhouse gas budget shown in Table 52.

Finally, most of the studies that were reviewed focus on extended rotations with alfalfa, rather than nonleguminous hay or other perennial forages. The percentage reductions in N₂O emissions for extended rotations with nonleguminous hay or other perennial forages are not substantially different from those for extended rotations with alfalfa. However, this is based on only a few studies of the former. A more robust dataset is needed to understand how N₂O emissions might change under extended rotations with nonleguminous hay or other non-alfalfa perennial forages.

Table 54. Descriptive Statistics: Add a perennial grass or alfalfa to crop rotation - N₂O

<table>
<thead>
<tr>
<th></th>
<th>emissions: % change in emissions per hectare</th>
<th>number of study results</th>
<th>change in emissions, ratio positive-to-negative: number of study results</th>
<th>standard error of mean (±)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>all studies</td>
<td>-5%</td>
<td>16</td>
<td>2/14</td>
<td>9%</td>
<td>-22%</td>
<td>13%</td>
</tr>
<tr>
<td>derivative statistical analyses or statistical summaries a</td>
<td>-3%</td>
<td>1</td>
<td>0/1</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>empirical site studies</td>
<td>-1%</td>
<td>11</td>
<td>2.9</td>
<td>13%</td>
<td>-27%</td>
<td>24%</td>
</tr>
<tr>
<td>modeling studies</td>
<td>-18%</td>
<td>3</td>
<td>0.3</td>
<td>6%</td>
<td>-30%</td>
<td>-6%</td>
</tr>
<tr>
<td>expert judgment/literature reviews</td>
<td>-2%</td>
<td>1</td>
<td>0/1</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>alfalfa</td>
<td>-3%</td>
<td>13</td>
<td>2/11</td>
<td>11%</td>
<td>-25%</td>
<td>18%</td>
</tr>
<tr>
<td>other hay or generic perennial</td>
<td>-10%</td>
<td>3</td>
<td>0.3</td>
<td>5%</td>
<td>-19%</td>
<td>0%</td>
</tr>
<tr>
<td>annual flux monitoring/modeling</td>
<td>6%</td>
<td>8</td>
<td>1.7</td>
<td>17%</td>
<td>-28%</td>
<td>39%</td>
</tr>
<tr>
<td>growing season flux monitoring/modeling</td>
<td>-14%</td>
<td>7</td>
<td>0.7</td>
<td>6%</td>
<td>-25%</td>
<td>-3%</td>
</tr>
</tbody>
</table>

a statistical summaries or derivative statistical analyses other than meta-analyses
b 16 study results, 15 studies (1 statistical summary or derivative statistical analysis, 3 modeling studies, 10 empirical site studies, 1 expert review)
c 1 study reports multiple results by study type

**M. 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 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 55 shows the estimated net annual greenhouse gas balance from converting cropland from continuous corn to a two-year corn-soybean rotation. For each 100,000 acres of cropland converted from continuous corn to corn and soybeans, an estimated additional 40,000 CO₂-equivalent short tons of greenhouse gases would be emitted annually, or 0.4 short CO₂-equivalent tons per acre. About 69,000 CO₂-equivalent short tons would be emitted from soils in the form of CO₂. A part of this emission would be offset by reductions in the direct emission of N₂O from soils, an estimated 11,000 CO₂-equivalent...
short tons. A further 17,000 would be offset by avoided upstream emissions from the manufacture of nitrogen fertilizer that would be avoided under a two-year corn-soybean rotation.  

Table 55. Corn-soybean rotation replacing continuous corn: Emissions-avoided

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Emission Source or Sink</th>
<th>Emission (CO₂-e short tons per 100,000 acres per year) a</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂O-direct</td>
<td>soils</td>
<td>(11,147)</td>
<td>crop production</td>
</tr>
<tr>
<td>N₂O-indirect volatilization</td>
<td>indirect emission-Nitrogen volatilization, redeposition</td>
<td>not known</td>
<td>crop production</td>
</tr>
<tr>
<td>N₂O-indirect leaching</td>
<td>indirect emission-Nitrogen leaching or runoff</td>
<td>not known</td>
<td>crop production</td>
</tr>
<tr>
<td>CH₄</td>
<td>soils</td>
<td>not known</td>
<td>crop production</td>
</tr>
<tr>
<td>CO₂ b</td>
<td>carbon accumulation in soils and biomass</td>
<td>69,182</td>
<td>crop production</td>
</tr>
<tr>
<td>CO₂</td>
<td>cultivated soils from lime or urea use</td>
<td>-</td>
<td>crop production</td>
</tr>
<tr>
<td>GHGs-energy</td>
<td>fossil fuel and electricity use in crop production</td>
<td>(909)</td>
<td>crop production</td>
</tr>
<tr>
<td>Out-of-State Upstream GHGs</td>
<td>upstream agricultural chemicals and fossil fuel production</td>
<td>(17,296)</td>
<td>crop production</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>39,830</td>
<td></td>
</tr>
</tbody>
</table>

a positive = emissions increase, negative = emissions reduction
b carbon accumulation in soils = net removal of CO₂ from the atmosphere = net emission reduction

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 CO₂ to the atmosphere. Direct emissions of N₂O 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 CH₄ emissions and N₂O 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 56 in CO₂-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 CO₂-equivalent tons for each 100,000 of conversions.

---

12 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.
CO₂ emissions from cropland soils are discussed below, as are avoided direct emissions of N₂O 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 CH₄ 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 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 CO₂ 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 Ga), soil macroaggregates are bound together by organic acids and polymers derived from decomposing soil organic matter.

---

**Table 56. Change in total greenhouse gases from conversion from continuous corn to corn-soybean rotation *"**

<table>
<thead>
<tr>
<th>Study</th>
<th>Type of study</th>
<th>CO₂-eq. short tons per acre per year</th>
<th>CO₂-eq. short tons per 100,000 acres per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adviento-Borbe et al. (2007)</td>
<td>empirical site study</td>
<td>0.78</td>
<td>78,461</td>
</tr>
<tr>
<td>Archer and Halvorson (2010)</td>
<td>empirical site study</td>
<td>0.34</td>
<td>34,483</td>
</tr>
<tr>
<td>Doberman et al. (2007)</td>
<td>empirical site study</td>
<td>0.21</td>
<td>21,412</td>
</tr>
<tr>
<td>Mosier et al. (2005)</td>
<td>empirical site study</td>
<td>0.29</td>
<td>29,040</td>
</tr>
<tr>
<td>Mosier et al. (2006)</td>
<td>empirical site study</td>
<td>0.42</td>
<td>42,141</td>
</tr>
<tr>
<td>Robertson et al. (2011)</td>
<td>modeling study</td>
<td>(0.54)</td>
<td>(53,942)</td>
</tr>
<tr>
<td>Walters et al. (2007)</td>
<td>modeling study</td>
<td>0.47</td>
<td>47,208</td>
</tr>
<tr>
<td>Sainju et al. (2016)</td>
<td>meta-analysis</td>
<td>0.22</td>
<td>22,483</td>
</tr>
<tr>
<td>This report</td>
<td>literature review</td>
<td>0.40</td>
<td>39,830</td>
</tr>
</tbody>
</table>

* results as reported without adjustments
Soybean residues are rich in nitrogen, which, it is thought, promotes 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 0.69 short tons of CO$_2$ per acre would be emitted to the atmosphere annually (0.19 short tons of carbon per acre). This estimate was developed from a simple arithmetic average of 27 studies that were reviewed. These included: one derivative statistical study of literature estimates, two modeling studies, 23 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 69,000 short tons of CO$_2$ would be emitted annually.

The descriptive statistics for the studies that were reviewed are shown in Table 57. Of the two modeling studies, one showed a net gain in soil organic carbon under corn-soybean rotation on cropland formerly in corn monoculture. In the other 26 studies, SOC storage in cropland under corn-soybean rotation declined after conversion from continuous corn. Using the average value for all 27 studies that were reviewed, cropland soils formerly under corn monoculture but converted to a two-year corn-soybean rotation are estimated to lose 0.42 ± 0.1 metric tons of carbon per hectare (0.19 short tons of carbon per acre) annually. Excluding the one odd modeling result, estimates of SOC loss in the reviewed studies range from 0.19 to 0.64 metric tons of carbon per hectare per year (0.08 to 0.29 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 (0.22 metric tons of carbon per hectare per year) than the mean value from the 27 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 somewhat less, suggesting that, beyond 20 years, soils may begin to approach a new equilibrium beyond which emissions cease.

**Table 57. Descriptive statistics: Corn-soybean rotation replacing continuous corn - carbon sequestration in soils**

<table>
<thead>
<tr>
<th>biogenic carbon sequestration (Mg C/ha/yr)</th>
<th>number of studies</th>
<th>ratio of sequestration to emission: study numbers</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>all studies</td>
<td>(0.42)</td>
<td>27</td>
<td>0.10</td>
<td>(0.62)</td>
<td>(0.22)</td>
</tr>
<tr>
<td>derivative statistical analyses or statistical summaries a</td>
<td>(0.19)</td>
<td>1</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>empirical site studies</td>
<td>(0.48)</td>
<td>23</td>
<td>0.11</td>
<td>(0.70)</td>
<td>(0.26)</td>
</tr>
<tr>
<td>modeling studies</td>
<td>0.06</td>
<td>2</td>
<td>0.29</td>
<td>(0.50)</td>
<td>(0.63)</td>
</tr>
<tr>
<td>5 to 30 cm soil sampling/modeling depth b</td>
<td>(0.38)</td>
<td>18</td>
<td>0.09</td>
<td>(0.56)</td>
<td>(0.19)</td>
</tr>
<tr>
<td>&gt; 30 cm soil sampling/modeling depth b</td>
<td>(0.64)</td>
<td>7</td>
<td>0.30</td>
<td>(1.22)</td>
<td>(0.06)</td>
</tr>
<tr>
<td>1 to 10 year annual sequestration rate</td>
<td>(0.59)</td>
<td>9</td>
<td>0.16</td>
<td>(0.90)</td>
<td>(0.28)</td>
</tr>
<tr>
<td>10 to 20 year annual sequestration rate</td>
<td>(0.40)</td>
<td>12</td>
<td>0.19</td>
<td>(0.78)</td>
<td>(0.02)</td>
</tr>
<tr>
<td>20 to 30 yr annual sequestration rate</td>
<td>(0.21)</td>
<td>7</td>
<td>0.04</td>
<td>(0.29)</td>
<td>(0.13)</td>
</tr>
</tbody>
</table>

a statistical summaries or derivative statistical analyses other than meta-analyses
b results for lowest reported sampling depth
c 27 studies, 27 study results
d ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions
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 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. (Ventera 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 55, 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 11,000 CO$_2$-equivalent tons. This estimate was developed using the results from 17 published studies. 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. We used the mean estimate from all 17 studies reviewed as the best estimate of the percentage change in $N_2O$ emission with corn-soybean rotation on croplands formerly in corn monoculture. Using the mean estimate for all reviewed studies, the conversion of cropland formerly in corn monoculture to a two-year corn-soybean rotation is estimated to reduce $N_2O$ emissions by 17.5 ± 8.3 percent.

The studies that were reviewed included: 15 empirical site studies, one modeling study and one meta-analysis. Of the 17 studies reviewed, 13 reported reduced $N_2O$ emissions with corn-soybean rotation on cropland formerly in corn monoculture and 4 reported increases. The one available meta-analysis reported a slight reduction in emissions, the modeling study showed an increase in emissions. The average value of the results from all of the studies was selected as most consistent with observed rates of synthetic nitrogen usage by rotations and the consensus in the scientific literature on the response of $N_2O$ soil emissions to nitrogen use on croplands, both directionally and in its magnitude.$^{13}$

---

$^{13}$ With fertilizer-based emissions comprising about 30 percent of average cropland emissions, and with a generally linear relationship between $N_2O$ and nitrogen applications, a 50 percent reduction in nitrogen application rates should result in about a 15 percent overall reduction in emissions. Of the estimates given in Table S8, the estimate using the mean of all studies is most in agreement with this understanding.
The descriptive statistics for the reviewed studies are shown in Table 58, 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 58. Descriptive statistics: Corn-soybean rotation replacing continuous corn - \text{N}_2\text{O}

<table>
<thead>
<tr>
<th>Category</th>
<th>Emissions: % change in emissions per hectare</th>
<th>Number of studies</th>
<th>Change in emissions, ratio positive-to-negative: study numbers</th>
<th>Standard error of mean (±-</th>
<th>Lower 95% confidence interval</th>
<th>Upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>All studies</td>
<td>-17%</td>
<td>17</td>
<td>4/13</td>
<td>8%</td>
<td>-34%</td>
<td>-1%</td>
</tr>
<tr>
<td>Meta-analysis</td>
<td>-2%</td>
<td>1</td>
<td>0/1</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Empirical site studies</td>
<td>-21%</td>
<td>15</td>
<td>3/12</td>
<td>9%</td>
<td>-38%</td>
<td>-3%</td>
</tr>
<tr>
<td>Modeling studies</td>
<td>15%</td>
<td>1</td>
<td>1/0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Annual flux monitoring/modeling</td>
<td>16%</td>
<td>6</td>
<td>4/2</td>
<td>14%</td>
<td>-11%</td>
<td>43%</td>
</tr>
<tr>
<td>Growing season flux monitoring/modeling</td>
<td>-41%</td>
<td>10</td>
<td>0/10</td>
<td>5%</td>
<td>-50%</td>
<td>-31%</td>
</tr>
<tr>
<td>1 to 2 yrs of observations</td>
<td>-8%</td>
<td>7</td>
<td>2/5</td>
<td>18%</td>
<td>-45%</td>
<td>28%</td>
</tr>
<tr>
<td>3 years-plus of observations</td>
<td>-22%</td>
<td>8</td>
<td>2/6</td>
<td>9%</td>
<td>-41%</td>
<td>-4%</td>
</tr>
</tbody>
</table>

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 \text{N}_2\text{O} emissions estimates, the anomalous increase in \text{N}_2\text{O} 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 \text{N}_2\text{O} emissions to rotation change.

V. Practices for which only preliminary estimates are available

In addition to the 13 practices for which we have final results for GHG-avoidance, we have developed preliminary analyses for an additional eight practices. These include:

- Restored and constructed wetlands
- Biochar
- Nitrification and urease inhibitors
- Controlled release nitrogen fertilizers
- Split nitrogen fertilizer application
- Subsurface nitrogen fertilizer application
- Spring nitrogen fertilizer application \textit{in lieu} of fall application
- Fifteen percent per acre nitrogen fertilizer use reduction

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 wetlands are drained wetlands that have been hydrologically restored, typically by blocking drainage ditches or disconnecting drainage piping.
Biochar is a charcoal-like soil amendment produced through pyrolysis using, among other feedstocks, crop residues. Biochar is highly resistant to microbial degradation in soils. As a soil amendment, biochar acts to rapidly build soil organic carbon in soils, in the process, offsetting CO₂ emissions elsewhere in the economy.

Nitrification inhibitors are chemical additives to nitrogen fertilizers that act to impede the operation of the soil enzyme responsible for nitrification, delaying nitrification until later in the growing season when crop nitrogen needs are greatest. Urea inhibitors act to impede the operation of the urease enzyme, which plays the central role in the hydrolysis of urea fertilizer to ammonium and CO₂. Urease inhibitors act similarly to nitrification inhibitors, delaying the availability of nitrogen, in the form of ammonium in the case of urease inhibitors, to crops until the time of greatest crop nitrogen needs.

Controlled release fertilizers are a polymer-coated granular form of nitrogen fertilizer that, through diffusion through the polymer coating, only slowly releases nutrients to the soil and plant roots. The rate of diffusion is controlled by soil temperature and moisture, allowing its rate of release to be coordinated with the time of greatest crop nutrient needs.

It is conventional to apply nitrogen fertilizer in a single application at, before or immediately after planting. In split fertilizer application, fertilizer is applied to soils in two or three applications spaced throughout the crop-growing season to coincide with crop nutrient needs. Nitrogen applied near the plant root zone is readily available to the plant. With subsurface application, nitrogen fertilizer is placed below the soil surface near the root zone through injection in a liquid form or surface broadcast followed by incorporation by tillage. Granular fertilizer also can be placed near the root zone with an air drill.

Finally, some crop producers apply fertilizer in the fall, a slower time of the year when there are fewer competing demands on farm labor. Fall fertilizer application can result in substantial losses of nitrogen to the environment through leaching and ammonia volatilization. With spring fertilizer application, nitrogen is applied closer in time to plant needs, lessening the risk of loss. With a 15 percent per acre nitrogen fertilizer reduction, average rates of application are brought nearer to agronomic rates. In the US, as much as 50 percent of applied nitrogen fertilizer is lost to the environment, in part due to over-application.

Preliminary analyses have been developed for these eight practices. The results of those analyses are provided in Appendices A through H in table form. For each practice, we provide preliminary results in the form of an itemized budget of emissions-avoidance by emissions source, along with descriptive statistics for the body of published literature on which those results reside.

Of these eight practices, the most effective in reducing GHG emissions, at least on a preliminary basis, are, in order: biochar, controlled release nitrogen fertilizers (CRFs), nitrification inhibitors (NIs) and urease inhibitors (UIs) as a group, and split nitrogen fertilizer application. GHG emissions are mitigated with a 15 percent nitrogen fertilizer reduction, but the overall effect on emissions is small on an area basis. In the case of biochar, the emissions-avoidance effect is principally a soil carbon effect. CRFs, NIs, UIs and split application all act to improve the nutrient use efficiency of crop production, lowering the availability of soil nitrate and ammonium at times when crop needs are least, and reducing N₂O emissions as a result.

GHG emissions rise substantially with continuously inundated constructed and restored wetlands. Wetlands of any type are CH₄ producers. In continuously inundated constructed and restored wetlands,
the effects of increased CH$_4$ production in wetland sediments tend to overwhelm all other effects, including enhanced carbon sequestration in wetlands soils. By contrast, wetlands that are seasonally inundated may act similarly to riparian buffers, resulting in net GHG reductions upon restoration. A wet meadow might be a good example of a seasonally inundated wetland. The preliminary results given in Appendix D suggest that subsurface nitrogen application and spring fertilizer application may lead to increased GHG emissions, although again these results are preliminary.

There is a general dearth of research results for these eight practices, excepting nitrification and urease inhibitors, controlled release fertilizers, and biochar. This inhibits the effort to form firm conclusions on emissions-avoidance for many of these practices.

For constructed and restored wetlands, there are interesting design questions to be explored, including possible use of specific types of vegetation and inundation regimes to minimize CH$_4$ production and to maximize sediment carbon storage.

As these explorations are completed, we will amend this report to provide updated, finalized emissions-avoidance estimates.
# Appendix A. Constructed and restored wetlands

Table A1. Constructed and restored wetlands: Emissions-avoided

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Emission Source or Sink</th>
<th>Emission (CO$_2$-e short tons per 100,000 acres per year) $^a$</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>N$_2$O-direct</td>
<td>soils or sediments</td>
<td>(4,856)</td>
<td>crop production</td>
</tr>
<tr>
<td>N$_2$O-indirect volatilization</td>
<td>indirect emission-Nitrogen volatilization, redeposition</td>
<td>(2,169)</td>
<td>crop production</td>
</tr>
<tr>
<td>N$_2$O-indirect leaching</td>
<td>indirect emission-Nitrogen leaching or runoff</td>
<td>(7,186)</td>
<td>crop production</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>soils or sediments</td>
<td>218,640</td>
<td>crop production</td>
</tr>
<tr>
<td>CO$_2$ $^b$</td>
<td>carbon accumulation in wetland sediments and biomass</td>
<td>(109,022)</td>
<td>crop production</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>cultivated soils from lime or urea use</td>
<td>(2,808)</td>
<td>crop production</td>
</tr>
<tr>
<td>GHGs-energy</td>
<td>fossil fuel and electricity use in crop production</td>
<td>(6,892)</td>
<td>crop production</td>
</tr>
<tr>
<td>Out-of-State Upstream GHGs</td>
<td>upstream agricultural chemicals and fossil fuel production</td>
<td>(20,190)</td>
<td>crop production</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>65,517 $^c$</strong></td>
<td></td>
</tr>
</tbody>
</table>

| Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass |
|----------------------------------------|--------------------------------------------------------------------------------------------|
| 40 year storage                       | all sources and sinks                                                                      | (43,505)                                                     |
| 100 year storage                      | all sources and sinks                                                                       | (370,571)                                                    |

$^a$ 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

---

Greenhouse gas reduction potential of agricultural best management practices • October 2019 Minnesota Pollution Control Agency
Table A2. Descriptive statistics: Constructed and restored wetlands – carbon sequestration in soils and biomass

<table>
<thead>
<tr>
<th></th>
<th>biogenic carbon sequestration (Mg C/ha/yr)</th>
<th>number of studies</th>
<th>ratio of sequestration to emission: study numbers</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>total ecosystem carbon (NECB/NBP)</td>
<td>1.73</td>
<td>38</td>
<td>32/6</td>
<td>0.44</td>
<td>0.88</td>
<td>2.59</td>
</tr>
<tr>
<td>soil organic carbon (SOC) only</td>
<td>1.92</td>
<td>38</td>
<td>25/3</td>
<td>0.32</td>
<td>1.28</td>
<td>2.55</td>
</tr>
<tr>
<td>eddy covariance empirical site studies (NECB/NBP)</td>
<td>1.78</td>
<td>19</td>
<td>18/1</td>
<td>0.55</td>
<td>0.70</td>
<td>2.86</td>
</tr>
<tr>
<td>chamber empirical site studies (NECB/NBP)</td>
<td>1.50</td>
<td>18</td>
<td>13/5</td>
<td>0.72</td>
<td>0.10</td>
<td>2.91</td>
</tr>
<tr>
<td>empirical site studies-soil sampling</td>
<td>2.16</td>
<td>32</td>
<td>30/2</td>
<td>0.38</td>
<td>1.41</td>
<td>2.91</td>
</tr>
<tr>
<td>meta-analyses</td>
<td>1.69</td>
<td>1</td>
<td>1/0</td>
<td>0.05</td>
<td>1.59</td>
<td>1.78</td>
</tr>
<tr>
<td>derivative statistical analyses or statistical summaries b</td>
<td>1.78</td>
<td>1</td>
<td>1/0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>modeling studies</td>
<td>0.18</td>
<td>1</td>
<td>1/0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>expert judgment/literature review</td>
<td>1.38</td>
<td>19</td>
<td>18/1</td>
<td>0.25</td>
<td>0.88</td>
<td>1.87</td>
</tr>
<tr>
<td>freshwater mineral wetlands</td>
<td>2.12</td>
<td>57</td>
<td>55/2</td>
<td>0.31</td>
<td>1.51</td>
<td>2.72</td>
</tr>
<tr>
<td>peatlands</td>
<td>1.44</td>
<td>36</td>
<td>29/7</td>
<td>0.45</td>
<td>0.56</td>
<td>2.33</td>
</tr>
<tr>
<td>1 to 9 year old constructed/restored wetlands</td>
<td>2.88</td>
<td>37</td>
<td>33/4</td>
<td>0.50</td>
<td>1.85</td>
<td>3.91</td>
</tr>
<tr>
<td>10 year old-plus constructed/restored wetlands</td>
<td>1.59</td>
<td>33</td>
<td>28/5</td>
<td>0.39</td>
<td>0.83</td>
<td>2.35</td>
</tr>
</tbody>
</table>

a NECB = Net Ecosystem Carbon Balance; NBP = Net Biome Productivity
b derivative statistical studies other than meta-analyses
c ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

Table A3. Descriptive statistics: Constructed and restored wetlands – CH₄

<table>
<thead>
<tr>
<th></th>
<th>emissions (kg CH₄/ hectare/yr)</th>
<th>number of studies</th>
<th>ratio, positive to negative results: study numbers</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>meta-analyses and other derivative statistical analyses or statistical summaries b</td>
<td>194</td>
<td>8</td>
<td>8/0</td>
<td>30.76</td>
<td>134</td>
<td>254</td>
</tr>
<tr>
<td>all studies</td>
<td>301</td>
<td>81</td>
<td>79/2</td>
<td>40.00</td>
<td>223</td>
<td>380</td>
</tr>
<tr>
<td>empirical site studies</td>
<td>278</td>
<td>66</td>
<td>64/2</td>
<td>39.69</td>
<td>200</td>
<td>356</td>
</tr>
<tr>
<td>eddy covariance site studies</td>
<td>375</td>
<td>12</td>
<td>12/0</td>
<td>83.80</td>
<td>211</td>
<td>540</td>
</tr>
<tr>
<td>other site studies</td>
<td>253</td>
<td>52</td>
<td>50/2</td>
<td>46.34</td>
<td>162</td>
<td>344</td>
</tr>
<tr>
<td>modeling studies</td>
<td>100</td>
<td>1</td>
<td>1</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>annual flux monitoring/modeling</td>
<td>379</td>
<td>50</td>
<td>49/1</td>
<td>53.47</td>
<td>274</td>
<td>484</td>
</tr>
<tr>
<td>growing season and subgrowing season flux monitoring/modeling</td>
<td>195</td>
<td>33</td>
<td>32/1</td>
<td>56.22</td>
<td>47</td>
<td>343</td>
</tr>
<tr>
<td>constructed wetlands studies</td>
<td>395</td>
<td>29</td>
<td>29/0</td>
<td>75.56</td>
<td>308</td>
<td>483</td>
</tr>
<tr>
<td>restored wetlands studies</td>
<td>250</td>
<td>52</td>
<td>50/2</td>
<td>44.68</td>
<td>162</td>
<td>337</td>
</tr>
<tr>
<td>1 year of observations or simulations</td>
<td>357</td>
<td>33</td>
<td>32/1</td>
<td>74.47</td>
<td>211</td>
<td>503</td>
</tr>
<tr>
<td>&gt; 1 year of observations or simulations</td>
<td>283</td>
<td>25</td>
<td>24/1</td>
<td>71.77</td>
<td>142</td>
<td>424</td>
</tr>
<tr>
<td>1 to 9 year old constructed/restored wetlands</td>
<td>178</td>
<td>29</td>
<td>27/2</td>
<td>42.02</td>
<td>96</td>
<td>260</td>
</tr>
<tr>
<td>10 year old-plus constructed/restored wetlands</td>
<td>365</td>
<td>40</td>
<td>40/0</td>
<td>62.29</td>
<td>243</td>
<td>487</td>
</tr>
<tr>
<td>studies with pre-restoration counterfactual</td>
<td>170</td>
<td>23</td>
<td>21/2</td>
<td>67.09</td>
<td>41</td>
<td>299</td>
</tr>
</tbody>
</table>

a negative emissions = removal from atmosphere and destruction in soils
b derivative statistical studies other than meta-analyses
Table A4. Descriptive statistics: Constructed and restored wetlands – N\textsubscript{2}O

<table>
<thead>
<tr>
<th>Greenhouse Gas Emission Source or Sink</th>
<th>Emission (CO\textsubscript{2}-e short tons per 100,000 acres per year) \textsuperscript{a}</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>N\textsubscript{2}O-direct soils</td>
<td>(17,996)</td>
<td>crop production</td>
</tr>
<tr>
<td>N\textsubscript{2}O-indirect volatilization</td>
<td>(325)</td>
<td>crop production</td>
</tr>
<tr>
<td>N\textsubscript{2}O-indirect leaching</td>
<td>(5,174)</td>
<td>crop production</td>
</tr>
<tr>
<td>CH\textsubscript{4} soils</td>
<td>(572)</td>
<td>crop production</td>
</tr>
<tr>
<td>CO\textsubscript{2} carbon accumulation in soils</td>
<td>(138,936)</td>
<td>crop production</td>
</tr>
<tr>
<td>CO\textsubscript{2} cultivated soils from lime or urea use</td>
<td>-</td>
<td>crop production</td>
</tr>
<tr>
<td>GHGs-energy fossil fuel and electricity use in crop production</td>
<td>13,224</td>
<td>crop production</td>
</tr>
<tr>
<td>Out-of-State Upstream GHGs upstream agricultural chemicals and fossil fuel production</td>
<td>2,929</td>
<td>crop production</td>
</tr>
<tr>
<td>In-State Upstream GHGs</td>
<td>27,136</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>(119,713)</td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{a} positive = emissions increase, negative = emissions reduction

Appendix B. Biochar

Table B1. Biochar: Emissions-avoided \textsuperscript{a}

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Emission Source or Sink</th>
<th>Emission (CO\textsubscript{2}-e short tons per 100,000 acres per year) \textsuperscript{a}</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>N\textsubscript{2}O-direct soils</td>
<td>(17,996)</td>
<td>crop production</td>
<td></td>
</tr>
<tr>
<td>N\textsubscript{2}O-indirect volatilization</td>
<td>(325)</td>
<td>crop production</td>
<td></td>
</tr>
<tr>
<td>N\textsubscript{2}O-indirect leaching</td>
<td>(5,174)</td>
<td>crop production</td>
<td></td>
</tr>
<tr>
<td>CH\textsubscript{4} soils</td>
<td>(572)</td>
<td>crop production</td>
<td></td>
</tr>
<tr>
<td>CO\textsubscript{2} carbon accumulation in soils</td>
<td>(138,936)</td>
<td>crop production</td>
<td></td>
</tr>
<tr>
<td>CO\textsubscript{2} cultivated soils from lime or urea use</td>
<td>-</td>
<td>crop production</td>
<td></td>
</tr>
<tr>
<td>GHGs-energy fossil fuel and electricity use in crop production</td>
<td>13,224</td>
<td>crop production</td>
<td></td>
</tr>
<tr>
<td>Out-of-State Upstream GHGs upstream agricultural chemicals and fossil fuel production</td>
<td>2,929</td>
<td>crop production</td>
<td></td>
</tr>
<tr>
<td>In-State Upstream GHGs</td>
<td>27,136</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>(119,713)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{a} positive = emissions increase, negative = emissions reduction
Table B2. Descriptive statistics: Biochar - carbon sequestration in soils

<table>
<thead>
<tr>
<th>Description</th>
<th>biogenic carbon sequestration (Mg C/ha/yr)</th>
<th>number of studies</th>
<th>ratio of sequestration to emission: study numbers</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>crop residue-derived biochar MRT</td>
<td>0.85</td>
<td>10</td>
<td>10/0</td>
<td>0.03</td>
<td>0.79</td>
<td>0.91</td>
</tr>
<tr>
<td>all studies-all MRT bases</td>
<td>0.78</td>
<td>39</td>
<td>39/0</td>
<td>0.02</td>
<td>0.73</td>
<td>0.82</td>
</tr>
<tr>
<td>meta-analyses-based mean residence time (MRT)</td>
<td>0.82</td>
<td>2</td>
<td>2/0</td>
<td>0.05</td>
<td>0.73</td>
<td>0.91</td>
</tr>
<tr>
<td>survey-based MRT</td>
<td>0.87</td>
<td>2</td>
<td>2/0</td>
<td>0.04</td>
<td>0.79</td>
<td>0.95</td>
</tr>
<tr>
<td>2 pool exponential model-based MRT</td>
<td>0.75</td>
<td>19</td>
<td>19/0</td>
<td>0.04</td>
<td>0.67</td>
<td>0.82</td>
</tr>
<tr>
<td>logistic degradation model-based MRT</td>
<td>0.82</td>
<td>3</td>
<td>3/0</td>
<td>0.02</td>
<td>0.78</td>
<td>0.86</td>
</tr>
<tr>
<td>literature review/expert judgment-based MRT</td>
<td>0.93</td>
<td>6</td>
<td>6/0</td>
<td>0.08</td>
<td>0.77</td>
<td>1.09</td>
</tr>
<tr>
<td>wood-derived biochar MRT</td>
<td>0.74</td>
<td>21</td>
<td>21/0</td>
<td>0.04</td>
<td>0.67</td>
<td>0.82</td>
</tr>
<tr>
<td>grassland bioenergy-derived biochar MRT</td>
<td>0.77</td>
<td>8</td>
<td>8/0</td>
<td>0.05</td>
<td>0.68</td>
<td>0.86</td>
</tr>
</tbody>
</table>

*a ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

Table B3. Descriptive statistics: Biochar – N₂O

<table>
<thead>
<tr>
<th>Description</th>
<th>emissions: % change in emissions per hectare</th>
<th>number of studies</th>
<th>change in emissions, ratio positive-to-negative: study numbers</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>meta-analyses</td>
<td>-28%</td>
<td>11</td>
<td>0/11</td>
<td>4%</td>
<td>-36%</td>
<td>-20%</td>
</tr>
<tr>
<td>empirical site studies</td>
<td>-38%</td>
<td>25</td>
<td>2/23</td>
<td>7%</td>
<td>-52%</td>
<td>-25%</td>
</tr>
<tr>
<td>expert judgment/literature reviews</td>
<td>-25%</td>
<td>3</td>
<td>0/3</td>
<td>10%</td>
<td>-45%</td>
<td>-5%</td>
</tr>
<tr>
<td>wood-based biochar</td>
<td>-52%</td>
<td>4</td>
<td>0/4</td>
<td>12%</td>
<td>-75%</td>
<td>-30%</td>
</tr>
<tr>
<td>crop residue-based biochar</td>
<td>-59%</td>
<td>4</td>
<td>0/4</td>
<td>17%</td>
<td>-92%</td>
<td>-27%</td>
</tr>
<tr>
<td>0 to 10 Mg biochar per hectare</td>
<td>-21%</td>
<td>6</td>
<td>1/5</td>
<td>18%</td>
<td>-56%</td>
<td>14%</td>
</tr>
<tr>
<td>11 to 20 Mg biochar per hectare</td>
<td>-38%</td>
<td>7</td>
<td>1/6</td>
<td>13%</td>
<td>-63%</td>
<td>-13%</td>
</tr>
<tr>
<td>21 to 30 Mg biochar per hectare</td>
<td>-43%</td>
<td>9</td>
<td>0/9</td>
<td>8%</td>
<td>-59%</td>
<td>-27%</td>
</tr>
<tr>
<td>&gt;30 Mg biochar per hectare</td>
<td>-54%</td>
<td>6</td>
<td>0/6</td>
<td>12%</td>
<td>-78%</td>
<td>-30%</td>
</tr>
<tr>
<td>annual flux monitoring</td>
<td>-19%</td>
<td>7</td>
<td>2/5</td>
<td>15%</td>
<td>-48%</td>
<td>11%</td>
</tr>
<tr>
<td>growing season flux monitoring</td>
<td>-41%</td>
<td>17</td>
<td>0/17</td>
<td>7%</td>
<td>-55%</td>
<td>-28%</td>
</tr>
</tbody>
</table>

Table B4. Descriptive statistics: Biochar – CH₄

<table>
<thead>
<tr>
<th>Description</th>
<th>emissions: % change in emissions per hectare</th>
<th>number of studies</th>
<th>change in emissions, ratio positive-to-negative: study numbers</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>all studies</td>
<td>-28%</td>
<td>15</td>
<td>5/10</td>
<td>16%</td>
<td>-59%</td>
<td>4%</td>
</tr>
<tr>
<td>meta-analyses</td>
<td>-56%</td>
<td>2</td>
<td>1/1</td>
<td>59%</td>
<td>-59%</td>
<td>170%</td>
</tr>
<tr>
<td>empirical site studies</td>
<td>-41%</td>
<td>13</td>
<td>4/9</td>
<td>14%</td>
<td>-68%</td>
<td>-13%</td>
</tr>
<tr>
<td>annual flux monitoring</td>
<td>-14%</td>
<td>2</td>
<td>1/1</td>
<td>18%</td>
<td>-63%</td>
<td>36%</td>
</tr>
<tr>
<td>growing season and subgrowing season flux monitoring</td>
<td>-45%</td>
<td>11</td>
<td>3/8</td>
<td>16%</td>
<td>-77%</td>
<td>-14%</td>
</tr>
<tr>
<td>0 to 20 Mg biochar application rate</td>
<td>-37%</td>
<td>6</td>
<td>2/5</td>
<td>19%</td>
<td>-73%</td>
<td>0%</td>
</tr>
<tr>
<td>&gt;20 Mg biochar application rate</td>
<td>-65%</td>
<td>5</td>
<td>0/5</td>
<td>25%</td>
<td>-115%</td>
<td>-15%</td>
</tr>
</tbody>
</table>
## Appendix C. Split fertilizer application

### Table C1. Split fertilizer application: Emissions-avoided

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Emission Source or Sink</th>
<th>Emission (CO$_2$-e short tons per 100,000 acres)</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>N$_2$O-direct</td>
<td>soils</td>
<td>(13,125)</td>
<td>single application</td>
</tr>
<tr>
<td>N$_2$O-indirect volatilization</td>
<td>indirect emission-Nitrogen volatilization, redeposition</td>
<td>108</td>
<td>single application</td>
</tr>
<tr>
<td>N$_2$O-indirect leaching</td>
<td>indirect emission-Nitrogen leaching or runoff</td>
<td>(1,006)</td>
<td>single application</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>soils</td>
<td>not known</td>
<td>single application</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>carbon accumulation in soils</td>
<td>-</td>
<td>single application</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>cultivated soils from lime or urea use</td>
<td>-</td>
<td>single application</td>
</tr>
<tr>
<td>GHGs-energy</td>
<td>fossil fuel and electricity use in crop production</td>
<td>568</td>
<td>single application</td>
</tr>
<tr>
<td>Out-of-State</td>
<td>upstream agricultural chemicals and fossil fuel production</td>
<td>-</td>
<td>single application</td>
</tr>
<tr>
<td>Upstream GHGs</td>
<td></td>
<td>(13,455)</td>
<td></td>
</tr>
</tbody>
</table>

*a positive = emissions increase, negative = emissions reduction

### Table C2. Descriptive statistics: Split fertilizer application - N$_2$O

<table>
<thead>
<tr>
<th></th>
<th>emissions: % change in emissions per hectare</th>
<th>number of studies</th>
<th>change in emissions, ratio positive-to-negative: study numbers</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>meta-analyses</td>
<td>-21%</td>
<td>5</td>
<td>2/3</td>
<td>12%</td>
<td>-31%</td>
<td>-10%</td>
</tr>
<tr>
<td>empirical site studies</td>
<td>-8%</td>
<td>25</td>
<td>11/14</td>
<td>6%</td>
<td>-20%</td>
<td>3%</td>
</tr>
<tr>
<td>modeling studies</td>
<td>-2%</td>
<td>9</td>
<td>2/7</td>
<td>6%</td>
<td>-13%</td>
<td>8%</td>
</tr>
<tr>
<td>single split versus no splits</td>
<td>-11%</td>
<td>35</td>
<td>12/23</td>
<td>5%</td>
<td>-20%</td>
<td>-2%</td>
</tr>
<tr>
<td>more splits versus fewer splits</td>
<td>-1%</td>
<td>6</td>
<td>3/3</td>
<td>7%</td>
<td>-14%</td>
<td>12%</td>
</tr>
<tr>
<td>surface nitrogen application</td>
<td>-7%</td>
<td>11</td>
<td>3/8</td>
<td>6%</td>
<td>-19%</td>
<td>5%</td>
</tr>
<tr>
<td>subsurface nitrogen application</td>
<td>-8%</td>
<td>19</td>
<td>7/12</td>
<td>8%</td>
<td>-23%</td>
<td>8%</td>
</tr>
<tr>
<td>growing season and subgrowing season flux monitoring/modeling</td>
<td>-9%</td>
<td>17</td>
<td>5/12</td>
<td>7%</td>
<td>-23%</td>
<td>5%</td>
</tr>
<tr>
<td>annual flux monitoring/modeling</td>
<td>-7%</td>
<td>21</td>
<td>9/12</td>
<td>5%</td>
<td>-17%</td>
<td>3%</td>
</tr>
<tr>
<td>1 year or less of observations or simulations</td>
<td>-23%</td>
<td>8</td>
<td>2/6</td>
<td>9%</td>
<td>-40%</td>
<td>-6%</td>
</tr>
<tr>
<td>&gt;1 to 2 years of observations or simulations</td>
<td>-11%</td>
<td>15</td>
<td>6/9</td>
<td>7%</td>
<td>-24%</td>
<td>3%</td>
</tr>
<tr>
<td>more than 2 years of observations or simulations</td>
<td>6%</td>
<td>10</td>
<td>4/6</td>
<td>7%</td>
<td>-8%</td>
<td>21%</td>
</tr>
</tbody>
</table>

### Table C3. Descriptive statistics: Split fertilizer application - CH$_4$

<table>
<thead>
<tr>
<th></th>
<th>emissions: % change in emissions per hectare</th>
<th>number of studies</th>
<th>change in emissions, ratio positive-to-negative: study numbers</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>all studies</td>
<td>-4%</td>
<td>8</td>
<td>3/5</td>
<td>9%</td>
<td>-22%</td>
<td>14%</td>
</tr>
</tbody>
</table>
## Appendix D. Subsurface fertilizer placement

### Table D1. Subsurface fertilizer placement: Emissions-avoided

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Emission Source or Sink</th>
<th>Emission (CO$_2$-e short tons per 100,000 acres)</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>N$_2$O-direct</td>
<td>soils</td>
<td>36,750</td>
<td>surface or shallow fertilizer placement</td>
</tr>
<tr>
<td>N$_2$O-indirect</td>
<td>redeposition</td>
<td>(1,187)</td>
<td>fertilizer placement</td>
</tr>
<tr>
<td>N$_2$O-indirect leaching</td>
<td>indirect emission-Nitrogen leaching or runoff</td>
<td>(4,999)</td>
<td>surface or shallow fertilizer placement</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>soils</td>
<td>not known</td>
<td>surface or shallow fertilizer placement</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>carbon accumulation in soils</td>
<td>-</td>
<td>surface or shallow fertilizer placement</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>cultivated soils from lime or urea use</td>
<td>-</td>
<td>surface or shallow fertilizer placement</td>
</tr>
<tr>
<td>GHGs-energy</td>
<td>fossil fuel and electricity use in crop production</td>
<td>405</td>
<td>surface or shallow fertilizer placement</td>
</tr>
<tr>
<td>Out-of-State Upstream GHGs</td>
<td>upstream agricultural chemicals and fossil fuel production</td>
<td>90</td>
<td>surface or shallow fertilizer placement</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>31,060</td>
<td></td>
</tr>
</tbody>
</table>

*positive = emissions increase, negative = emissions reduction

### Table D2. Descriptive statistics: Subsurface fertilizer placement – N$_2$O

<table>
<thead>
<tr>
<th>Emissions: % change in emissions per hectare</th>
<th>Number of studies</th>
<th>Change in emissions, ratio positive-to-negative: study numbers</th>
<th>Standard error of mean (±)</th>
<th>Lower 95% confidence interval</th>
<th>Upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Meta-analyses</strong></td>
<td>58%</td>
<td>7</td>
<td>5/2</td>
<td>37%</td>
<td>-1.5%</td>
</tr>
<tr>
<td><strong>Meta-analyses (synthetic nitrogen-only)</strong></td>
<td>10%</td>
<td>2</td>
<td>1/1</td>
<td>20%</td>
<td>-2.9%</td>
</tr>
<tr>
<td><strong>Empirical site studies</strong></td>
<td>61%</td>
<td>53</td>
<td>38/15</td>
<td>18%</td>
<td>25%</td>
</tr>
<tr>
<td><strong>Modeling studies</strong></td>
<td>21%</td>
<td>5</td>
<td>4/1</td>
<td>20%</td>
<td>-1.9%</td>
</tr>
<tr>
<td><strong>Expert judgment/literature reviews</strong></td>
<td>100%</td>
<td>1</td>
<td>1/0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Synthetic nitrogen</strong></td>
<td>30%</td>
<td>35</td>
<td>22/13</td>
<td>16%</td>
<td>-1%</td>
</tr>
<tr>
<td><strong>Manure nitrogen</strong></td>
<td>125%</td>
<td>25</td>
<td>23/2</td>
<td>33%</td>
<td>60%</td>
</tr>
<tr>
<td><strong>Conventional tillage</strong></td>
<td>99%</td>
<td>13</td>
<td>8/5</td>
<td>66%</td>
<td>-30%</td>
</tr>
<tr>
<td><strong>Reduced tillage</strong></td>
<td>26%</td>
<td>7</td>
<td>5/2</td>
<td>14%</td>
<td>-1%</td>
</tr>
<tr>
<td><strong>No till tillage</strong></td>
<td>7%</td>
<td>12</td>
<td>7/5</td>
<td>12%</td>
<td>-17%</td>
</tr>
<tr>
<td><strong>Surface versus deep application</strong></td>
<td>78%</td>
<td>52</td>
<td>40/12</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td><strong>Shallow versus deep application</strong></td>
<td>21%</td>
<td>18</td>
<td>13/5</td>
<td>11%</td>
<td>1%</td>
</tr>
<tr>
<td><strong>Annual flux monitoring/modeling</strong></td>
<td>41%</td>
<td>16</td>
<td>11/5</td>
<td>17%</td>
<td>7%</td>
</tr>
<tr>
<td><strong>Growing season and subgrowing season flux monitoring/modeling</strong></td>
<td>75%</td>
<td>43</td>
<td>33/10</td>
<td>23%</td>
<td>30%</td>
</tr>
</tbody>
</table>
Table D3. Descriptive statistics: Subsurface fertilizer placement – CH₄

<table>
<thead>
<tr>
<th></th>
<th>emissions: % change in emissions per hectare</th>
<th>number of studies</th>
<th>change in emissions, ratio positive-to-negative: study numbers</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>all studies</td>
<td>2%</td>
<td>9</td>
<td>4/5</td>
<td>209%</td>
<td>-409%</td>
<td>412%</td>
</tr>
</tbody>
</table>

Appendix E. Spring fertilizer placement

Table E1. Spring fertilizer application: Emissions-avoided

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Emission Source or Sink</th>
<th>Emission (CO₂-e short tons per 100,000 acres) a</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂O-direct</td>
<td>soils</td>
<td>2,236</td>
<td>crop production</td>
</tr>
<tr>
<td>N₂O-indirect</td>
<td>redeposition</td>
<td>116</td>
<td>crop production</td>
</tr>
<tr>
<td>N₂O-indirect leaching</td>
<td>indirect emission-Nitrogen leaching or runoff</td>
<td>(237)</td>
<td>crop production</td>
</tr>
<tr>
<td>CH₄</td>
<td>soils</td>
<td>not known</td>
<td>crop production</td>
</tr>
<tr>
<td>CO₂</td>
<td>carbon accumulation in soils</td>
<td>-</td>
<td>crop production</td>
</tr>
<tr>
<td>CO₂</td>
<td>cultivated soils from lime or urea use</td>
<td>-</td>
<td>crop production</td>
</tr>
<tr>
<td>GHGs-energy</td>
<td>fossil fuel and electricity use in crop production</td>
<td>-</td>
<td>crop production</td>
</tr>
<tr>
<td>Out-of-State</td>
<td>upstream agricultural chemicals and fossil fuel production</td>
<td>-</td>
<td>crop production</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>2,115</td>
<td></td>
</tr>
</tbody>
</table>

a positive = emissions increase, negative = emissions reduction

Table E2. Descriptive statistics: Spring fertilizer application - N₂O

<table>
<thead>
<tr>
<th></th>
<th>emissions: % change in emissions per hectare</th>
<th>number of studies</th>
<th>change in emissions, ratio positive-to-negative: study numbers</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>meta-analyses</td>
<td>4%</td>
<td>2</td>
<td>1/0/1</td>
<td>4%</td>
<td>-3%</td>
<td>10%</td>
</tr>
<tr>
<td>site studies</td>
<td>5%</td>
<td>19</td>
<td>10/9</td>
<td>12%</td>
<td>-18%</td>
<td>27%</td>
</tr>
<tr>
<td>modeling studies</td>
<td>-28%</td>
<td>19</td>
<td>0/4</td>
<td>12%</td>
<td>-51%</td>
<td>-5%</td>
</tr>
<tr>
<td>annual flux monitoring/modeling</td>
<td>-8%</td>
<td>17</td>
<td>6/11</td>
<td>9%</td>
<td>-27%</td>
<td>10%</td>
</tr>
<tr>
<td>growing season and subgrowing season flux monitoring/modeling</td>
<td>20%</td>
<td>6</td>
<td>4/2</td>
<td>28%</td>
<td>-35%</td>
<td>75%</td>
</tr>
<tr>
<td>1 to 2 years of observations</td>
<td>16%</td>
<td>10</td>
<td>5/5</td>
<td>20%</td>
<td>-24%</td>
<td>56%</td>
</tr>
<tr>
<td>3 years of observations</td>
<td>-9%</td>
<td>10</td>
<td>5/5</td>
<td>8%</td>
<td>-25%</td>
<td>7%</td>
</tr>
</tbody>
</table>
### Appendix F. Controlled release fertilizers

**Table F1. Controlled release fertilizers: Emissions-avoided**

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Emission Source or Sink</th>
<th>Emission (CO_{2-e} short tons per 100,000 acres per year)</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>N_{2}O-direct</td>
<td>soils</td>
<td>(21,152)</td>
<td>urea</td>
</tr>
<tr>
<td>N_{2}O-indirect</td>
<td>redeposition</td>
<td>(1,475)</td>
<td>urea</td>
</tr>
<tr>
<td>N_{2}O-indirect leaching</td>
<td>indirect emission-Nitrogen leaching or runoff</td>
<td>(4,743)</td>
<td>urea</td>
</tr>
<tr>
<td>CH_{4}</td>
<td>soils</td>
<td>not known</td>
<td>urea</td>
</tr>
<tr>
<td>CO_{2}</td>
<td>carbon accumulation in soils</td>
<td>-</td>
<td>urea</td>
</tr>
<tr>
<td>GHGs-energy</td>
<td>fossil fuel and electricity use in crop production</td>
<td>-</td>
<td>urea</td>
</tr>
<tr>
<td>Out-of-State</td>
<td>upstream agricultural chemicals and fossil fuel production</td>
<td>-</td>
<td>urea</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>(27,369)</td>
<td></td>
</tr>
</tbody>
</table>

*a positive = emissions increase, negative = emissions reduction

**Table F2. Descriptive statistics: Controlled release fertilizer - N{\textsubscript{2}}O**

<table>
<thead>
<tr>
<th>Source of Study</th>
<th>Change in Emissions, %</th>
<th>Number of Studies</th>
<th>Change in Emissions, Ratio Positive-to-Negative: Study Numbers</th>
<th>Standard Error of Mean (+/-)</th>
<th>Lower 95% Confidence Interval</th>
<th>Upper 95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meta-analyses</td>
<td>-33%</td>
<td>9</td>
<td>0/9</td>
<td>10%</td>
<td>-53%</td>
<td>-13%</td>
</tr>
<tr>
<td>Modeling studies</td>
<td>-7%</td>
<td>1</td>
<td>0/1</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Empirical site studies</td>
<td>-10%</td>
<td>54</td>
<td>15/39</td>
<td>8%</td>
<td>-26%</td>
<td>6%</td>
</tr>
<tr>
<td>Surface nitrogen application</td>
<td>6%</td>
<td>18</td>
<td>5/13</td>
<td>16%</td>
<td>-25%</td>
<td>38%</td>
</tr>
<tr>
<td>Subsurface nitrogen application</td>
<td>-6%</td>
<td>23</td>
<td>9/14</td>
<td>12%</td>
<td>-34%</td>
<td>22%</td>
</tr>
<tr>
<td>Single nitrogen application</td>
<td>6%</td>
<td>29</td>
<td>11/18</td>
<td>13%</td>
<td>-18%</td>
<td>31%</td>
</tr>
<tr>
<td>Split nitrogen application</td>
<td>-23%</td>
<td>16</td>
<td>4/15</td>
<td>10%</td>
<td>-43%</td>
<td>-3%</td>
</tr>
<tr>
<td>&lt;1 to 2 years of observations or simulations</td>
<td>-1%</td>
<td>32</td>
<td>12/20</td>
<td>11%</td>
<td>-22%</td>
<td>19%</td>
</tr>
<tr>
<td>3 years-plus of observations or simulations</td>
<td>-13%</td>
<td>2,120</td>
<td>3/18</td>
<td>12%</td>
<td>-36%</td>
<td>10%</td>
</tr>
<tr>
<td>Annual flux monitoring/modeling</td>
<td>2%</td>
<td>11</td>
<td>4/7</td>
<td>17%</td>
<td>-31%</td>
<td>35%</td>
</tr>
<tr>
<td>Growing season and subgrowing season flux monitoring/modeling</td>
<td>-13%</td>
<td>44</td>
<td>12/32</td>
<td>9%</td>
<td>-31%</td>
<td>5%</td>
</tr>
</tbody>
</table>

**Table F3. Descriptive statistics: Controlled release fertilizer – CH_{4}**

<table>
<thead>
<tr>
<th>Source of Study</th>
<th>Change in Emissions, %</th>
<th>Number of Studies</th>
<th>Change in Emissions, Ratio Positive-to-Negative: Study Numbers</th>
<th>Standard Error of Mean (+/-)</th>
<th>Lower 95% Confidence Interval</th>
<th>Upper 95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>All studies</td>
<td>44%</td>
<td>7</td>
<td>3/4</td>
<td>107%</td>
<td>-165%</td>
<td>253%</td>
</tr>
</tbody>
</table>
## Appendix G. Nitrification and urease inhibitors

### Table G1. Nitrification and urease inhibitors: Emissions-avoided

<table>
<thead>
<tr>
<th>Greenhouse Gas</th>
<th>Emission Source or Sink</th>
<th>Emission (CO&lt;sub&gt;2&lt;/sub&gt;-e short tons per 100,000 acres per year)</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>N&lt;sub&gt;2&lt;/sub&gt;O-direct</td>
<td>soils</td>
<td>(20,415)</td>
<td>no inhibitors</td>
</tr>
<tr>
<td>N&lt;sub&gt;2&lt;/sub&gt;O-indirect</td>
<td>redeposition</td>
<td>(995)</td>
<td>no inhibitors</td>
</tr>
<tr>
<td>N&lt;sub&gt;2&lt;/sub&gt;O-indirect leaching</td>
<td>indirect emission-Nitrogen leaching or runoff</td>
<td>(2,012)</td>
<td>no inhibitors</td>
</tr>
<tr>
<td>CH&lt;sub&gt;4&lt;/sub&gt;</td>
<td>soils</td>
<td>(612)</td>
<td>no inhibitors</td>
</tr>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>carbon accumulation in soils</td>
<td>-</td>
<td>no inhibitors</td>
</tr>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>cultivated soils from lime or urea use</td>
<td>-</td>
<td>no inhibitors</td>
</tr>
<tr>
<td>GHGs-energy</td>
<td>fossil fuel and electricity use in crop production</td>
<td>-</td>
<td>no inhibitors</td>
</tr>
<tr>
<td>Out-of-State Upstream GHGs</td>
<td>upstream agricultural chemicals and fossil fuel production</td>
<td>-</td>
<td>no inhibitors</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>(24,033)</td>
<td></td>
</tr>
</tbody>
</table>

*positive = emissions increase, negative = emissions reduction

### Table G2. Descriptive statistics: Nitrification and urease inhibitors - N<sub>2</sub>O

<table>
<thead>
<tr>
<th>Emissions: % change in emissions per hectare or acre</th>
<th>Number of studies</th>
<th>Change in emissions, ratio positive-to-negative: study numbers</th>
<th>Standard error of mean (+/-)</th>
<th>Lower 95% confidence interval</th>
<th>Upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>meta-analyses and other derivative statistical studies</td>
<td>-32%</td>
<td>23, 2/21</td>
<td>5%</td>
<td>-41%</td>
<td>-23%</td>
</tr>
<tr>
<td>empirical site studies</td>
<td>-31%</td>
<td>130, 18/12</td>
<td>2%</td>
<td>-35%</td>
<td>-26%</td>
</tr>
<tr>
<td>modeling studies</td>
<td>-17%</td>
<td>4, 0/4</td>
<td>9%</td>
<td>-35%</td>
<td>2%</td>
</tr>
<tr>
<td>expert judgment/literature reviews</td>
<td>-26%</td>
<td>4, 0/4</td>
<td>7%</td>
<td>-40%</td>
<td>-12%</td>
</tr>
<tr>
<td>nitrification inhibitors</td>
<td>-39%</td>
<td>88, 5/3</td>
<td>3%</td>
<td>-44%</td>
<td>-34%</td>
</tr>
<tr>
<td>urease inhibitors</td>
<td>-15%</td>
<td>28, 8/20</td>
<td>5%</td>
<td>-25%</td>
<td>-4%</td>
</tr>
<tr>
<td>nitrification plus urease inhibitors</td>
<td>-24%</td>
<td>42, 6/36</td>
<td>3%</td>
<td>-30%</td>
<td>-18%</td>
</tr>
<tr>
<td>synthetic nitrogen</td>
<td>-28%</td>
<td>108, 16/1/1</td>
<td>3%</td>
<td>-33%</td>
<td>-23%</td>
</tr>
<tr>
<td>manure/urine nitrogen</td>
<td>-36%</td>
<td>36, 2/34</td>
<td>3%</td>
<td>-42%</td>
<td>-29%</td>
</tr>
<tr>
<td>surface nitrogen application</td>
<td>-33%</td>
<td>71, 9/62</td>
<td>4%</td>
<td>-40%</td>
<td>-26%</td>
</tr>
<tr>
<td>subsurface nitrogen application</td>
<td>-27%</td>
<td>27, 4/22/1</td>
<td>4%</td>
<td>-35%</td>
<td>-18%</td>
</tr>
<tr>
<td>growing season and subgrowing season flux monitoring/modeling</td>
<td>-31%</td>
<td>86, 9/77</td>
<td>3%</td>
<td>-37%</td>
<td>-26%</td>
</tr>
<tr>
<td>annual flux monitoring/modeling</td>
<td>-25%</td>
<td>43, 9/34</td>
<td>3%</td>
<td>-31%</td>
<td>-20%</td>
</tr>
</tbody>
</table>
Table G 3. Descriptive statistics: Nitrification and urease inhibitors – CH₄

<table>
<thead>
<tr>
<th></th>
<th>emissions: % change in emissions per hectare</th>
<th>number of studies</th>
<th>change in emissions, ratio positive-to-negative: study numbers</th>
<th>standard error of mean (+/-)</th>
<th>lower 95% confidence interval</th>
<th>upper 95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>all studies</td>
<td>-32%</td>
<td>21</td>
<td>4/17</td>
<td>14%</td>
<td>-59%</td>
<td>-4%</td>
</tr>
<tr>
<td>meta-analyses</td>
<td>12%</td>
<td>1</td>
<td>1/0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>empirical site studies</td>
<td>-34%</td>
<td>20</td>
<td>3/17</td>
<td>15%</td>
<td>-63%</td>
<td>-6%</td>
</tr>
<tr>
<td>nitrification inhibitors-only</td>
<td>-34%</td>
<td>12</td>
<td>3/9</td>
<td>19%</td>
<td>-72%</td>
<td>5%</td>
</tr>
<tr>
<td>urease inhibitors-only</td>
<td>3%</td>
<td>2</td>
<td>1/1</td>
<td>18%</td>
<td>-31%</td>
<td>37%</td>
</tr>
<tr>
<td>nitrification and urease inhibitors</td>
<td>-46%</td>
<td>6</td>
<td>0/6</td>
<td>30%</td>
<td>-105%</td>
<td>12%</td>
</tr>
<tr>
<td>growing season and subgrowing season flux monitoring/modeling</td>
<td>-56%</td>
<td>12</td>
<td>1/11</td>
<td>21%</td>
<td>-98%</td>
<td>-15%</td>
</tr>
<tr>
<td>annual flux monitoring/modeling</td>
<td>2%</td>
<td>6</td>
<td>2/4</td>
<td>14%</td>
<td>-25%</td>
<td>29%</td>
</tr>
</tbody>
</table>

Appendix H. Emissions-avoided from 15% reduction in nitrogen fertilizer use

Avoided-emissions = N₂O emissions from cropland fertilizer use * -0.15

Endnotes


P. Jacinthe and P. Vidon, "Hydro-geomorphic Controls of Greenhouse Gas Fluxes in Riparian Buffers of the White River Watershed, IN (USA)," *Geoderma* 301 (2017): 30-41


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**Cropland retirement to grasslands or forested land—N₂O**


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Cropland retirement to grasslands-live biomass, SOC/CO₂


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**Cropland retirement to forestland-live biomass, litter, SOC/CO₂**


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Shelterbelts/Hedges–N₂O


Shelterbelts/Hedges–CH₄


Shelterbelts/Hedges–living biomass, litter, SOC–CO₂


**Field borders, filter strips, contour buffer strips, vegetated barriers–N₂O**


Grassland references above in “Cropland Retirement to Grasslands or Forested land – N₂O”

**Field borders, filter strips, contour buffer strips, vegetated barriers–CH₄**

Grassland references above in “Cropland Retirement to Grasslands or Forested land – CH₄”
Field borders, filter strips, contour buffer strips, vegetated barriers–SOC/CO$_2$


Grassland references above in “Cropland Retirement to Grasslands- live biomass, SOC/CO$_2$”

Riparian buffers–N$_2$O


P. Jacinthe and P. Vidon, "Hydro-geomorphic Controls of Greenhouse Gas Fluxes in Riparian Buffers of the White River Watershed, IN (USA)," Geoderma 301 (2017): 30-41


U. Mander, "Dynamics of Greenhouse Gas Emissions from Riparian Buffer Zones and Wetlands as Hot Spots in Agricultural Landscapes," in Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, Management and Area-Wide Evaluation of Water Conservation Zones in Agricultural


**Riparian buffers–CH₄**


P. Jacinthe and P. Vidon, "Hydro-geomorphic Controls of Greenhouse Gas Fluxes in Riparian Buffers of the White River Watershed, IN (USA)," *Geoderma* 301 (2017): 30-41


Riparian buffers—living biomass, litter, SOC–CO₂


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**Winter cover crops/catch crops–N2O**


**Winter cover crops/catch crops–CH₄**


**Winter cover crops/catch crops–SOC-CO₂**


**No tillage and reduced tillage—N₂O**


S. Yonemura, et al., "Soil Respiration, N\textsubscript{2}O and CH\textsubscript{4} Emissions from an Andisol under Conventional-Tillage and No-Tillage Cultivation for 4 Years," *Biology and Fertility of Soils* 50 (2014): 63-74


**No tillage and reduced tillage—CH4**


**No tillage and reduced tillage—SOC/CO₂**


J. Brenner, et al., Quantifying the Change in Greenhouse Gas Emissions due to Natural Resource Conservation Practice Application in Iowa, Final Report to the Iowa Conservation Partnership, Colorado State University Natural Resource Ecology Laboratory, and USDA Natural Resources Conservation Services, 2001


P. Smith, et al., *Quantifying the Change in Greenhouse Gas Emissions due to Natural Resource Conservation Practice Application in Indiana*. Final Report to the Indiana Conservation Partnership, Colorado State University Natural Resource Ecology Laboratory, and USDA Natural Resources Conservation Services, 2002


**Hay (alfalfa, nonleguminous perennial grasses) replacing annual crops: N₂O**


**Hay (alfalfa, nonleguminous perennial grasses) replacing annual crops: SOC/CO₂**


Extend rotation by adding alfalfa or nonleguminous hay: N₂O


Extend rotation by adding alfalfa or nonleguminous hay: SOC/CO₂


**Corn-soybean rotation replacing continuous corn-N₂O**


**Corn-soybean rotation placing continuous corn-SOC/CO2**


**Database references for practices for which only preliminary results are available**

**Constructed wetlands—CH₄**


**Constructed wetlands–N₂O**


**Constructed wetlands–SOC/CO2**


B. Bernal and W. Mitsch, "Carbon Sequestration in Two Created Riverine Wetlands in the Midwestern United States," *Journal of Environmental Quality* 42 (2013): 1,236-1,244


**Restored wetlands—CH₄**


M. Cooper, et al., "Infilled Ditches Are Hotspots of Landscape Methane Flux Following Peatland Rewetting," *Ecosystems* 17 (2014): 1,227-1,241

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**Restored wetlands–N₂O**


**Restored wetlands–SOC/CO$_2$**


K. Ballantine and R. Schneider, "Fifty-five Years of Soil Development in Restored Freshwater Depressional Wetlands," Ecological Applications 19 (2009): 1467-1480


F. Renou-Wilson, et al., "Rewetting Degraded Peatlands for Climate and Biodiversity Benefits: Results from Two Raised Bogs," *Ecological Engineering* 127 (2019): 547-560


**Controlled release fertilizer–N₂O**


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**Controlled release fertilizer–CH₄**


Greenhouse gas reduction potential of agricultural best management practices


**Nitrification and urease inhibitors—N₂O**


M. Bell., et al., "Quantifying N₂O Emissions from Intensive Grassland Production: The Role of Synthetic Fertilizer Type, Application Rate, Timing, and Nitrification Inhibitors," *Journal of Agricultural Science* 154 (2016): 812-827


H. Di and K. Cameron, "How Does the Application of Different Nitrification Inhibitors Affect Nitrous Oxide Emissions and Nitrate Leaching from Cow Urine in Grazed Pastures?" *Soil Use and Management* 28 (2012): 54-61


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M. Yang, et al. (2016) "Efficiency of Two Nitrification Inhibitors (Dicyandiamide and 3,4-Dimethylpyrazole Phosphate) on Soil Nitrogen Transformations and Plant Productivity: a Meta-Analysis," *Scientific Reports* 6:22075.doi:10.1038/srep22075


**Nitrification and urease inhibitors—CH₄**


M. Yang, et al. (2016) "Efficiency of Two Nitrification Inhibitors (Dicyandiamide and 3,4-Dimethylpyrazole Phosphate) on Soil Nitrogen Transformations and Plant Productivity: a Meta-Analysis," *Scientific Reports* 6:22075.doi:10.1038/srep22075

**Fertilizer application timing: Split application–N₂O**


M. Bell., et al., "Quantifying N₂O Emissions from Intensive Grassland Production: The Role of Synthetic Fertilizer Type, Application Rate, Timing, and Nitrification Inhibitors," *Journal of Agricultural Science* 154 (2016): 812-827


**Fertilizer application timing: Delayed application–N$_2$O**


Fertilizer application timing: Split or delayed application—CH₄


Fertilizer placement: Subsurface placement—N₂O

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Fertilizer placement: Subsurface placement—CH₄


Spring fertilizer application in lieu of fall application—N₂O

D. Abalos, et al., "Micrometeorological Measurements over a 3 Years Reveal Differences in N₂O Emissions between Annual and Perennial Crops," *Global Change Biology* 22 (2016): 1,244-1,255


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**Biochar – N₂O**


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Biochar–CH₄


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Biochar–Mean residence time-SOC/CO₂


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**Biochar: Crop residue removal-SOC/CO₂**


**Biochar: Crop residue removal-N$_2$O**


