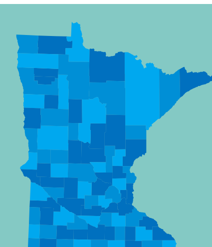
Climate change

October 2019

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.

MINNESOTA POLLUTION CONTROL AGENCY



Authors

Peter Ciborowski, Principal Author

Contributors/acknowledgements

Leslie Hunter-Larson, MPCA Librarian

We are grateful to the following people who reviewed the study and provided comments:

Marco Graziani, Minnesota Pollution Control Agency
Gregory Johnson, Minnesota Pollution Control Agency
Dave Wall, Minnesota Pollution Control Agency
Suzanne Rhees, Minnesota Board of Soil and Water
Dan Shaw, Minnesota Board of Soil and Water
Peter Gillitzer, Minnesota Department of Agriculture
Brad Redlin, Minnesota Department of Agriculture
Amanda Kueper, Minnesota Department of Natural Resources
Joseph Fargione, Nature Conservancy
Jessica Gutknecht, University of Minnesota
Amy Swan, Colorado State University
Tom Wirth, US Environmental Protection Agency

Editing and graphic design

Risikat Adesaogun
Jennifer Holstad
Barb Olafson

Minnesota Pollution Control Agency

520 Lafayette Road North | Saint Paul, MN 55155-4194 |

651-296-6300 | 800-657-3864 | Or use your preferred relay service. | Info.pca@state.mn.us

This report is available in alternative formats upon request, and online at www.pca.state.mn.us.

Document number: p-gen4-19

Table of contents

List of Tables

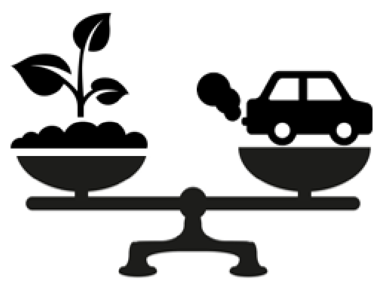
Executive summary

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?



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

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

This report quantifies the climate co-benefits of certain agricultural practices based on existing research. The report estimates greenhouse gas reductions for 21 agricultural best management practices[1]. The emission reductions per acre range are small, but implementing best management practices across the 20 million acres of Minnesota cropland could reduce overall agriculture emissions by 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.

For more information:

Frank Kohlasch

Environmental Analysis & Outcomes Division Manager

Frank.Kohlasch@state.mn.us

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.

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 (CO_2-equivalent) short tons per 100,000 acres per year. Given some specific practice, they represent the estimated annual emissions-avoidance in the present that result from the implementation of that practice. 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 (N_2O) and carbon dioxide (CO_2). N_2O is produced in fertilized and tilled cropland rich in ammonium (NH_4^+), nitrate (NO_3^-), and organic nitrogen. Tillage and fertilization with synthetic nitrogen and manure act to stimulate the microbial production of nitrous oxide in soils and its subsequent emission. N_2O can be produced in

---

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

[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 CO_2 from the atmosphere. But this usually occurs only after 20 to 25 years from the initiation of those practices.(Marland *et al*., 2003; West and Six, 2007) For some practices like cropland conversion to permanent grassland, soils begin to saturate with respect to soil organic carbon only after 40 to 50 years after conversion.(Poeplau *et al*., 2011) Less is known about soil emissions of N_2O and CH_4 (or soil CH_4 oxidation), besides some initial indications that, with time, cropped soils under no-tillage practice may become progressively lower emitters of N_2O.(Six *et al*., 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_2O or CH_4 or biogenic carbon sequestration. Emissions from fuel use in crop production are small, as are emissions in the form of CO_2 from the use of urea fertilizer or crushed limestone. The same is true for indirect N_2O emissions from leached nitrate or NH_3 volatilization and downwind deposition.

Table 1. Agricultural practices examined in this study

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

a 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 CO_2-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 (CO_2-equivalent short tons per 100,000 acres per year)

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

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

[b] descriptive statistics for the soil organic carbon, direct soil N_2O and soil CH_4 oxidation components of each emissions-avoided estimate are shown for in Tables 11-13, 15-17, 19-21, 24-26, 28-30, 33-35, 38-40, 42-44, 46-47, 50-51, 53-54 and 57-58 and Appendices A-H.

[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 CO_2-equivalent short tons per acre and, from cropland idling in grass or trees and related conservation land-use, annual avoidance of 1.23 to 1.92 CO_2-equivalent short tons per acre. (Eagle *et 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 CO_2-equivalent short tons per acre, while those for tillage and cropping practices[4] 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).[5] 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_2O and CH_4. Sources of GHG emission include cropped soils, fuel use, surface waters, land surfaces downwind of crop production on which volatilized ammonia might be deposited, and the mostly out-of-state manufacture of agricultural chemicals and fuels used in crop production. Emissions and emissions-avoidance are expressed on an area-basis in a common unit, CO_2-equivalent short tons, which cumulatively give the net impact of the practice on emissions in the form of a single value. In this analysis, these are annualized to give the average annual change in GHG emissions – whether an increase or a decrease - associated with the establishment of some practice. The change in emissions is calculated on a 100,000-acre basis. The results for each practice are reported as the change in CO_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-

[4] All cropping and tillage practices shown in Table 2 except cropping change from continuous corn to corn and soybeans in rotation, a practice not treated in Eagle *et al*. (2012)., Gelford and Robertson (2015), Robertson *et al*. (2000), or Swan *et al*. (2015).
[5] MPCA Greenhouse Gas Emissions data for 2016, available at: https://www.pca.state.mn.us/air/greenhouse-gas-emissions-data

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.[6] 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, CO_2 is removed from the atmosphere and incorporated into plant biomass and, potentially, through roots and crop residue inputs to soil, to soil organic carbon. This results in a net drawdown of atmospheric CO_2 levels, which, as with most other researchers, we treat as a negative emission.

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

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

In converting nominal units of sequestered soil carbon (or rates of sequestration) to CO_2-equivalent units, we used a global warming potential value of 0.4. This corresponds to a period of persistent storage of newly sequestered carbon in agricultural landscapes of about 20 years. This is the longest period over which, in our judgment, persistent storage safely can be assumed. The larger calculation of

[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 CO_2 retention in the atmosphere for emitted CO_2 from fossil fuel combustion. Once emitted to the atmosphere, a unit of mass of CO_2, e.g., ton, kilogram, lbs., is only partially retained in the atmosphere. One-hundred years after emission, an estimated 38 percent of that mass will remain in the atmosphere. Expressed in ton-years, an emission of one ton of CO_2 to the atmosphere will, over the one hundred year period, result in 52 ton-years of atmospheric retention. To offset one ton of emission, a ton of sequestered organic carbon must remain in storage an equal 52 years. At 20 years, storage of organic carbon would offset only 20-ton-years of emissions or about 40 percent what might be needed to offset a ton of emitted CO_2 from oil or coal combustion.

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

Regarding the larger lifecycle approach using GWP-weightings, this is a longstanding approach in the scientific literature stretching back to 2000. (Adviento-Borbe *et al*., 2007; Amadi *et al*., 2017; Archer and Halvorson, 2010; Del Grosso *et al*., 2005; Dendooven *et al*., 2012; Gan *et al*., 2011; Gan *et al*., 2014; Gelfand and Robertson, 2015; Hernandez-Ramirez *et al*., 2009; Johnson *et al*., 2011; Kaye and Quemada, 2017; Kim and Dale, 2008; Kusterman *et al.*, 2008; Liebig *et al*., 2010; Merbold *et al*., 2014; Robertson *et al*., 2000; Sainju *et al*., 2014; Six *et al*., 2004; Smith *et al*., 2008; Soussana *et al*., 2007) Recent applications have been in meta-analysis of the results of published lifecycle analyses using GWP-weightings (Sainju, 2016) and in related comparative assessments of net emissions-avoidance by practice, built-up emissions source by emissions source from statistical analyses of study results of GHG-avoidance taken from the scientific literature. (Eagle *et al*., 2012; Fargione *et al*., 2018; Swan *et al*., 2015)

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

Table 3 lists emission sources or sources of emissions-avoidance for the 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 N_2O emissions, and soil CH_4 emissions from wet anoxic soils. In the following subsections, we focus on these sources, including how in each case response rates for emissions-avoided (or, if this is the case, emissions increases) are estimated and the issues associated with that estimation. Response rates are at the heart of the analysis presented here.

[7] Perhaps the best example might be Conservation Reserve Program lands in Minnesota, which include lands that are temporarily idled, mostly as unmanaged grassland. These lands stored large amounts of organic carbon, which, as is often noted, will be quickly reemitted to the atmosphere as CO_2 if placed back into intensive cultivation. (Gelfand *et al*., 2011) Based on the most recently available statistics, once enrolled in CRP, only about 10 percent of these idled lands were re-enrolled beyond the initial 15-year contract period. (USDA-FSA, 2017) If, at initial enrollment, it had been assumed that this organic carbon build-up would be retained indefinitely, that would have been an incorrect assumption.

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

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

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

A. Terrestrial carbon sequestration response rates

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

In this study, response rates of terrestrial carbon sequestration to different practices are developed from review of the scientific literature, principally from the review of results taken from long-term and short-term controlled experiments of sequestration potential using side-by-side experimental plots, or, more often, derivative statistical studies of those results. The results from literature reviews and studies that propose mean values for response rates based on expert judgment also are used, as are results from numerical modeling studies. 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_2O and CH_4 response rates

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

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

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

For agricultural practices that involve a change in cropping or tillage practice, response rates for N_2O and CH_4 are the product of average cropland net annual flux rates and the estimated percentage change in that annual flux under the new practice. 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_2O, the MPCA Greenhouse Gas Emission Inventory, and, for CH_4, from Aronson and Helliker (2010) for average temperate cropland soils. Estimated flux rates for cropland under improved tillage or rotations most often are taken from meta-analysis-type studies. For the reasons discussed above with respect to terrestrial carbon sequestration, in estimating average flux rates for N_2O and CH_4, preference is given to the results of meta-analyses, if any, followed by the mean of the results for all studies across study type.

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

C. Database practices

To understand the potential role of agriculture in GHG emission mitigation, we examine, on a practice-by-practice basis, the GHG avoidance-potential of practices that, in the scientific literature, have been identified as potentially effective in mitigating emissions. To date, we have assessed the effect of 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, CH_4, or N_2O with changed practices against a conventional agricultural practice baseline, side-by-side studies under controlled condition are required. This is true regardless of whether changes are presented in absolute units of change, e.g., tons per acre per year, as in the case of terrestrial soil carbon, or in terms of percentage changes from a baseline. The vast majority of study results housed in the database are from side-by-side studies conducted under controlled conditions. In the studies housed in the database, changes in soils carbon typically are evaluated over periods of time of 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 N_2O and CH_4 emissions-avoidance and CO_2-avoidance in the form of carbon sequestration, we use a weight of the evidence test in assessing how well an estimate of mitigation potential is known. Throughout this study, we provide estimates of the numbers of study results for each practice by study type, the ratio of positive-to-negative results, again by study type, along with standard errors and confidence intervals. We also provide in the case of each practice and soil emittant (or sequestered gas) a discussion of the underlying science at the process level, including what the science tells us should be happening, based on underlying scientific understanding. The corporate judgment of the community of involved scientists, as expressed in expert reviews, is particularly informative of the larger state of the science.

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

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

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

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

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

Table 4 delineates the simplified calculative approaches taken with respect to response rates of emissions in the case of each of these minor sources. In the case of indirect N_2O from leached nitrate or NH_3 volatilization and redeposition, response rates are the product of average emission rates from these sources at a statewide level and estimated percentage rates of emission reduction per practice. 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_2O flux rates statewide from these sources, on a per acre basis, and emissions per acre under alternative practices, like grassland restoration or shelterbelt establishment. Estimated average flux rates for cropland are from the MPCA GHG emission inventory, while, for idled land in upland or riparian grass or trees, they are taken from Bouwman *et al*. (1997).

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

GHG	Calculative Approach to Emissions-avoidance	Base emission level
N_2O-Indirect, nitrate leaching, NH_3 redeposition	% reduction in NO_3- runoff to surface waters [a, b]; % reduction in NH_3 volatilization and redeposition [a, c]	Minnesota N_2O emissions from NO_3^- leaching and from NH_3 deposition to cropland, 2012-2015 average [g] Data source: MPCA GHG emission inventory
	(N_2O-leaching under changed land-use) – (average N_2O-leaching rate from cropland) [d]; (N_2O-NH_3 deposition under changed land-use) – (average N_2O-NH_3 deposition to cropland) [d]	
	Data sources for reduction potential: nitrate leaching -- MPCA (2014),[b] MPCA GHG emission inventory (MPCA GHG EI) [d]; NH_3 redeposition—Pan *et al*., (2015); Bouwman *et al*. (1997); MPCA GHG EI	
CO_2-urea use, liming	urea: (no urea use, idled cropland) – (CO_2 from urea use on cropland) [e]; liming: (CO_2 from crushed limestone applications to alfalfa) – (CO_2 from crushed limestone applications to average MN cropland) [f]	Minnesota N_2O and CO_2 emissions from Nitrogen fertilizer and limestone use, respectively, 2012-2015 average Data source: MPCA GHG emission inventory
	Data source for reduction potential: Russelle (1997)	
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.	Minnesota fuel use emissions, 2012-2015 average, using a weighted average of fuel use per rotation from Camargo *et al*. (2013)
	Data source for per acre fuel use intensity by practice and fuel use rate per operation: 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	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)
	Data source for emissions rates per lbs. of N, P and K fertilizer, herbicides, insecticides and fungicides manufactured: Camargo *et al.* (2013)	

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

[b] cover crops, no-till, reduced tillage, riparian buffers, shelterbelts/hedges, afforestation on idled cropland

[c] no till, reduced tillage

[d] field borders, grassland restoration, cropland conversion to hayland, expanded rotations with perennials

[e] grassland restoration, afforestation on idled upland cropland, shelterbelts/hedges, field borders/vegetative barriers, riparian buffers

[f] cropland to hayland conversion, extended rotations with perennials

[g] 0.75 percent of leached nitrogen is assumed to be emitted to the atmosphere as N_2O, after the IPCC (2006) methodology. 1 percent of nitrogen that is redeposited on land surface after ammonia volatilization is assumed to be emitted to the atmosphere as N_2O, again after IPCC (2006)

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

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

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

Practice	Equation Giving the Basis for the Calculated Change in Emissions from Avoided Manufacture of Agricultural Chemicals
Cover Crops	– (Nitrogen credit for cover crops) – (–15% reduction, herbicide use) + (energy input to cover crop seed production)
Cropland to Hayland Conversion	(P,K and lime applications to alfalfa) – (N, P, K, lime, herbicide, insecticide applications to cropland)
Extended Rotations with Alfalfa or Other Hay or Grass	(P,K and lime applications to alfalfa) – (N, P, K, lime, herbicide, insecticide applications to cropland), 2 years of 4 year rotation – N credit to corn after alfalfa, 140 and 70 lbs. per acre, first and second year after alfalfa
Continuous corn to corn-soybean rotation	no N applications to soybean phase of corn-soybean rotation, plus N credit 35 lbs. N/acre credit to corn after soybeans
All Other	(no fertilizer or chemical use) - (N, P, K, lime, herbicide, insecticide applications to cropland)

[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 of cropland. While cropland idling, buffer establishment and related practices might be established in Minnesota on tens of thousands to hundreds of thousands of acres, these practices are unlikely to be implemented in Minnesota on millions of acres.

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_2-e tons per 100,000 acres per year)

	Emissions-avoided [a,b]	
	in-state plus out-of-state	in-state-only [c]
	CO_2-e short tons	CO_2-e short tons
Practices that Involve Land-Use Change from Cropland to Cropland-Supporting Role or Long-term Idling [d,e]		
Shelterbelts, Hedgerows	(269,265)	(249,074)
Land Retirement/Long-term Idling: Afforestation	(262,611)	(242,421)
Forested and Multispecies Riparian Buffers	(203,251)	(183,061)
Land Retirement/Long-term Idling: Grassland Restoration	(162,411)	(142,221)
Field Borders, Contour Buffer Strips, Vegetated Barriers, Herbaceous Wind Barriers	(161,038)	(140,847)
Grassland Riparian Buffers	(77,299)	(57,109)
Cropping and Tillage Practices [d,e]		
Cropland to Hayland	(121,339)	(107,966)
Add a Perennial Grass to Crop Rotation	(49,685)	(37,799)
No-Till Tillage-reduced tillage counterfactual	(22,565)	(22,332)
Winter Cover Crops/Catch Crops	(20,474)	(19,287)
Reduced Tillage	(14,543)	(14,176)
No-Till Tillage	(13,807)	(13,208)
Corn-Soybean Rotation Replacing Continuous Corn	39,830	57,127
Preliminary Results-Only: [f]		
Practices that Involve Land-Use Change from Cropland to Cropland-Supporting Role or Long-term Idling [d,e]		
Contructed and Restored Wetlands	65,517	85,708
Nutrient Reduction Practices		
Biochar	(119,713)	(122,642)
Controlled Release Fertilizers	(27,369)	(27,369)
Nitrification and Urease Inhibitors	(24,033)	(24,033)
Split Fertilizer Application	(13,455)	(13,455)
15% Fertilizer Use Reduction	(5,878)	(3,757)
Spring Fertilizer Application	2,115	2,115
Subsurface Fertlilizer Placement	31,060	30,970

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

b descriptive statistics for the soil organic carbon, direct soil N_2O and soil CH_4 oxidation components of each emissions-avoided estimate are shown for in Tables 11-13, 15-17, 19-21, 24-26, 28-30, 33-35, 38-40, 42-44, 46-47, 50-51, 53-54 and 57-58 and Appendices A-H.

[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

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_2-equivalent tons per 100,000 acres or 1.2 CO_2-equivalent tons per acre. Nitrification and urease inhibitors 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 CO_2-equivalent short tons per acre, respectively (24,000 and 27,000 CO_2-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 CH_4 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 CO_2 from fossil fuel combustion, rates of sequestration fall into a range of 0.5 to 2 tons of CO_2 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 CO_2-equivalent tons per acre per year (13,000 to 43,000 CO_2-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 N_2O are next in importance, often accounting in the practices examined for between 5 and 30 percent of total GHG-avoidance.

N_2O emissions do not always decline under the practices that were examined. Emissions of N_2O in soils tend to increase in saturated soil, in which rates of denitrification are accelerated. This occurs most obviously in riparian buffer soils, particularly buffer soils in trees, offsetting a part of the mitigating effects of enhanced biogenic carbon sequestration in buffer soils and in aboveground and belowground buffer live biomass. This largely explains the advantage that idled upland soils enjoy over wet riparian soils with respect to GHG-avoidance or mitigation (see Table 8). Based on the analysis, N_2O emissions increase with the use of cover cropping, and likewise with a change in tillage practice from conventional tillage to no-till, at a rate of about 0.04 and 0.08 CO_2-equivalent short tons per acre, respectively (3,800 and 7,500 CO_2-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 8 Emissions-avoided from agricultural practices (short CO_2-e tons per 100,000 acres per year) [a]

	N_2O-direct	N_2O-indirect volatilization	N_2O-indirect leaching	CH_4	CO_2-carbon sequestration	CO_2-urea, liming	GHGs-energy	Out-of-State Upstream GHGs	In-State Upstream GHGs	Total
Practices that Involve Land-Use Change from Cropland to Cropland-Supporting Role or Long-term Idling										
Shelterbelts, Hedgerows	(48,242)	(2,148)	(14,020)	(184)	(174,780)	(2,808)	(6,892)	(20,190)	-	(269,265)
Land Retirement/Long-term Idling: Afforestation	(48,242)	(2,148)	(14,020)	(184)	(168,126)	(2,808)	(6,892)	(20,190)	-	(262,611)
Forested and Multispecies Riparian Buffers	7,033	(2,148)	(13,653)	33,466	(198,058)	(2,808)	(6,892)	(20,190)	-	(203,251)
Land Retirement/Long-term Idling: Grassland Restoration	(41,091)	(2,107)	(11,703)	468	(78,089)	(2,808)	(6,892)	(20,190)	-	(162,411)
Field Borders, Contour Buffer Strips, Vegetated Barriers, Herbaceous Wind Barriers	(41,091)	(2,107)	(11,703)	468	(78,089)	(2,808)	(5,518)	(20,190)	-	(161,038)
Grassland Riparian Buffers	(9,405)	(2,107)	(13,653)	27,176	(49,420)	(2,808)	(6,892)	(20,190)	-	(77,299)
Cropping and Tillage Practices										
Cropland to Hayland	(52,012)	(2,107)	(11,703)	NK	(43,040)	(2,786)	3,681	(13,373)	-	(121,339)
Add a Perennial Grass to Crop Rotation	(2,897)	(1,053)	(6,826)	NK	(32,490)	(1,393)	6,861	(11,886)	-	(49,685)
No-Till Tillage-reduced tillage counterfactual	(8,260)	553	-	NA	(13,575)	-	(1,051)	(233)	-	(22,565)
Winter Cover Crops/Catch Crops	7,511	NK	(7,329)	131	(20,118)	-	519	(1,187)	-	(20,474)
Reduced Tillage	(102)	553	-	52	(13,026)	-	(1,653)	(366)	-	(14,543)
No-Till Tillage	3,815	553	-	(283)	(14,589)	-	(2,704)	(599)	-	(13,807)
Corn-Soybean Rotation Replacing Continuous Corn	(11,147)	NK	NK	NK	69,182	-	(909)	(17,296)	-	39,830
Preliminary Results-Only [b]										
Biochar	(17,996)	(325)	(5,174)	(572)	(138,936)	-	13,224	2,929	27,136	(119,713)
Controlled Release Fertilizers	(21,152)	(1,475)	(4,743)	NK	-	-	-	-	-	(27,369)
Nitrification and Urease Inhibitors	(20,415)	(995)	(2,012)	(612)	-	-	-	-	-	(24,033)
Split Fertilizer Application	(13,125)	108	(1,006)	NK	-	-	568	-	-	(13,455)
15% Fertilizer Use Reduction	(2,545)	(255)	(573)	NK	-	(385)	-	(2,120)	-	(5,878)
Spring Fertilizer Application	2,236	116	(237)	NK	-	-	-	-	-	2,115
Subsurface Fertilizer Placement	36,750	(1,187)	(4,999)	NK	-	-	405	90	-	31,060
Constructed and Restored Wetlands	(4,856)	(2,169)	(7,186)	218,640	(109,022)	(2,808)	(6,892)	(20,190)	-	65,517

[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_2O emissions to various nutrient reduction practices. In the published literature, the analysis of GHG-avoidance with these practices is largely restricted to direct N_2O 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_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_2O soil emissions and CH_4 emission from or oxidation in soils. As noted in earlier sections, with the exception of avoided out-of-state emissions from the manufacture of agricultural fertilizer, most of these non-soil sources of emissions-avoidance (or increase) are small. In the case of agricultural fertilizer manufacture, the methods conventionally used to estimate emissions-avoidance are throughput-based calculations based on a set of simplified emission factors that might be described in a sentence or two.

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

We begin the discussion with practices that involve cropland idling or the conversion of cropland to a supporting role in crop production in the form of buffers, shelterbelts, field borders and herbaceous barriers. Subsections A through 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 N_2O emissions. As was noted there, for nitrate control, the source of emissions-avoidance for indirect N_2O from nitrogen run-off and leaching, we defer to the expertise on nitrate control embedded in the MPCA, Nutrient Reduction Strategy. (MPCA, 2014)

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 CO_2-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 CO_2-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 N_2O 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 CO_2-equivalent short tons. Had a 40-year period of assured storage been assumed, avoided-emissions from grassland restoration would have totaled 241,000 CO_2-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 475,000 CO_2-equivalent short tons (see Table 9). The approach that we

[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

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(41,091)	crop production
N_2O-indirect volatilization	indirect emission-Nitrogen volatilization, redeposition	(2,107)	crop production
N_2O-indirect leaching	indirect emission-Nitrogen leaching or runoff	(11,703)	crop production
CH_4 [b]	soils	468	crop production
CO_2 [c,d]	carbon accumulation in soils and biomass	(78,089)	crop production
CO_2	cultivated soils from lime or urea use	(2,808)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	(6,892)	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(20,190)	crop production
Total		**(162,411)**	
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_2O from soils and the effects of grassland restoration on soil CH_4 oxidation. The methods and sources used to estimate avoided indirect N_2O emissions from nitrate leaching and ammonia volatilization, avoided- emissions from fuel use, and avoided-emissions from foregone agricultural chemicals and fuels manufacture were discussed above in the Methodology section (Section II, Subsection E) of this report.

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

Study	Type of study	CO_2-eq. short tons per acre per year	CO_2-eq. short tons per 100,000 acres per year
Gelfand and Robertson (2015)	site study	1.92	192,007
Miao *et al.* (2015) [b]	site study	1.09	108,916
Robertson *et al.* (2000)	site study	1.23	122,653
Del Grosso *et al.* (2002)	modeling study	0.10	9,561
Del Grosso *et al* . (2005)	modeling study	0.83	83,350
Desjardins *et al.* (2005) [b]	modeling study	1.80	180,129
Grant *et al* . (2004)	modeling study	1.14	113,733
Robertson (2011) [b]	modeling study	0.74	73,544
Smith *et al.* (2008) [b,c]	modeling study	2.39	239,061
Swan *et al.* (2015) [b]	literature review/expert judgment	1.39	138,866
Eagle *et al* . (2012)	derivative statistical analysis	1.59	159,226
Kim and Kirschbaum (2015) [b,d]	derivative statistical analysis	1.18	117,573
This report	literature review	1.62	162,411

[a] 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 CO_2. (Guo and Gifford, 2002; Mann, 1986; Post and Kwan, 2000) These losses occur quickly, over period of less than 20 years. (Davidson and Ackerman, 1993; Poeplau *et al*., 2011) In general, cultivated soils are more highly aerated and warmer than unmanaged grassland soils, which accelerates microbial decomposition of organic matter. 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

	biogenic carbon sequestration (Mg C/ha/yr)	number of studies [d]	ratio of sequestration to emission: number of studies [e]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
total ecosystem carbon (soil organic carbon, above and belowground biomass)	1.24	18	17/1	0.30	0.66	1.82
soil organic carbon-only	0.59	107	100/7	0.05	0.49	0.68
meta-analyses	0.69	6	6/0	0.10	0.49	0.89
other derivative statistical analyses or statistical summaries [a]	0.68	7	7/0	0.14	0.41	0.95
eddy covariance empirical site studies (NECB/NBP) [b]	1.32	13	12/1	0.40	0.55	2.10
modeling studies	0.73	20	19/1	0.13	0.47	0.99
empirical site studies-soil sampling	0.47	48	42/6	0.08	0.31	0.63
expert judgment/literature reviews	0.71	27	27/0	0.06	0.59	0.83
restored grasslands	0.66	118	110/8	0.06	0.54	0.78
existing grasslands	0.81	9	9/0	0.27	0.27	1.35
10 to 30 cm soil sampling/modeling depth [c]	0.55	48	47/1	0.06	0.44	0.67
> 40 cm soil sampling/modeling depth [c]	0.54	16	12/4	0.20	0.14	0.94
15 to 25 year annual sequestration rate	0.47	33	30/3	0.09	0.29	0.66
0 to 14 year annual sequestration rate	0.70	42	37/5	0.13	0.45	0.95
25 year-plus annual sequestration rate	0.32	10	10/0	0.08	0.17	0.48

[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 N_2O. N_2O is produced in converted grassland soils and cropland soils. N_2O emissions from croplands are often four-fold higher than those of unmanaged restored or existing grasslands. In croplands, emissions are sustained by large inputs of mineral and organic nitrogen in the form of synthetic fertilizer, manure and crop residues. 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 N_2O emissions, taken from the MPCA Greenhouse Gas Emission Inventory. For each 100,000 acres of cropland converted to grassland, an estimated 41,000 CO_2-equivalent short tons of emissions are avoided or some 138 tons of N_2O.

N_2O emissions from restored grassland were estimated using emission rates developed on a per hectare basis from the scientific literature, and converted to lbs. per acre for use in the calculation. In developing the average N_2O emission rate for unmanaged grasslands, 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 N_2O from restored grassland. No other study attribute pointed to one study type as clearly superior in estimating N_2O annual emissions from unmanaged grassland. Using the average value for the studies that were reviewed, restored grasslands were estimated to emit on an annual basis 1.71 ± 0.6 kg N_2O per hectare (1.52 ± 0.54 lbs. N_2O per acre).

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

The descriptive statistics for the various studies that were reviewed are shown in Table 12. In these studies, annual emission rates for restored and existing grasslands ranged from 0.8 to 2 kg N_2O per hectare (0.71 to 1.78 lbs. N_2O per acre). The results for studies that report results on an annual basis were three times higher than those that report growing season-only emissions. The results for studies that were conducted over more than one year were about 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 N_2O 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 N_2O per hectare (2.77 lbs. N_2O per acre) less than cropland or pastureland. In the calculation for avoided N_2O emissions shown in Table 9, the difference between cropland emissions and emissions from restored grassland is some 3.2 kg N_2O per hectare per year (3.64 lbs. N_2O per acre per year), or quite near the literature estimate.

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

Table 12. Descriptive statistics: Land retirement/Long-term idling - Grassland restoration, N_2O

	emissions (kg N_2O/ hectare/yr) [a]	number of study results[c,d]	ratio of positive-to-negative results: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	1.71	55	55/0	0.58	0.59	2.84
empirical site studies	2.02	36	36/0	0.88	0.30	3.74
modeling studies	1.22	12	12/0	0.37	0.49	1.94
derivative statistical analyses or statistical summaries [b]	1.00	5	5/0	0.29	0.43	1.57
expert judgment/literature reviews	0.79	2	2/0	0.29	0.23	1.35
grassland restorations	1.18	31	31/0	0.23	0.74	1.63
existing grasslands	2.80	18	18/0	1.73	(0.59)	6.18
annual flux monitoring/modeling	2.20	36	36/0	0.88	0.48	3.92
growing season and subgrowing season flux monitoring/modeling	0.75	18	18/0	0.14	0.48	1.02
1 year of observations or simulations	4.18	11	11/0	2.77	(1.25)	9.61
> 1 year of observations or simulations	1.10	36	36/0	0.22	0.66	1.54
grassland restorations against cropland or pastureland counterfactual	(3.07)	34	34/0	0.90	(4.83)	(1.31)

[a] negative emissions = removal from atmosphere and destruction in soils
[b] statistical summaries or analyses other than meta-analyses
[c] 55 study results, 53 studies (5 statistical summaries or derivative statistical analyses, 11 modeling studies, 35 empirical site studies, 2 expert reviews)
[d] 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 CH_4 oxidation is enhanced, but the timeframes for recovery are likely long, as long as 200 years, with limited recovery over periods as short as 20 years. (Allen *et al*., 2009; Suwanaree and Robertson, 2005) The extra microbial CH_4 destruction that occurs in soils from the conversion of cropland to grassland is calculated as the difference in CH_4 soil oxidation in cropland and in grassland converted from cropland. Average cropland oxidation rates are taken from Aronson and Helliker (2010). In converting 100,000 acres of cropland to grassland, CH_4 oxidation is estimated to decrease slightly, 468 CO_2-equivalent short tons or some 19 tons of CH_4.

In developing the average soil CH_4 oxidation rate for unmanaged grasslands, 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

	soil CH_4 oxidation (kg CH_4/ hectare/yr) [a]	number of study results[c,d]	ratio of positive-to-negative results: number of	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	1.43	31	26/5	0.33	0.79	2.07
empirical site studies	0.80	20	15/5	0.33	0.16	1.45
modeling studies	3.02	6	6/0	1.01	1.04	5.00
derivative statistical analyses or statistical summaries [b]	2.03	5	5/0	0.39	1.26	2.80
grassland restorations	0.61	12	9/3	0.36	(0.09)	1.31
existing grasslands	2.02	17	16/1	0.49	1.05	2.99
annual flux monitoring/modeling	2.03	18	16/2	0.49	1.07	2.98
growing season and subgrowing season flux monitoring/modeling	0.61	13	10/3	0.28	0.07	1.15
1 year of observations or simulations	0.50	6	5/1	0.31	(0.10)	1.10
> 1 year of observations or simulations	1.52	16	12/4	0.58	0.38	2.66
grassland restorations against cropland or pastureland counterfactual	0.20	18	8/9/1	0.26	(0.31)	0.71

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

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

[c] 31 study results, 30 studies (5 statistical summaries or derivative statistical analyses, 6 modeling studies, 19 empirical site studies)

[d] 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, CO_2 is photosynthetically removed from the atmosphere and incorporated into live tree biomass and, eventually, into soils and the forest floor. For each 100,000 acres of cropland retired to trees, an estimated 263,000 CO_2-equivalent short tons of GHGs are avoided annually, much of it in the form of atmospheric CO_2 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 N_2O (18 percent); avoided out-of-state emissions associated with the manufacture of fertilizer, agricultural chemicals and fuels no longer consumed in crop production (8 percent); and avoided-emissions of N_2O from nitrate not leached to surface and groundwater (5 percent). As discussed above, during biogenic carbon sequestration, CO_2 is removed photosynthetically from the atmosphere and is sequestered in live tree biomass, soil organic carbon, tree detritus and the forest floor.

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

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(48,242)	crop production
N_2O-indirect volatilization	indirect emission-Nitrogen volatilization, redeposition	(2,148)	crop production
N_2O-indirect leaching	indirect emission-Nitrogen leaching or runoff	(14,020)	crop production
CH_4 [b]	soils	(184)	crop production
CO_2 [c,d]	carbon accumulation in soils and biomass	(168,126)	crop production
CO_2	cultivated soils from lime or urea use	(2,808)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	(6,892)	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(20,190)	crop production
Total		**(262,611)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass			
40 year storage	all sources and sinks	**(430,737)**	crop production
100 year storage	all sources and sinks	**(935,115)**	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

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 CO_2-equivalent short tons. Had a 40-year period of assured storage been assumed, avoided-emissions from afforestation of former croplands would have totaled 431,000 CO_2-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 935,000 CO_2-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 N_2O from soils and the effects of afforestation of cropland on soil CH_4 uptake and oxidation. The methods and sources used to estimate avoided indirect N_2O emissions from nitrate leaching and ammonia volatilization, avoided-emissions from fuel use, and avoided-emissions from foregone agricultural chemicals and fuels manufacture were discussed in the Methodology section (Section II, Subsection E) of this report.

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 CO_2 or 45,882 tons of carbon, covering 100,000 afforested acres. As discussed

[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 CO_2-equivalent tons for inclusion in the summary Table 14. During afforestation, CO_2 is removed from the atmosphere and incorporated into tree biomass and, eventually, into woody detritus and soils. This acts to offset emissions of CO_2 from elsewhere in the economy.

The average sequestration rate per acre was developed from 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.

Table 15. Descriptive statistics: Land retirement/Long-term idling - Afforestation, carbon sequestration in soils and biomass

	biogenic carbon sequestration (Mg C/ha/yr)	number of studies [d]	ratio of sequestration to emission: number of studies [e]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
total ecosystem carbon (soil organic carbon [SOC], above and belowground biomass)	2.67	22	22/0	0.46	1.77	3.58
aboveground forest plus SOC	3.62	10	10/0	0.65	2.35	4.89
above and belowground live biomass	3.65	6	6/0	1.18	1.33	5.97
soil organic carbon-only	0.59	31	25/6	0.18	0.24	0.94
meta-analyses	0.56	7	6/1	0.19	0.19	0.92
derivative statistical analyses or statistical summaries [a]	2.63	6	6/0	0.96	0.74	4.52
modeling studies	2.79	12	12/0	0.59	1.64	3.94
empirical site studies	2.16	33	29/3/1	0.42	1.32	2.99
eddy covariance empirical site studies (NECB/NBP) [b]	3.40	2	2/0	0.14	3.13	3.67
expert judgment/literature review	1.44	15	15/0	0.35	0.76	2.13
15 to 25 year annual sequestration rate	1.58	26	24/2	0.30	0.99	2.18
15 to 25 year annual sequestration rate (total ecosystem carbon-only)	2.06	9	9/0	0.40	1.28	2.84
less than 15 year annual sequestration rate	3.37	11	10/1	0.96	1.49	5.24
25 year-plus annual sequestration rate	2.13	20	19/1	0.41	1.33	2.92
10 to 40 cm soil sampling/modeling depth [c]	1.18	16	13/2/1	0.59	0.03	2.33
> 40 cm soil sampling/modeling depth [c]	2.50	14	13/1	0.58	1.37	3.63

[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] 75 study results, 75 studies
[e] ratio of the number of studies reporting net sequestration to the number of studies reporting net emissions

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_2O fluxes from forestland are typically one-third those of cultivated cropland. (Dalal and Allen, 2008) Emissions from cropland are sustained by inputs of synthetic and organic nitrogen in the form of mineral fertilizer, manure and crop residues, as well as nitrogen made available through soil nitrogen mineralization. On newly afforested former cropland, most exogenous inputs of nitrogen are foregone, minimizing the pool of soil nitrate and ammonium that sustains N_2O production in soils. Of what remains, a part is immobilized in plant biomass, as a result of the large nutrient needs of young trees, and eventually as organic nitrogen in soils. (Gelfand *et al*., 2016) Immobilized in plant biomass, nitrogen is no longer available for microbial production of N_2O.

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

N_2O emissions from forestland converted from cropland are estimated using emission rates developed on a per hectare basis from the scientific literature, and converted to lbs. per acre for use in the calculation. In deriving the latter, 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 N_2O emissions from afforested former cropland. No formal meta-analysis was available for N_2O from restored grassland. Using the average value for the studies that were reviewed, afforested former croplands are estimated to emit on an annual basis 1.18 ± 0.22 kg of N_2O per hectare (1.05 ± 0.2 lbs. of N_2O 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 N_2O per hectare (0.86 to 1.25 lbs. of N_2O per acre).

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

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 N_2O emissions of converting cropland to forestland, with a mean annual reduction in emissions across all nine studies of 1.72 kg of N_2O per hectare (1.53 lbs. N_2O per acre). Using the mean for all studies for afforested former cropland and average Minnesota cropland N_2O emissions, taken from the MPCA Greenhouse Gas Emission Inventory, we derive a higher value of 3.67 kg N_2O per hectare per year (3.27 lbs. N_2O per acre per year). The estimates agree that, with afforestation, N_2O emissions will decline. Generally there is little sense in the scientific literature that, with cropland abandonment to trees, and nitrogen fertilizer inputs to soils essentially eliminated, N_2O emissions will do anything but decline.

c. Methane

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

Table 16. Descriptive statistics: Land retirement/Long-term idling - Afforestation, N_2O

	emissions (kg N_2O/ hectare/yr) [a]	number of study results[c,d]	ratio of positive-to-negative results: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	1.18	41	41/0	0.22	0.72	1.63
empirical site studies	1.16	28	27/1	0.31	0.56	1.76
modeling studies	1.30	8	8/0	0.54	0.25	2.35
derivative statistical analyses or statistical summaries [b]	1.08	5	5/0	0.28	0.53	1.62
afforestation	0.97	13	13/0	0.38	0.22	1.72
existing forestland	1.27	28	28/0	0.29	0.70	1.85
annual flux monitoring/modeling	1.39	33	33/0	0.28	0.89	1.89
growing season and subgrowing season flux monitoring/modeling	0.30	8	7/1	0.09	0.13	0.47
1 year of observations or simulations	2.11	6	6/0	0.58	0.97	3.26
>1 year of observations or simulations	1.12	25	24/1	0.34	0.46	1.78
afforestation against cropland or pastureland counterfactual	(1.72)	9	9/0	0.39	(2.57)	(0.87)

[a] negative emissions = removal from atmosphere and destruction in soils
[b] statistical summaries or analyses other than meta-analyses
[c] 41 study results, 40 studies (5 statistical summaries or derivative statistical analyses, 8 modeling studies, 27 empirical site studies)
[d] 1 study reports multiple results by forest status (existing vs afforested)

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.

Table 17. Descriptive statistics: Land retirement/Long-term idling - Afforestation, CH_4

	soil CH_4 oxidation (kg CH_4/ hectare/yr) [a]	number of study results[c,d]	ratio of positive-to-negative results: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	2.02	35	32/3	0.52	1.00	3.03
empirical site studies	1.70	23	20/3	0.73	0.27	3.12
modeling studies	2.20	6	6/0	0.81	0.61	3.79
derivative statistical analyses or statistical summaries [b]	3.06	6	6/0	0.81	1.47	4.64
afforestation	1.82	16	16/0	0.49	0.86	2.78
existing forestland	2.18	19	16/3	0.87	0.48	3.88
annual flux monitoring/modeling	2.19	28	26/2	0.60	1.01	3.36
growing season and subgrowing season flux monitoring/modeling	1.33	7	6/1	0.98	(0.59)	3.24
1 year of observations or simulations	2.16	4	4/0	0.64	0.92	3.41
more than 1 year of observations or simulations	1.68	20	18/2	0.83	0.06	3.31
afforestation against cropland or pastureland counterfactual	2.55	8	8/0	1.30	0.01	5.09

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

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

[c] 35 study results, 34 studies (6 statistical summaries or derivative statistical analyses, 6 modeling studies, 22 empirical site studies)

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

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

Finally, studies that report on the difference in CH_4 oxidation from cropland and land planted to trees indicate rates of CH_4 oxidation above cropland levels of 2.55 kg CH_4 per hectare per year (2.27 lbs. CH_4 per acre per year). This is substantially higher than the 0.3 kg CH_4 per hectare (0.27 lbs. CH_4 per acre per year) additional CH_4 oxidation given in this review.[10]

C. Shelterbelts and hedgerows

Shelterbelts and hedgerows are installed at field edges or around farmsteads to protect soils from crosswinds and, on cropland, wind-driven erosion. In Minnesota, white spruce and poplar are popular tree species for use in shelterbelts or windbreaks. Hedgerow species are shorter lived and of smaller stature. 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 CO_2-equivalent short tons of emission that otherwise would have occurred are avoided. Of this, about two-thirds, results from CO_2 that, during plant growth, is removed from the atmosphere and is photosynthetically incorporated into live biomass and, with time, into standing and down dead tree detritus, the forest floor and soils. Of the remainder, about one-fifth, are avoided direct emissions of N_2O from cropland soils. Slightly more than 90 percent of all emissions avoided through the

[10] Estimated oxidation in afforested soils (see Table 17) minus oxidation in cropland soils, from Aronson and Heliker (2010): 2.02 – 1.85 kg CH_4/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 N_2O and uptake and oxidation of CH_4. (See Section IV, Subsection B) Since the same processes discussed earlier for general upland afforestation of former cropland are operative in recently established shelterbelts and hedges, this discussion will not be repeated. It simply might be noted that, due to the linear array of shelterbelts and hedges, trees in these plantings face fewer competitive pressures than trees in a closed forest. As a result, they may accumulate carbon more rapidly. Shelterbelts and hedges are open on two sides to sunlight and, bordering on fertilized farm fields, are less likely to be nutrient-limited than trees in a closed forest. (Amichev *et al*., 2017)

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

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

In developing the emission-avoided estimates shown in Table 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 CO_2-equivalent short tons. Had a 40-year period of assured storage been assumed, avoided-emissions from shelterbelt establishment would have been greater, totaling 444,000 CO_2-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 968,000 CO_2-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 N_2O that are avoided by cropland conversion and generally enhanced rates of CH_4 oxidation in afforested soils. The methods and sources used to estimate avoided indirect N_2O emissions from nitrate leaching and ammonia volatilization, avoided-emissions from fuel use, and avoided-emissions from foregone agricultural chemicals and fuels manufacture were discussed in the Methodology section of this report, Section II, Subsection E above.

Table 18. Shelterbelts and hedgerows: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(48,242)	crop production
N_2O-indirect volatilization	indirect emission-Nitrogen volatilization, redeposition	(2,148)	crop production
N_2O-indirect leaching	indirect emission-Nitrogen leaching or runoff	(14,020)	crop production
CH_4 [b]	soils	(184)	crop production
CO_2 [c,d]	carbon accumulation in soils and biomass	(174,780)	crop production
CO_2	cultivated soils from lime or urea use	(2,808)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	(6,892)	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(20,190)	crop production
Total		**(269,265)**	
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 a*l., 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 ± 0.73 metric tons of carbon per hectare (1.24 ± 0.33 short tons of carbon per acre).[11] 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

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

There exist relatively few published estimates of N_2O fluxes from shelterbelts and hedges. *In lieu* of N_2O emission estimates specific to shelterbelts and hedges, in calculating avoided N_2O emissions, we use the average emission rate for upland afforestation of former cropland, which is discussed above in Section IV, Subsection Bb. Afforested former croplands are estimated annually to emit 1.18 kg N_2O per hectare (1.05 lbs. N_2O per acre). Estimated average annual cropland emissions of nitrous oxide are 4.8 kg N_2O per hectare (4.3 lbs. N_2O per acre) or roughly four-fold higher.

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

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

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

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

[b] 26 study results, 26 studies

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

Six studies of N_2O emissions from shelterbelts and hedges were identified in the scientific literature. The mean rate of emission for these six studies is some 0.81 kg N_2O per hectare per year, which is not too different from the average value calculated for upland afforested former croplands. The descriptive statistics for these six studies of N_2O emissions from shelterbelts and hedges are shown below in Table 20.

Table 20. Descriptive statistics: Shelterbelts and hedgerows - N_2O

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

[a] 6 study results, 5 studies (4 empirical site studies, 1 modeling/empirical site study)

[b] 1 study reports multiple results by study type

c. Methane

Methane is oxidized in both cropland and forested soils. The change in the rate of CH_4 oxidation in soils from establishing shelterbelts and hedges is calculated as the difference in the rate of soil CH_4 oxidation in cropped soils, as taken from Aronson and Helliker (2010), and estimated annual oxidation in shelterbelts and hedges. Relatively few published estimates of CH_4 oxidation rates for soils of shelterbelts and hedges can be found in the literature; we were able to identify five studies. *In lieu* of an adequate set of estimates for soil CH_4 oxidation rates specific to shelterbelts and hedges, in estimating the change in CH_4 uptake by shelterbelts establishment we use the mean rate of CH_4 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 CH_4 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 CH_4 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 CH_4 oxidation from land-use change to overall GHG-avoidance is small.

Table 21. Descriptive statistics: Shelterbelts and hedgerows - CH_4

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

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

[b] 6 study results, 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 N_2O generally are lower in these unfertilized, mostly perennial plantings, though only a few studies exist to verify this understanding.

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

Table 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 CO_2-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]

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(41,091)	crop production
N_2O-indirect volatilization	indirect emission-Nitrogen volatilization, redeposition	(2,107)	crop production
N_2O-indirect leaching	indirect emission-Nitrogen leaching or runoff	(11,703)	crop production
CH_4 [b]	soils	468	crop production
CO_2 [c,d]	carbon accumulation in soils	(78,089)	crop production
CO_2	cultivated soils from lime or urea use	(2,808)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	(5,518)	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(20,190)	crop production
Total		**(161,038)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass			
40 year storage	all sources and sinks	**(239,127)**	crop production
100 year storage	all sources and sinks	**(473,395)**	crop production

[a] positive = emissions increase, negative = emissions reduction
[b] reduction in soil CH_4 oxidation = relative increase in emissions
[c] carbon accumulation in soil and biomass = net removal of CO_2 from the atmosphere = net emission reduction
[d] assumes 20 years of sustained storage of newly sequestered organic carbon in soils and biomass

About half of the calculated emission-avoidance potential results from biogenic carbon sequestration, mostly in grassland soils, but also in live roots and aboveground biomass. A value of 0.55 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 N_2O flux rates from N_2O production in upland grass filter strips of 0.89 lbs. N_2O per acre (1 kg N_2O per hectare), which is not too different from the 1.28 lbs. N_2O per acre per year (1.44 kg N_2O per hectare per year) value used in Table 22 to calculate avoided N_2O emissions from field borders, contour buffer strips, and vegetative and herbaceous wind barriers.

No similar estimates specific to field borders or intra-field buffers or barriers were available for soil CH_4 uptake and oxidation for use in evaluating the suitability of the approach taken here on in soil CH_4 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 N_2O losses than are upland soils. Whereas upland soils generally act to oxidize CH_4, riparian buffer soils often act as net sources of emission of CH_4 to the atmosphere, although field observations of CH_4 emissions from or uptake and oxidation in riparian buffer soils are limited in number.

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

Table 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 CO_2-equivalent short tons of GHGs would be avoided annually, or less than half of what is estimated above for upland soils temporarily idled in grass (see Section IV, Subsection A).

Of total estimated 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 CH_4 from generally wetter riparian soils offset reductions in the emission of N_2O from these soils. The average acre of cropland in Minnesota is heavily fertilized with synthetic and manure-based nitrogen. Emissions of N_2O to the atmosphere result from the application of nitrogen to soils, as well as from enhanced mineralization of organic nitrogen in soils during tillage and the addition to soils of large amounts of crop residues, particularly those high in nitrogen content. Some emissions of N_2O occur downstream of crop production in river, stream and lake sediments as a result of runoff and leaching of nitrate and nitrogen in other forms to surface and groundwater.

Estimated atmospheric removals of CO_2 through biogenic carbon sequestration on 100,000 acres of riparian soils are 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 CO_2-equivalent short tons. Had a 40-year period of assured storage been assumed, avoided-emissions from the establishment of grassland riparian buffers would have been greater, totaling 127,000 CO_2-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 275,000 CO_2-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.

Table 23. Grassland riparian buffers: Emissions-avoided [a]

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(9,405)	crop production
N_2O-indirect volatilization	indirect emission-Nitrogen volatilization, redeposition	(2,107)	crop production
N_2O-indirect leaching	indirect emission-Nitrogen leaching or runoff	(13,653)	crop production
CH_4	soils	27,176	crop production
CO_2 [b,c]	carbon accumulation in soils and biomass	(49,420)	crop production
CO_2	cultivated soils from lime or urea use	(2,808)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	(6,892)	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(20,190)	crop production
Total		**(77,299)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass			
40 year storage	all sources and sinks	**(126,719)**	crop production
100 year storage	all sources and sinks	**(274,981)**	crop production

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

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

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

A number of estimates have been published of the net change in total greenhouse gas emissions resulting from the conversion of cropland to grassland riparian buffers. These include estimates by Eagle *et al*. (2012) and Swan *et al*. (2015), which report avoided-emissions for cropland conversion to riparian buffers of 1.59 and 1.39 CO_2-equivalent short tons per acre per year, respectively, or 159,000 and 139,000 CO_2-equivalent short tons per year on 100,000 acres. These estimates are generally similar to, if smaller than, the estimates given in Table 23 above.

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

a. Carbon sequestration in soils and biomass

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

Cropland cultivation disrupts soil structure, breaking up protective soil macroaggregates and exposing soil organic carbon 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 CO_2 (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 CO_2-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

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

[a] 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 CO_2 emissions elsewhere in the economy. More studies may be needed, particularly at the level of total ecosystem carbon, to more firmly establish, within the range noted above, a mean best estimate for carbon sequestration in these systems.

b. Nitrous oxide

Nitrous oxide is produced in riparian buffers that are adjacent to cropland predominantly by denitrification of nitrate 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_2O or N_2 under anaerobic conditions. Riparian buffers are much wetter that the soils of upland croplands. Maximum N_2O production in soils occurs around water-filled pore space of 70 to 80 percent, which is also optimal soil wetness for denitrification. (Hefting *et al*., 2006; Machefert *et al*., 2002) Nitrate-laden groundwater flows from cropland to riparian grassland buffers sustain substantial emissions of N_2O from buffers to the atmosphere. (Schelde *et al*., 2012)

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

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

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

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

Using the average of the results from the 15 studies that were reviewed, riparian grassland buffers are estimated to annually emit 4.1 ± 0.88 kg N_2O per hectare (3.66 ± 0.78 lbs. N_2O per acre), or about three times as much as upland restored grassland.

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

The descriptive statistics for the 15 studies that were reviewed are shown in Table 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_2O per hectare per year estimate for all 15 studies, but too few studies report multiple year results for much to be concluded here. Seven studies report on the difference in N_2O emissions in paired, side-by-side experiments between riparian grassland buffers and adjacent cropland. In these studies, on an annual basis, riparian grassland buffers emitted 13.93 kg N_2O per hectare (12.43 lbs. N_2O per acre) less than adjacent cropland, which is directionally consistent with our results, if also more extreme in terms of reported reductions. From table 23, we estimate annual reductions of 0.72 kg N_2O per hectare (0.63 lbs. N_2O per acre).

A good deal more empirical research 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 N_2O 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 - N_2O

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

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

[b] 15 study results, 15 studies

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 CH_4 and its emission to the atmosphere. Methane is produced microbially in soils under anaerobic or anoxic conditions by methanogenic bacteria. Across the course of a year, riparian buffers experience wet and dry conditions, During dry seasons, CH_4 is taken up by soils and oxidized by methanotrophic bacteria and, as just noted, under near-saturated conditions, CH_4 is produced by methanogenic bacteria. On an annual basis, the balance between these processes of methane consumption (methanotrophy) and CH_4 production (methanogenesis) determines whether a riparian buffer is a net source or net sink of CH_4. (Jacinthe and Vidon, 2017)

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

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

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

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

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

[b] 11 study results, 11 studies

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_2O, although in the case of N_2O, just barely. Large net emissions of CH_4 from forested and multi-species riparian buffers account for the large advantage of upland afforestation over afforestation in the riparian zone, although, as we will discuss in the subsection on CH_4, the number of studies that address CH_4 emissions from forested buffers is limited. In upland forested acres, soils act to oxidize atmospheric CH_4, thereby offsetting a small part of surface emissions of other GHGs. In much wetter, occasionally inundated riparian soils, anoxic conditions favor the production of CH_4.

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

Avoided-emissions from forested and multispecies buffers on former cropland are shown in Table 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.

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

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	7,033	crop production
N_2O-indirect volatilization	indirect emission-Nitrogen volatilization, redeposition	(2,148)	crop production
N_2O-indirect leaching	indirect emission-Nitrogen leaching or runoff	(13,653)	crop production
CH_4	soils	33,466	crop production
CO_2 [b,c]	carbon accumulation in soils and biomass	(198,058)	crop production
CO_2	cultivated soils from lime or urea use	(2,808)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	(6,892)	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(20,190)	crop production
Total		**(203,251)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass			
40 year storage	all sources and sinks	**(401,309)**	crop production
100 year storage	all sources and sinks	**(995,484)**	crop production

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

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

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

Biogenic carbon sequestration from forested buffer establishment on idled soils is discussed immediately below. Avoided direct emissions of N_2O from soils and the effects of forested riparian buffer creation on soil CH_4 oxidation are discussed in the subsequent two subsections. The methods and sources used to estimate avoided indirect N_2O emissions from nitrate leaching and ammonia volatilization, avoided-emissions from fuel use, and avoided-emissions from foregone agricultural chemicals and fuels manufacture 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 CO_2. As noted elsewhere in this report, this is the longest period that, in our judgment, sustained terrestrial carbon storage, once initiated, can be assumed in estimating its value as a GHG offset. Under this assumption, avoided-emissions are an estimated 203,000 CO_2-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 CO_2-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 995,000 CO_2-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, 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 macroaggegates and microaggregates and in mineral-organic complexes, leading to the long-term accumulation of organic carbon in soils.

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

From Table 27, we estimate that, on 100,000 afforested acres, riparian buffers on former cropland will sequester 198,000 short tons of carbon as CO_2, 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 CO_2-equivalent tons for inclusion in the summary Table 27. During afforestation, CO_2 is removed from the atmosphere and incorporated into tree biomass and, eventually, into woody detritus and soils. This acts to offset emissions of CO_2 from elsewhere in the economy.

The average per acre sequestration rate for forests in riparian areas was developed from 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

	biogenic carbon sequestration (Mg C/ha/yr) [a]	number of studies [c]	ratio of sequestration to emission: study numbers [d]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
total ecosystem carbon (soil organic carbon [SOC], above and belowground biomass)	3.15	15	15/0	0.69	1.79	4.51
soil organic carbon-only	1.57	5	5/0	0.57	0.46	2.68
above and below ground biomass	3.16	5	5/0	0.80	1.58	4.73
empirical site study-eddy covariance (NECB/NBP)	2.92	3	3/0	0.30	2.33	3.52
empirical site study-SOC soil sampling	1.93	3	3/0	0.81	0.34	3.52
empirical site study-soil sampling, bole measurements, destructive biomass sampling, allometric relationships	5.58	4	4/0	1.95	1.75	9.41
meta-analyses	2.60	1	1/0	NA	NA	NA
other derivative statistical analyses or statistical summaries [b]	3.00	1	1/0	NA	NA	NA
modeling study	2.18	4	4/0	0.30	1.60	2.77
expert judgment/literature review	2.33	6	6/0	1.06	0.26	4.40
15 to 25 year annual rate of sequestration	3.86	8	8/0	1.29	1.33	6.40
0 to 15 year annual rate of sequestration	4.72	7	7/0	1.25	2.28	7.17
>25 year annual rate of sequestration	3.91	6	6/0	1.44	1.09	6.72

[a] all estimates developed against cropland counterfactuals except other derivative statistical 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] 27 study results, 27 studies

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

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 N_2O 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 N_2O emissions from Minnesota cropland. N_2O emissions from Minnesota cropland are taken from the MPCA Greenhouse Gas Inventory. N_2O emissions from forested riparian buffers are estimated using emission rates developed on a per hectare basis from the scientific literature and converted to lbs. N_2O per acre for use in the calculation. To estimate N_2O 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 N_2O per hectare per year [4.76 lbs. N_2O per acre per year]) as the best estimate of mean annual N_2O emissions from forested riparian buffers.

No meta-analyses were available to support the calculation. 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 N_2O emissions from forested riparian buffers with emissions from adjacent cropland. These suggest a difference in emissions between forested buffers and cropland of 6.61 kg N_2O per hectare per year (5.9 lbs. N_2O per acre per year), favoring croplands as by far the higher emitting source. These results contrast substantially with the results we present in Table 27, which suggests that uncertainty still shrouds these issues. Based on the side-by-side studies, few as they are, it seems possible that N_2O 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 - N_2O

	emissions (kg N_2O/ hectare/yr) [a]	number of study results [c,d]	ratio, positive to negative results: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	5.33	33	32/1	1.94	1.53	9.14
empirical site studies	5.22	32	31/1	2.00	1.29	9.14
derivative statistical analyses or statistical summaries [b]	9.10	1	1/0	NA	NA	NA
annual flux monitoring/modeling	6.76	24	23/1	2.62	1.63	11.90
growing season and subgrowing season flux monitoring/modeling	1.49	9	9/0	0.47	0.56	2.42
1 year or less of observations or simulations	6.79	20	19/1	2.67	1.56	12.01
> 1 year of observations or simulations	3.76	21	21/0	1.75	0.32	7.19
forested riparian buffers against cropland or pastureland counterfactuals	(6.61)	8	3/5	4.29	(15.01)	1.80

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

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

[a] negative emissions = removal from atmosphere and destruction in soils
[b] statistical summaries or derivative statistical analyses other than meta-analyses
[c] 15 study results, 15 studies

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 a*l., 2015) As of 2012, four percent of cropland in the US lake states (Minnesota, Wisconsin and Michigan) that was planted with corn was also cropped with cover crops. (Baranski *et al*., 2018)

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

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 CO_2-equivalent short tons of GHGs are avoided annually. Of this, most derives from biogenic carbon sequestration in cover crop soils. Also important are reduced N_2O emissions from surface water and groundwater resulting from reduced leaching. Emissions of N_2O 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_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_2-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 101,000 CO_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

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	7,511	no cover crop
N_2O-indirect volatilization	indirect emission-Nitrogen volatilization, redeposition	not known	no cover crop
N_2O-indirect leaching	indirect emission-Nitrogen leaching or runoff	(7,329)	no cover crop
CH_4 [b]	soils	131	no cover crop
CO_2 [c,d]	carbon accumulation in soils	(20,118)	no cover crop
CO_2	cultivated soils from lime or urea use	-	no cover crop
GHGs-energy	fossil fuel and electricity use in crop production	519	no cover crop
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(1,187)	no cover crop
Total		**(20,474)**	
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

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

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

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

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

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_2-equivalent short tons of GHGs would be avoided annually on 100,000 acres. The use of leguminous winter cover crops acts to increase direct N_2O emissions from cropland soils, more than offsetting any emission reduction resulting from reduced use and manufacture of synthetic fertilizer.

A 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_2-equivalent short tons per acre (1.35 CO_2-equivalent metric tons per hectare).

Table 32. Published estimates of greenhouse gas-avoidance from cover crop use [a]

Study	Type of study	CO_2-eq. short tons per acre per year	CO_2-eq. short tons per 100,000 acres per year
Gelfand and Robertson (2015)	site study	0.50	49,953
Robertson *et al.* (2000)	site study	0.23	22,747
DeGryze *et al* . (2010)	modeling study	0.60	59,840
DeGryze *et al* . (2011)	modeling study	0.53	53,465
Kaye and Quemada (2017)	literature review/expert judgment	0.67	67,125
Swan *et al* . (2015) [b]	literature review/expert judgment	0.41	40,778
Abdalla *et al* . (2019)	derivative statistical analysis	0.92	91,878
Eagle *et al* . (2012)	derivative statistical analysis	0.86	85,634
This report	literature review	0.20	20,474

[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 N_2O and the effects of winter cover corps on soil CH_4 oxidation. The methods and sources used to estimate avoided indirect N_2O emissions from nitrate leaching and ammonia volatilization, avoided-emissions from fuel use, and avoided-emissions from foregone agricultural chemicals and fuels manufacture were discussed 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 CO_2-equivalent short tons of annual sequestration. As noted in the Methodology section of this report, formal meta-analysis is a powerful tool for aggregating estimates across study types with differing designs. Using the meta-analysis estimate, winter cover crops are estimated to annually sequester 0.32 metric tons of carbon per hectare (0.52 short tons of CO_2). 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 CO_2-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 CO_2 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 CO_2 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.

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

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

[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

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. (Necpalova *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).

b. Nitrous oxide

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

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

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

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

In this study, avoided-emissions from the use of cover crops are calculated as the product of the estimated percentage change in emissions resulting from use of cover crops and average Minnesota cropland N_2O emissions. Average Minnesota cropland N_2O emissions are taken from the MPCA Greenhouse Gas Inventory. To estimate the percentage change in N_2O emissions under cover crops we reviewed 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 N_2O emission with cover crops. Using the meta-analysis mean estimate, the use of winter cover crops is estimated to increase N_2O emissions by 12 ± 1 percent, a relatively minor change. By study type, the estimate percentage change ranged from +12 to +81 percent. The mean value for all 24 full-year studies that were reviewed was +26 ±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 N_2O emissions will prove muted.

By cover crop type, the increase in full-year N_2O 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 N_2O emissions under conventional or reduced tillage, although on the basis of only a handful of observations for conventional and reduced tillage. The measured increase in N_2O emissions in empirical site studies with one to two years of results was more than double the more subdued rate suggested by the two meta-analyses. The percent increase in emissions in site studies with three years or more of results was less dramatic, but still about 15 percent.

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

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

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

Table 34. Descriptive statistics: Winter cover crops/Catch crops - N_2O

	emissions: % change in emissions per hectare	number of study results	change in emissions, ratio positive-to-negative: numbers of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
full crop studies: [a,b]						
meta-analyses	12%	2	2/0	1%	9%	14%
all studies	26%	34	23/11	8%	10%	42%
empirical site studies	27%	22	11/11	11%	5%	49%
modeling studies	14%	8	8/0	6%	1%	26%
expert judgment/literature reviews	81%	2	2/0	44%	-6%	168%
nonleguminous cover crop	8%	16	9/7	8%	-8%	23%
leguminous and mixed legiminous/nonleguminous cover crop	39%	16	15/4	13%	14%	64%
no-till tillage	46%	11	9/2	18%	11%	82%
reduced tillage	25%	4	1/3	31%	-36%	86%
conventional tillage	5%	4	3/1	3%	-1%	11%
1-2 years of observations or simulations	36%	12	7/5	12%	11%	60%
3 years or more of observations or simulations	15%	18	12/6	11%	-7%	38%
partial and full crop-year studies:						
meta-analyses	76%	9	8/1	54%	-31%	183%
all studies	37%	57	42/15	10%	17%	58%

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

[b] 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 CO_2-equivalent tons annually. The calculation of net greenhouse gas-avoidance from the use of winter cover crops is largely unaffected by changes in CH_4 emission from or oxidation in soils.

Methane is oxidized in soils by methantrophic bacteria and is produced in cropland soils in anaerobic microsites by methanogenic bacteria. The balance between the two processes determines whether CH_4

is emitted from soils on a net basis or is consumed and whether a change in CH_4 from cropland, described in terms of CH_4 oxidation, enhances or reduces CH_4 oxidation.

In evaluating the effect of winter cover crops on CH_4 soil oxidation, we reviewed 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 CH_4 soil oxidation by 6 percent, which applied on 100,00 acres, results in the reported 131 CO_2-equivalent tons of reduction in cropland CH_4 soil oxidation. As noted above, in some cases, more than one observation was reported per study to accommodate results developed for specific important parameters, in the case of cover crops, multiple types of tillage (conventional tillage, reduced tillage and no till practice) and two cover crop types (nonleguminous and leguminous).

Care should be taken with this estimate. Of the 13 studies, 40 percent favor an increase in CH_4 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 CH_4 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 - CH_4

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

[a] 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. (Baranski *et al*., 2018)

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

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

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 CO_2-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 N_2O 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 CO_2. 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 CO_2-equivalent short tons. Had a 40-year period of assured storage been assumed, avoided-emissions from the use of no-till practice would have totaled 28,000 CO_2-equivalent short tons. Had 100-years of assured storage been assumed, avoided-emissions would have totaled 72,000 CO_2-equivalent short tons (see Table 36).

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

The published literature contains a number of studies of the integrated effect of no-till practice across all greenhouse gases and all emissions sources. The results of these, shown in Table 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 CO_2-equivalent short tons.

Table 36. No-till tillage: Emissions-avoided [a]

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [b]	Counterfactual
N_2O-direct	soils	3,815	conventional tillage
N_2O-indirect volatilization	indirect emission-Nitrogen volatilization, redeposition	553	conventional tillage
N_2O-indirect leaching	indirect emission-Nitrogen leaching or runoff	-	conventional tillage
CH_4 [c]	soils	(283)	conventional tillage
CO_2 [d,e]	carbon accumulation in soils	(14,589)	conventional tillage
CO_2	cultivated soils from lime or urea use	-	conventional tillage
GHGs-energy	fossil fuel and electricity use in crop production	(2,704)	conventional tillage
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(599)	conventional tillage
Total		**(13,807)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils			
40 year storage	all sources and sinks	**(28,396)**	conventional tillage
100 year storage	all sources and sinks	**(72,162)**	conventional tillage

[a] conventional tillage counterfactual
[b] positive = emissions increase, negative = emissions reduction
[c] increase in soil CH_4 oxidation = relative decrease in emissions
[d] carbon accumulation in soil and biomass = net removal of CO_2 from the atmosphere = net emission reduction
[e] assumes 20 years of sustained storage of newly sequestered organic carbon in soils

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

a. Carbon sequestration in soils

No-till is a crop production practice in which cropland soils are untilled. This acts to restore to soils some of the physical and chemical protections against the decomposition of soil organic matter that is lost when soil undergoes intensive tillage.

In an undisturbed soil, biogenic carbon is deposited in the soil profile through the growth and decay of plant roots and rhizodeposition in the form of sloughed-off plant cells or root exudates. Some biogenic carbon is also deposited into deep soil layers in the form of leached dissolved organic carbon. In undisturbed soils, organic carbon is physically protected from decomposition by soil bacteria by soil macroaggregates, mostly in soil pores that, due to small size, are inaccessible to bacteria and fungi (or water-soluble enzymes) or too anaerobic for aerobic soil bacteria. (Jones and Donnelly, 2004) Most protected or ‘stabilized’ soil organic carbon 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]

		emissions-avoided	
Study	**Type of study**	**CO_2-eq. short tons per acre per year**	**CO_2-eq. short tons per 100,000 acres per year**
Archer and Halvorson (2010)	site study	0.89	88,711
Gelford and Robertson (2015)	site study	0.51	51,291
Krauss *et al*. (2017)	site study	0.79	78,632
Mosier *et al*. (2005)	site study	0.71	71,495
Mosier *et al*. (2006)	site study	1.21	120,958
Robertson *et al*. (2000)	site study	0.45	44,601
Sainju *et al*. (2014)	site study	0.18	17,796
Tellez *et al*. (2017)	site study	0.64	63,811
Del Grosso *et al*. (2005)	modeling study	0.78	78,052
Grant *et al*. (2004)	modeling study	0.27	27,207
Eagle *et al*. (2012)	other derivative statistical analysis [c]	0.66	65,563
Six *et al*. (2004)	other derivative statistical analysis [c]	0.31	30,772
Swan *et al*. (2015) [b]	literature review/expert judgment	0.34	34,166
Sainju *et al*. (2016)	meta-analysis	0.69	69,265
This report	literature review	0.14	13,807

[a] results as reported without adjustments
[b] change in soil N_2O 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 CO_2, the principal gaseous product of microbial decomposition, to the atmosphere. Intensively tilled soils also are more prone to soil losses through wind and water erosion. Once removed from cropland, eroded sediments may enter inland surface waters, where some soil carbon may be mineralized and emitted to the atmosphere as CO_2. Inland waters are known be to larger emitters of CO_2. (Butman *et al*., 2016)

No-till practice reverses the processes of soil degradation, slowly building carbon in soils through renewed physical and biochemical protection of soil organic matter. (Balesdent *et al*., 2000) This returns soils to a condition somewhat analogous to that of undisturbed soil. In no-till soils, soil organic carbon is increased by reducing the respiratory loss of carbon from soils, all the while holding constant the input of organic carbon to soils in the form of roots, rhizodeposits and aboveground crop residues. (Ogle *et al*., 2005)

Observationally, no-till soils lose much less CO_2 to the atmosphere in the form of emissions than intensive tillage (21 percent), and have much lower mineralization rates for organic carbon (35 to 45 percent less). (Abdalla *et al*., 2016; Clay *et al*., 2015) Again, observationally speaking, the mean residence time of organic carbon in no-till soils is about 15 percent longer than in intensively tilled soils. (Ogle *et al*., 2012) The conversion from intensive tillage to no-till practice is associated with enhanced aggregate stability. (Jastrow *et al*., 1996) Meta-analyses of data from published site studies are uniform, or nearly so, in their conclusion that, while there is substantial variability in the estimates, no-till stores more organic carbon in soils than do the more intensive forms of tillage. (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 CO_2-equivalent tons). (Paustian *et al*., 1997) By contrast, crop residue carbon is implicitly included in the measurement of SOC under more intensive forms of tillage, as incorporated residues. This may act to bias low estimates of the response of SOC to no-till. Methods for evaluating changes of soil carbon that measure carbon across a fixed depth may, due to changes in bulk density with changed tillage practice, overestimate the effectiveness of no-till in sequestering carbon. (Du *et al*., 2017) Sampling of carbon deep in the soil column is inherently difficult due to the large variability of soil carbon at these levels. (Kravchenko *et al*., 2011) At this time, no objective analysis has addressed the relative effects of these difficulties or omissions on estimates of sequestration drawn from the literature.

A number of studies have examined the effect on soil organic carbon of an occasional year of full inversion tillage interspersed in a general no-till regimen. Empirical site studies have found limited or no effect on soil carbon. (Yang *et al*., 2008; Wortman *et a*l., 2010; Dimassi *et al*., 2013) 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 CO_2-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 CO_2-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 CO_2-equivalent short tons for use in summary Table 36.

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

	biogenic carbon sequestration (Mg C/ha/yr)	number of study results [d,e]	ratio of sequestration to emission: number of study results [f]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	0.23	7	7/0	0.06	0.11	0.35
other derivative statistical analyses or statistical summaries	0.27	8	7/1	0.06	0.15	0.39
empirical site studies	0.41	76	62/14	0.08	0.25	0.56
modeling studies	0.20	20	20/1	0.06	0.08	0.32
expert judgment/literature reviews	0.29	11	11/0	0.03	0.23	0.36
40 cm-plus soil sampling/modeling depth [b]	0.35	39	29/10	0.11	0.14	0.57
10 to 30 cm soil sampling/modeling depth [b]	0.34	65	59/6	0.07	0.21	0.48
10 to 20 year annual sequestration rate	0.32	60	52/8	0.07	0.19	0.45
20 to 30 year annual sequestration rate	0.24	24	21/3	0.06	0.12	0.35
0 to10 year annual sequestration rate	0.49	26	21/5	0.17	0.15	0.83
No-till with cover crop	0.40	9	9/0	0.10	0.21	0.60
no-till on former conventional till/reduced till acres: meta-analyses[c]	0.24	8	8/0	0.05	0.14	0.35

[a] conventional tillage counterfactual

[b] results for lowest reported sampling depth

[c] counterfactual either conventional tillage or undifferentiated between conventional tillage and reduced till

[d] 122 study results, 117 studies (7 meta-analyses, 8 statistical summaries or other derivative statistical analyses, 19 modeling studies, 3 IPCC-inventory studies, 69 empirical site studies, 11 expert reviews)

[e] 7 studies report multiple results by cover crop treatment

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

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 CO_2-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_2O from cropland, modulated by soil physical and chemical properties, including structure and porosity, soil bulk density, SOC content, soil texture and pH, soil temperature, and water-filled pore space, along with weather. Soil management practices also play a role, particularly with respect to the timing of specific management practices like irrigation or crop residue incorporation. Synthetic nitrogen fertilizer is the principal source of NH_4^+ and NO_3^- in soils, along with organic forms of nitrogen like soil organic nitrogen and crop residue nitrogen.

Tillage affects the physical properties of soils, thereby influencing the production of N_2O in soils. No-till soils are often wetter with higher bulk densities and greater concentrations of residues at the soil surface, leading in at least some soils and some experiments, to the formation of anaerobic soil conditions. (Regina and Alukku, 2010; Gregorich *et al*., 2008) The formation of anaerobic conditions acts to stimulate N_2O production through denitrification. Generally, denitrification is the dominant source of N_2O in soils prone to anaerobic conditions through excessive wetness. Measured against water filled pore space (WFPS), a measure of soil wetness, denitrification is the dominant source of N_2O once WFPS passes 60 to 65 percent. (Liu *et al*., 2007; Metivier *et al*., 2009) Rates of N_2O formation through denitrification generally increase exponentially as soil water filled pore space increases beyond 60 percent. (David *et al*., 2009) Maximum N_2O production in soils typically occurs at water filled pore space of somewhere between 60 and 85 percent, which also generally coincides with soil wetness at which N_2O production is mostly or entirely through denitrification. (Almaraz *et al*., 2009; Davidson *et al*., 1991; Liu *et al*., 2007)

Multiple effects of no-till on N_2O emissions have been observed, often moving in opposing directions. (Venterea and Stanenas, 2008) For instance, no-till soils are often cooler than tilled soils, due to the presence of surface residues. This acts to depress the rate of microbial activity in the soil, leading to rates of N_2O production lower than they would be otherwise with warmer soils. (Liu *et al*., 2005) With less aeration and reduced soil temperature, mineralization rates in no-till topsoils also are lower than in soils under conventional tillage, reducing the supply of nitrate available for denitrification, and presumably N_2O production. (Bayer *et al*., 2015; Venterea and Stanenas, 2008) In the long-term, no-till practice should act to increase the rate of formation of soil aggregates, leading potentially to enhanced soil porosity, and increased, rather than reduced, soil aeration. (Plaza-Bonilla *et al*., 2014; Six *et al*., 2004)

Much effort has been directed to verifying the long-term effect of no-till practice on N_2O through enhanced soil aggregate formation. All other things equal, with enhanced aggregate formation and enhanced soil aeration, anaerobic conditions are less likely to form in no-till soils, reducing rather than increasing denitrification rates, and presumably N_2O production. (van Kessel *et al*., 2013) Of four statistical analyses of results from the published literature that address this question (three formal meta-analyses, one other derivative statistical analysis), three have found reduced N_2O emissions from soils in no-till practice for longer than ten to twenty years, suggesting that such an effect may be operative, albeit in the out-years of our 20-year window. (Huang *et al*., 2018; Mei *et al*., 2018; Six *et al*., 2004; van Kessel *et al*., 2013)

A reading of the scientific literature indicates that no-till practice on fine-textured soils, like clay, tends to increase N_2O emissions. (Ball *et al*., 2014; Perego *et al*., 2016) On medium and coarse textured soils, like silt loam or sand, the reported effects of no-till are ambiguous, showing 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 N_2O production in soils and its emission, a wide variety of results are possible and often occur at different sites or at the same site under different meteorological conditions. The interactions between the controls on N_2O emissions from tillage change are complex. Simple relationships between, on the one hand, N_2O emissions and, on the other hand, environmental conditions and the specifics of different agricultural practices have yet to be developed or revealed. Regarding the experimental data, it is extremely noisy and, depending on the data considered, can and often does yield contradictory results, whether for tillage or other agricultural practices. Because of this, to extract from the experimental data a firm understanding of the direction of the likely effect of no-till practices on N_2O emissions, and its magnitude, a very large data set is necessary, one now probably beyond our grasp.

The best that now might be done is to develop a sense of the response of N_2O emissions to no-till practice based on best available knowledge, accompanied by a commitment to update that understanding going forward as additional experimental data is developed.

In Table 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 CO_2-equivalent short tons (4,000 CO_2-equivalent short ton emission increase). This was developed consistent with the approach outlined immediately above, using the mean response rates to this practice change given in nine published meta-analyses. The mean response rate of N_2O 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 N_2O emissions on 100,000 acres. Average annual Minnesota cropland N_2O emissions are from the MPCA Greenhouse Gas Inventory. As noted in the Methodology section (Section II) of this report, meta-analysis is a powerful statistical used to integrate results from experiments of different designs and 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 N_2O 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_2O emissions with tillage change, while 47 percent reported increasing N_2O 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_2O emissions were 4.2 percent higher than paired soils in conventional tillage. For soils in no-till practice 10 or more years, N_2O emissions were 0.7 percent higher than paired soils in conventional tillage, based on the results from 60 studies. N_2O 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)

Table 39. Descriptive statistics: No-till tillage - N_2O [a]

	emissions: % change in emissions per hectare or acre	number of study results[d,e]	change in emissions, ratio positive-to-negative: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	6.0%	9	6/3	4.9%	-3.7%	15.6%
other derivative statistical analyses or statistical summaries [b,c]	3.9%	5	3/2	7.5%	-10.8%	18.7%
modeling studies	-4.0%	13	5/8	9.1%	-21.8%	13.9%
empirical site studies	2.9%	58	27/31	5.2%	-7.3%	13.2%
expert judgment/literature review	19.8%	3	3/0	11.9%	-3.5%	43.1%
annual flux monitoring/modeling	-1.9%	35	13/22	6.9%	-15.4%	11.6%
growing season and subgrowing season flux monitoring/modeling	6.8%	45	27/18	4.9%	-2.9%	16.6%
1 year of observations or simulations	12.3%	21	12/8	11.1%	-9.6%	34.1%
2 to 3 years of observations or simulations	-4.3%	34	13/21	5.9%	-15.8%	7.3%
3 years-plus of observations or simulations	1.0%	17	7/10	5.6%	-10.0%	12.1%
< 10 years in no-till	4.2%	45	21/24	6.1%	-7.8%	16.2%
10 years or more in no-till	0.7%	25	11/14	6.4%	-11.9%	13.3%
no-till with cover crop	-15.5%	7	2/5	10.2%	-35.5%	4.5%
no till/reduced tillage on former conventional tillage acres: meta-analyses	4.0%	3	2/1	3.8%	-3.3%	11.4%

[a] conventional tillage counterfactual

[b] one additional other derivative statistical analysis, not included above, with conventional tillage and reduced tillage jointly as counterfactual, yielded a 33.6% emission reduction

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

[d] 88 study results, 82 studies (9 meta-analyses, 4 statistical summaries or other derivative statistical analyses, 11 modeling studies, 56 empirical site studies, 2 expert reviews)

[e] 6 studies report multiple results by cover crop treatment or multiple geographies

The estimated annual change in soil CH_4 oxidation resulting from the use of no-till practice is small, an increase of 283 CO_2-equivalent short tons (see Table 36). This was calculated using the average percent change in soil CH_4 oxidation in four published meta-analyses with a change in upland soils from conventional tillage to no-till practice. As noted above, formal meta-analysis is a powerful statistical tool useful for aggregating estimates across study types with differing designs. Baseline CH_4 oxidation rates in temperate cropland soils were taken from Aronson and Helliker (2010).

The descriptive statistics from the four meta-analyses are shown in Table 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 CH_4 oxidation is estimated to increase by 13.7 ± 5.5 percent with a change in tillage from conventional tillage to no-till practice. By contrast, using the results from the modeling and empirical site studies, soil CH_4 uptake and oxidation would be expected to decline 6 and 83 percent, respectively, but based on only a relatively few studies.

The contribution of CH_4 oxidation to overall GHG-avoidance from tillage change is small, with little effect on the larger budget totals developed in Table 36.

Table 40. Descriptive statistics: No-till tillage - CH_4 [a]

	% change in oxidation per hectare or acre	number of study results [b,c]	change in oxidation, ratio positive-to-negative: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	13.7%	4	3/1	5.5%	3%	24%
empirical site studies	-83.4%	18	5/13	36.6%	-155%	-12%
modeling studies	-6.5%	4	2/2	15.7%	-37%	24%

[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

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 CO_2. 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 CO_2-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 CO_2 emissions from fossil fuel combustion elsewhere in the economy. This determines the present-day offset value of sequestration. In calculating the emissions-avoidance effects of reduced tillage, we assumed a 20-year timespan of assured storage of carbon in soils, resulting in annual emissions-avoidance on 100,000 acres of cropland of 15,000 CO_2-equivalent tons. Had we instead assumed a 40-year period of assured storage of carbon in soils, GHG-avoidance from the use of reduced tillage in place of full inversion tillage on 100,000 acres of cropland would have totaled 28,000 CO_2-equivalent short tons. Had we assumed a 100-year timespan for sustained storage, estimated avoidance would have totaled 67,000 CO_2-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 CO_2, is incorporated into plant biomass and, eventually, soils.

Table 41. Reduced tillage: Emissions-avoided [a]

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres pear year) [b]	Counterfactual
N_2O-direct	soils	(102)	conventional tillage
N_2O-indirect volatilization	indirect emission-Nitrogen volatilization, redeposition	553	conventional tillage
N_2O-indirect leaching	indirect emission-Nitrogen leaching or runoff	-	conventional tillage
CH_4 [c]	soils	52	conventional tillage
CO_2 [d,e]	carbon accumulation in soils	(13,026)	conventional tillage
CO_2	cultivated soils from lime or urea use	-	conventional tillage
GHGs-energy	fossil fuel and electricity use in crop production	(1,653)	conventional tillage
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(366)	conventional tillage
Total		**(14,543)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils			
40 year storage	all sources and sinks	**(27,568)**	conventional tillage
100 year storage	all sources and sinks	**(66,645)**	conventional tillage

[a] conventional tillage counterfactual

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

[b] 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_2O from soils and the effects of reduced tillage on soil CH_4 oxidation. The methods and sources used to estimate avoided indirect N_2O emissions from nitrate leaching and ammonia volatilization, avoided-emissions from fuel use, and avoided-emissions from foregone agricultural chemicals and fuels manufacture 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 CO_2-equivalent short tons of sequestration. This is an annual estimate and is the difference in soil carbon storage between conventional full inversion tillage and various forms of reduced tillage like chisel till or disk till. The results shown in Table 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 CO_2-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 [a]

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

[a] conventional tillage counterfactual

[b] results for lowest reported sampling depth

[c] 74 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)

[d] 5 studies report multiple results by cover crop treatment

[e] 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 N_2O emissions, again on 100,000 acres. As discussed in the Methodology section of this report, average Minnesota cropland N_2O emissions are from the MPCA Greenhouse Gas Inventory. To estimate the percentage change in N_2O emissions under reduced-till on cropland formerly in conventional tillage, we reviewed 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 N_2O emission with reduced tillage practice on croplands formerly under conventional tillage practice. Of the five meta-analyses, three reported N_2O 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 N_2O emissions by 0.2 ± 4.9 percent. As in the case of no-till on cropland formerly under conventional tillage, the estimated percentage N_2O change selected for the calculation of avoided-emissions should be seen as what is now best available information, but probably without larger statistical significance. As in the case of no-till, it is intended for use in developing tentative results, with full understanding that the underlying database for analysis is inadequate and that much yet needs to be done for a sound understanding of N_2O response to tillage change to be developed.

Descriptive statistics are shown in Table 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 N_2O fluxes, do so on an annual basis is negative, but again the confidence intervals are wide.

Of the 27 empirical site studies reviewed, N_2O 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 N_2O 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 CO_2-equivalent tons.

Table 43. Descriptive statistics: Reduced tillage - N_2O [a]

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

[a] conventional tillage counterfactual

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

[c] 1 study reports multiple results by cover crop treatment

c. Methane

Tillage acts to disrupt methanotrophic communities that oxidize CH_4 to CO_2. With no-till, some recovery in rates of soil oxidation is evident, but with conversion from conventional tillage to reduced tillage, less so. It is thought that CH_4 oxidation in cropland soils is about one-third of that of undisturbed grassland soils (Aronson and Helliker, 2010; Aronson *et al*., 2013). It is also thought that recovery of soil CH_4 oxidizing capacity might take up to several hundred years after disruptions cease. (Allen *et al*., 2009)

The estimated annual change in soil CH_4 oxidation resulting from the use of reduced tillage practice in is small, a 52 CO_2-equivalent short ton decrease in oxidation (see Table 41). This was calculated using the average percent change in soil CH_4 oxidation from a single available meta-analysis with a change in upland soils from conventional tillage to reduced tillage. Formal meta-analysis is probably the most powerful tool now available for aggregating estimates across study types with differing designs. Baseline CH_4 oxidation rates in temperate cropland soils were taken from Aronson and Helliker (2010).

Using the single meta-analysis estimate, developed by Feng *et al*. (2018) using a global database, the use of reduced tillage practice on cropland formerly under conventional tillage is estimated to reduce CH_4 oxidation slightly, by 2.5 percent (see Table 44). In perusing the scientific literature, we also reviewed ten empirical site studies. Using the results from the empirical site studies, soil CH_4 uptake and oxidation might be expected to increase by 49 percent, but based on a very few number of studies showing widely scattered results (+217 to -50 percent change in soil CH_4 oxidation).

Table 44. Descriptive statistics: Reduced tillage - CH_4 [a]

	% change in oxidation per hectare	number of studies [b]	change in emissions, ratio positive-to-negative: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	-2.5%	1	0/1	NA	NA	NA
empirical site studies	49.2%	10	6/3/1	30%	-10%	109%

[a] conventional tillage counterfactual
[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_2O emissions from tillage change. No estimate is available for CH_4 oxidation in reduced tillage soils converted to no-till practice.

As of the last available tillage survey, six percent of Minnesota cropland was in no-till practice and 44 percent in some form of reduced tillage. (US Department of Agriculture, 2019) In 2016, an estimated 10 percent of cropland in the US lake States (Minnesota, Wisconsin, and Michigan) was in continuous no-till and 38 percent in continuous reduced tillage. (Baranski *et al*., 2018)

The estimated GHG emission-avoidance resulting from the conversion of cropland tillage from reduced tillage to no-till is shown in Table 45. From Table 45, an estimated 23,000 CO_2-equivalent short tons of emissions would be avoided from the conversion of 100,000 acres from reduced tillage to less impacting no-till. Of this, two-thirds is from enhanced carbon storage in no-till soils. Of the remainder, most of this is due to reduced direct N_2O soil emissions.

In quantifying avoided-emissions, we assumed that carbon stored in soils would remain there for 20 years, followed by microbial decomposition and emission to the atmosphere as CO_2. This is the longest period over which, in our opinion, sustained storage safely can be assumed. Under this assumption, avoided-emissions are estimated 23,000 CO_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_2-equivalent short tons. Had 100-year assured storage been assumed, avoided-emissions would have totaled 77,000 CO_2-equivalent short tons (again see Table 45).

Table 45. No-till tillage: Emissions-avoided [a]

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [b]	Counterfactual
N_2O-direct	soils	(8,260)	reduced tillage
N_2O-indirect volatilization	indirect emission-Nitrogen volatilization, redeposition	553	reduced tillage
N_2O-indirect leaching	indirect emission-Nitrogen leaching or runoff	-	reduced tillage
CH_4	soils	not known	reduced tillage
CO_2 [c,d]	carbon accumulation in soils	(13,575)	reduced tillage
CO_2	cultivated soils from lime or urea use	-	reduced tillage
GHGs-energy	fossil fuel and electricity use in crop production	(1,051)	reduced tillage
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(233)	reduced tillage
Total		**(22,565)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils			
40 year storage	all sources and sinks	**(36,140)**	reduced tillage
100 year storage	all sources and sinks	**(76,865)**	reduced tillage

[a] reduced tillage counterfactual

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

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

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

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

a. Carbon sequestration in soils

In Table 45, an estimate for annual carbon sequestration in cropland formerly under reduced tillage and converted to no-till of 14,000 short tons of CO_2 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, CO_2 is removed from the atmosphere and incorporated into the roots and aboveground live crop biomass and, eventually, into cropland litter and soils. This offsets emissions of CO_2 from 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]

	biogenic carbon sequestration (Mg C/ha/yr)	number of study results [c,d]	ratio of sequestration to emission: number of study results [e]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	0.22	103	79/23/1	0.07	0.09	0.35
empirical site studies	0.22	89	68/20/1	0.08	0.07	0.37
modeling studies	0.11	10	8/2	0.04	0.03	0.19
derivative statistical analyses or summaries	0.33	3	3/0	0.07	0.20	0.47
40 cm-plus soil sampling/modeling depth [b]	0.15	33	23/9/1	0.15	(0.14)	0.44
10 to 30 cm soil sampling/modeling depth [b]	0.22	58	44/14	0.08	0.06	0.37
10 to 20 year annual sequestration rate	0.09	40	32/8	0.10	(0.10)	0.28
20 to 30 year annual sequestration rate	0.26	14	10/3/1	0.13	0.01	0.51
0 to10 year annual sequestration rate	0.31	39	27/12	0.13	0.05	0.56

[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

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

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_2O emissions. Average Minnesota cropland N_2O emissions are from the MPCA Greenhouse Gas Inventory. To estimate the percentage change in N_2O emissions under no-till on cropland formerly in reduced tillage, we reviewed 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_2O 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_2O 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_2O 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_2O 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_2O to the atmosphere. Fewer upstream emissions from the out-of-state manufacture of synthetic fertilizer also result.

Table 47. Descriptive statistics: No-till tillage - N_2O [a]

	emissions: % change in emissions per hectare	number of study results [b,c]	change in emissions, ratio positive-to-negative: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	-12.9%	50	14/35/1	4.9%	-22.6%	-3.2%
modeling studies	-35.9%	4	0/4	11.4%	-58.2%	-13.6%
empirical site studies	-10.9%	46	13/32/1	5.1%	-20.9%	-0.9%
annual flux monitoring/modeling	-12.6%	23	6/16/1	8.0%	-28.3%	3.2%
growing season and subgrowing season flux monitoring/modeling	-10.7%	23	7/16	6.8%	-24.0%	2.6%
1 year of observations or simulations	-31.3%	15	2/13	6.2%	-43.5%	-19.0%
2 to 3 years of observations or simulations	1.2%	28	11/16/1	6.8%	-12.1%	14.5%
3 yrs-plus of observations or simulations	-31.2%	6	0/6	8.2%	-47.3%	-15.0%

[a] 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

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 48. Cropland to hayland: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(52,012)	crop production
N_2O-indirect volatilization	indirect emission-Nitrogen volatilization, redeposition	(2,107)	crop production
N_2O-indirect leaching	indirect emission-Nitrogen leaching or runoff	(11,703)	crop production
CH_4 [b]	soils	not known	crop production
CO_2 [c,d]	carbon accumulation in soils and biomass	(43,040)	crop production
CO_2	cultivated soils from lime or urea use	(2,786)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	3,681	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(13,373)	crop production
Total		**(121,339)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass			
40 year storage	all sources and sinks	**(164,379)**	crop production
100 year storage	all sources and sinks	**(293,501)**	crop production

[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]

Study	Type of study	CO_2-eq. short tons per acre per year	CO_2-eq. short tons per 100,000 acres per year
Barsottti *et al*. (2012)	site study	2.04	203,960
Gelford and Robertson (2015)	site study	0.37	36,796
Meyer-Aurich, et al. (2006)	site study	1.20	120,021
Robertson *et al*. (2000)	site study	0.37	37,465
Sulaiman *et al.* (2017) [b]	site study	2.98	298,381
Shafer and Thompson (2015)	modeling study	1.38	138,263
Eagle *et al*. (2012)	other derivative statistical analysis [c]	0.64	63,779
Swan *et al*. (2015) [b]	literature review/expert judgment	0.41	40,778
Sainju *et al*. (2016)	meta-analysis	0.66	66,411
This report	literature review	1.21	121,339

[a] results as reported w ithout adjustments

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

[c] other than formal meta-analyses

Biogenic carbon sequestration in soils from the conversion of cropland to hayland is discussed below, as are avoided direct emissions of N_2O from soils. Little is known about the effects of cropland to hayland conversion on CH_4 oxidation rates, although these effects are likely to be minor. The methods and sources used to estimate avoided indirect N_2O emissions from nitrate leaching and ammonia volatilization, avoided-emissions from fuel use, and avoided-emissions from foregone agricultural chemicals and fuels manufacture were discussed above in Section II, Subsection E.

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 CO_2-equivalent short tons was given for annual carbon sequestration on 100,000 acres of cropland converted to hayland. As discussed above, this was developed using an average rate of sequestration per acre, discounted to account for an assumed 20-year persistence time of newly stored carbon in soils and biomass. Since most of the science of terrestrial carbon sequestration is developed in metric units, this average annual rate is given first in metric tons of carbon per hectare (see Table 50 below) and converted to CO_2-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

	biogenic carbon sequestration (Mg C/ha/yr)	number of study results [c,d]	ratio of sequestration to emission: number of study results [e]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	0.68	36	33/3	0.17	0.35	1.02
derivative statistical analyses or statistical summaries [a]	1.30	3	3/0	1.08	(0.82)	3.42
empirical site studies	0.72	21	18/3	0.25	0.23	1.21
modeling studies	0.51	7	7/0	0.12	0.28	0.74
expert judgment/literature review	0.43	5	5/0	0.11	0.21	0.64
alfalfa	0.74	11	9/2	0.45	(0.14)	1.63
nonalfalfa perennial grasses	0.64	18	17/1	0.20	0.24	1.04
mix of alfalfa and nonalfalfa perennial grasses or unidentified	0.78	5	5/0	0.20	0.38	1.17
5 to 30 cm soil sampling/modeling depth [b]	0.63	15	13/2	0.24	0.15	1.11
>30 cm soil sampling/modeling depth [b]	0.44	6	5/1	0.56	(0.66)	1.54
1 to 10 year annual sequestration rate	0.12	9	7/2	0.31	(0.49)	0.73
10 to 20 year annual sequestration rate	0.85	7	6/1	0.52	(0.17)	1.87
20 to 30 yr annual sequestration rate	0.64	10	10/0	0.14	0.36	0.92

[a] statistical summaries or derivative statistical analysis other than meta-analyses
[b] results for lowest reported sampling depth
[c] 36 study results, 35 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

N_2O is produced in cropland during nitrification and denitrification by soil bacteria that oxidize ammonia or reduce nitrate to gain energy. The processes and environmental controls on N_2O production in 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.

N_2O emissions from the conversion of cropland to hayland are calculated as the difference between average annual cropland emissions, as developed using data from the MPCA greenhouse gas emission inventory, and emissions estimated for cropland soils converted to perennial grasses and alfalfa for harvest. Mean cropland N_2O emissions in Minnesota are, on an annual basis, an estimated 4.81 kilograms per hectare (4.29 lbs. N_2O per acre). From a 2017 meta-analysis, we estimate annual N_2O emissions of 1.89 kilograms per hectare (1.69 lbs. per acre) from soils in alfalfa or perennial grass. (See Table 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 N_2O emissions from hayland averaged 2.03 kilograms per hectare (1.81 lbs. N_2O 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 - N_2O

	emissions (kg N_2O/ hectare/yr)	number of study results [b,c]	ratio, positive to negative results: number of study results	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	1.89	1	1/0	NA	NA	NA
all studies	2.03	33	33/0	0.39	1.11	2.66
derivative statistical analyses or statistical summaries [a]	1.70	4	4/0	0.35	1.35	2.72
empirical site studies	1.22	20	20/0	0.30	1.12	2.28
modeling studies	3.56	8	8/0	1.36	(1.45)	3.90
alfalfa studies	1.75	17	17/0	0.29	2.99	4.13
other hay and grasses studies	2.77	10	10/0	1.18	0.82	5.46
fertilized grassland	3.14	10	10/0	1.12	(0.46)	3.95
annual flux monitoring/modeling	2.27	24	24/0	0.53	1.74	3.81
growing season flux monitoring/modeling	0.95	6	6/0	0.15	2.84	3.43
1-2 years of observations	2.40	13	13/0	0.93	0.44	4.10
3 years plus of observations	1.92	13	13/0	0.38	0.20	1.69

[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 aanlyses, 5 modeling studies, 19 empirical site studies)

[c] 4 studies report multiple results by forage type

By study type, in Table 51 N_2O 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 CO_2 removal from the atmosphere.

Additionally, the conversion of cropland to perennial grasses or alfalfa, even on a rotational basis, results in reduced synthetic nitrogen applications to cropland, hence reduced soil emissions of N_2O, as well as reduced downstream N_2O emissions from surface waters from nitrate leached from cropped soils. Reduced greenhouse gas emissions from the avoided manufacture of nitrogen fertilizer, other agricultural chemicals and fuels used in crop production also result.

With several years of perennial grasses or alfalfa added to annual rotations, soil carbon increases and N_2O emissions, during cultivation, as well as upstream and downstream of cultivation, decline, albeit to a lesser degree than in the complete conversion of cropland to hayland without interspersed years of annual crops.

Table 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 CO_2-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 N_2O from cropland soil and reduced indirect nitrate leaching-related emissions from surface waters. Reduced out-of-state emissions from the avoided manufacture of fertilizer and other agricultural chemicals also are important, accounting for about one-quarter of total avoided-emissions.

Table 52. Add a perennial grass to crop rotation: Emissions-avoided

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(2,897)	crop production
N_2O-indirect volatilization	indirect emission-Nitrogen volatilization, redeposition	(1,053)	crop production
N_2O-indirect leaching	indirect emission-Nitrogen leaching or runoff	(6,826)	crop production
CH_4	soils	not known	crop production
CO_2 [b,c]	carbon accumulation in soils and biomass	(32,490)	crop production
CO_2	cultivated soils from lime or urea use	(1,393)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	6,861	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(11,886)	crop production
Total		**(49,685)**	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass			
40 year storage	all sources and sinks	**(82,175)**	crop production
100 year storage	all sources and sinks	**(179,646)**	crop production

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

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

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

In this calculation, we assumed that biogenic carbon stored in cropland soils will persist in storage for 20 years, after which it will be reemitted to the atmosphere as CO_2. 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 CO_2-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 CO_2-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-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_2O 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

	biogenic carbon sequestration (Mg C/ha/yr)	number of study results [b,c]	ratio of sequestration to emission: number of study results [d]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	0.52	29	26/3	0.17	0.18	0.85
derivative statistical analyses or statistical summaries [a]	0.40	4	4/0	0.21	(0.02)	0.81
empirical site studies	0.71	16	13/3	0.30	0.11	1.30
modeling studies	0.22	6	6/0	0.05	0.12	0.32
expert judgment/literature reviews	0.27	3	3/0	0.12	0.04	0.50
alfalfa added to rotation	0.59	10	9/1	0.29	0.02	1.16
generic perennial added to rotation	0.51	4	4/0	0.19	0.14	0.87
other hay, unidentified hay or grass leys added to rotation	0.20	12	11/1	0.03	0.14	0.27
5 to 30 cm soil sampling/modeling depths	0.42	14	13/1	0.17	0.09	0.75
>30 cm soil sampling/modeling depths	0.42	8	6/2	0.26	(0.09)	0.93
1 to 10 year annual sequestration rate	1.93	3	3/0	1.22	(0.45)	4.31
10 to 30 year annual sequestration rate	0.53	12	11/1	0.24	0.06	0.99
>30 year sequestration rate	0.19	9	8/1	0.05	0.10	0.28

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

[b] 29 study results, 28 studies (4 statistical summaries or derivative statistical analyses, 5 modeling studies, 15 empirical site studies, 3 expert reviews, 1 modeling/empirical site study)

[c] 1 study reports multiple results by study type

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

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_2O 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 *et al*., 2015; Ellert and Janzen, 2008; MacKenzie *et al*., 1997; Osterholz *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 *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_2O 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 N_2O 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 N_2O 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 N_2O 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 N_2O 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 N_2O 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 - N_2O

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

[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 CO_2-equivalent short tons of greenhouse gases would be emitted annually, or 0.4 short CO_2-equivalent tons per acre. About 69,000 CO_2-equivalent short tons would be emitted from soils in the form of CO_2. A part of this emission would be offset by reductions in the direct emission of N_2O from soils, an estimated 11,000 CO_2-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. [12]

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

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(11,147)	crop production
N_2O-indirect volatilization	indirect emission-Nitrogen volatilization, redeposition	not known	crop production
N_2O-indirect leaching	indirect emission-Nitrogen leaching or runoff	not known	crop production
CH_4	soils	not known	crop production
CO_2 [b]	carbon accumulation in soils and biomass	69,182	crop production
CO_2	cultivated soils from lime or urea use	-	crop production
GHGs-energy	fossil fuel and electricity use in crop production	(909)	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(17,296)	crop production
Total		**39,830**	

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

[b] carbon accumulation in soils = net removal of CO_2 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 CO_2 to the atmosphere. Direct emissions of N_2O decline in a corn-soybean rotation due to zero or near-zero synthetic nitrogen requirements of soybeans and reduced synthetic nitrogen applications to corn.

Out of state emissions from fertilizer manufacture decline as nitrogen, fertilizer needs contract. Regarding CH_4 emissions and N_2O emissions downstream after nitrate leaching or ammonium volatilization, not enough is known to support an analysis of how emissions from these sources might change.

A number of estimates have been developed of the net change in greenhouse gas emissions resulting from use of a two-year corn-soybean rotation *in lieu* of corn following corn. These are shown below in Table 56 in CO_2-equivalent short tons per 100,000 acres. With one notable exception, they support a range of emissions increase of 21,000 to 78,000 short CO_2-equivalent tons for each 100,000 of conversions.

[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.

Table 56. Change in total greenhouse gases from conversion from continuous corn to corn-soybean rotation [a]

		emissions increase	
Study	**Type of study**	**CO_2-eq. short tons per acre per year**	**CO_2-eq. short tons per 100,000 acres per year**
Adviento-Borbe *et al*. (2007)	empirical site study	0.78	78,461
Archer and Halvorson (2010)	empirical site study	0.34	34,483
Doberman *et al*. (2007)	empirical site study	0.21	21,412
Mosier *et al*. (2005)	empirical site study	0.29	29,040
Mosier *et al*. (2006)	empirical site study	0.42	42,141
Robertson *et al*. (2011)	modeling study	(0.54)	(53,942)
Walters *et al*. (2007)	modeling study	0.47	47,208
Sainju *et al*. (2016)	meta-analysis	0.22	22,483
This report	literature review	0.40	39,830

[a] results as reported without adjustments

CO_2 emissions from cropland soils are discussed below, as are avoided direct emissions of N_2O from reduced mineral fertilizer needs under a two-year corn-soybean rotation. As noted just above, insufficient information is available to support an assessment of how soil CH_4 oxidation under continuous corn might change under a two-year corn-soybean rotation.

a. Carbon sequestration in soils

Crop residues contain substantial amounts of organic carbon in the form of biomass. After grain harvest, these are returned to the soil either as surface residues or, after incorporation, as buried crop residues. In soil in which the mass of soil organic carbon is stable, returned crop residues act to offset respiration losses of carbon. With reduced residue inputs to soils, a part of respiration losses are not offset, leading to a net loss of carbon from soils in the form of CO_2 emission to the atmosphere.

Soybeans produce substantially less crop residue than does corn, 60 to 70 percent less. Because of this, averaged over two years, a corn-soybean rotation produces and returns to soil 20 to 30 percent less biomass carbon than does continuous corn. (Gal *et al*., 2007; Pikul *et al*., 2008) As a result, soils under a two-year corn-soybean rotation lose soil organic carbon relative to soils under continuous corn, typically 0.1 to 0.3 short tons of carbon per acre per year. (West and Post, 2002; Pikul *et al*., 2008; Adviento-Borbe *et al*., 2007) Of this loss, most or all is incurred during the soybean year of the rotation, based on eddy covariance studies of net ecosystem carbon change under a corn-soybean rotation. (Baker and Griffis, 2005; Verma *et al*., 2005)

Generally, all other things being equal, soil organic carbon is positively correlated with residue returns to the soil, increasing linearly with residue return. (Clapp *et al*., 2000; Havlin *et al*., 1990; Huggins *et al*., 2007; Larson *et al*., 1972) Other factors that might play a role in the observed difference in soil organic carbon under continuous corn and the two–year corn-soybean rotation include possible decreased soil aggregation under the two year rotation and accelerated residue decomposition with high nitrogen soybean residues. (Coulter *et al*., 2009) With decreased soil aggregation, organic carbon in soils is less protected against microbial decomposition, leading to soil carbon loss. Soil aggregation is known to decline with decreased inputs of organic matter to soils. As discussed above in the cover crop section of this report (see Section IV, Subsection Ga), soil macroaggregates are bound together by organic acids and polymers derived from decomposing soil organic matter.

Soybean residues are rich in nitrogen, which, it is thought, promotes 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

	biogenic carbon sequestration (Mg C/ha/yr)	number of studies [c]	ratio of sequestration to emission: study numbers [d]	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	(0.42)	27	2/25	0.10	(0.62)	(0.22)
derivative statistical analyses or statistical summaries [a]	(0.19)	1	0/1	NA	NA	NA
empirical site studies	(0.48)	23	1/22	0.11	(0.70)	(0.26)
modeling studies	0.06	2	1/1	0.29	(0.50)	0.63
5 to 30 cm soil sampling/modeling depth [b]	(0.38)	18	1/17	0.09	(0.56)	(0.19)
> 30 cm soil sampling/modeling depth [b]	(0.64)	7	0/7	0.30	(1.22)	(0.06)
1 to 10 year annual sequestration rate	(0.59)	9	0/9	0.16	(0.90)	(0.28)
10 to 20 year annual sequestration rate	(0.40)	12	2/10	0.19	(0.78)	(0.02)
20 to 30 yr annual sequestration rate	(0.21)	7	0/7	0.04	(0.29)	(0.13)

[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. (Venterea and Coulter, 2015) Where N_2O emissions do not decline with a change to a corn-soybean rotation, this is sometimes attributed to the effect of confounding influences. (Decock, 2014) Where soil fertilization is a dominant control on N_2O emissions, this control is substantially modulated by the influence of soil qualities like soil texture, clay content, water-holding capacity, aeration and SOC content, as well as weather and weather events, particularly in relation to fertilization events. At any one site in any one year, these influences can overwhelm the influence of nitrogen fertilizer on observed N_2O emissions.

From Table 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 58, 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 - N_2O

	emissions: % change in emissions per hectare	number of studies [a]	change in emissions, ratio positive-to-negative: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	-17%	17	4/13	8%	-34%	-1%
meta-analysis	-2%	1	0/1	NA	NA	NA
empirical site studies	-21%	15	3/12	9%	-38%	-3%
modeling studies	15%	1	1/0	NA	NA	NA
annual flux monitoring/modeling	16%	6	4/2	14%	-11%	43%
growing season flux monitoring/modeling	-41%	10	0/10	5%	-50%	-31%
1 to 2 yrs of observations	-8%	7	2/5	18%	-45%	28%
3 years-plus of observations	-22%	8	2/6	9%	-41%	-4%

[a] 17 studies, 17 study results

Also troubling is the mean percent change estimated for studies that give results on an annual basis, rather than growing season basis. The number of studies is quite small, and if we limit the population of studies to empirical site studies, is but four studies. While this is far too few studies to conclude anything, particularly with respect to notoriously variable N_2O emissions estimates, the anomalous increase in N_2O emissions in these studies argues for caution. Clearly a good many more empirical studies of this question are required for a more certain quantitative estimate of response of N_2O emissions to rotation change.

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 *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 CO_2 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 CO_2. 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 result 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 N_2O emissions as a result.

GHG emissions rise substantially with continuously inundated constructed and restored wetlands. Wetlands of any type are CH_4 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 question 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

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils or sediments	(4,856)	crop production
N_2O-indirect volatilization	indirect emission-Nitrogen volatilization, redeposition	(2,169)	crop production
N_2O-indirect leaching	indirect emission-Nitrogen leaching or runoff	(7,186)	crop production
CH_4	soils or sediments	218,640	crop production
CO_2 [b]	carbon accumulation in wetland sediments and biomass	(109,022)	crop production
CO_2	cultivated soils from lime or urea use	(2,808)	crop production
GHGs-energy	fossil fuel and electricity use in crop production	(6,892)	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	(20,190)	crop production
Total		**65,517** [c]	
Emissions with Alternative Number of Years of Assumed Carbon Storage in Soils and Biomass			
40 year storage	all sources and sinks	**(43,505)**	crop production
100 year storage	all sources and sinks	**(370,571)**	crop production

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

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

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

Table A2. Descriptive statistics: Constructed and restored wetlands – carbon sequestration in soils and biomass

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

[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 – CH_4

	emissions (kg CH_4/ hectare/yr) [a]	number of studies	ratio, positive to negative results: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses and other derivative statistical analyses or statistical summaries [b]	194	8	8/0	30.76	134	254
all studies	301	81	79/2	40.00	223	380
empirical site studies	278	66	64/2	39.69	200	356
eddy covariance site studies	375	12	12/0	83.80	211	540
other site studies	253	52	50/2	46.34	162	344
modeling studies	100	1	1	NR	NR	NR
annual flux monitoring/modeling	379	50	49/1	53.47	274	484
growing season and subgrowing season flux monitoring/modeling	195	33	32/1	56.22	47	343
constructed wetlands studies	395	29	29/0	75.56	308	483
restored wetlands studies	250	52	50/2	44.68	162	337
1 year of observations or simulations	357	33	32/1	74.47	211	503
> 1 year of observations or simulations	283	25	24/1	71.77	142	424
1 to 9 year old constructed/restored wetlands	178	29	27/2	42.02	96	260
10 year old-plus constructed/restored wetlands	365	40	40/0	62.29	243	487
studies with pre-restoration counterfactual	170	23	21/2	67.09	41	299

[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_2O

	emissions (kg N_2O/ hectare/yr) [a]	number of studies	ratio, positive to negative results: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	0.0020	31	31/0	1.31	1.87	7.01
empirical site studies	0.0017	26	26/0	1.31	1.28	6.40
derivative statistical analyses or statistical summaries [b]	0.0000	1	1/0	NA	NA	NA
constructed wetlands	0.0036	10	10/0	2.68	2.81	13.32
restored wetlands	0.0012	21	21/0	1.34	0.08	5.35
1 to 9 year old constructed/restored wetlands	0.0027	13	13/0	2.42	1.26	10.74
10 year old-plus constructed/restored wetlands	0.0036	14	14/0	2.13	3.98	12.34
growing season and subgrowing season flux monitoring/modeling	0.0010	16	16/0	2.06	(1.72)	6.34
annual flux monitoring/modeling	0.0023	12	12/0	2.09	1.06	9.24
1 year of observations or simulations	0.0024	16	16/0	1.85	1.69	8.93
>1 year of observations or simulations	0.0021	13	13/0	2.15	0.47	8.91
studies with cropland counterfactuals	(0.0010)	7	1/5/1	1.92	(6.08)	1.43

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

[b] derivative statistical studies other than meta-analyses

Appendix B. Biochar

Table B1. Biochar: Emissions-avoided [a]

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(17,996)	crop production
N_2O-indirect volatilization	indirect emission-Nitrogen volatilization, redeposition	(325)	crop production
N_2O-indirect leaching	indirect emission-Nitrogen leaching or runoff	(5,174)	crop production
CH_4	soils	(572)	crop production
CO_2	carbon accumulation in soils	(138,936)	crop production
CO_2	cultivated soils from lime or urea use	-	crop production
GHGs-energy	fossil fuel and electricity use in crop production	13,224	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	2,929	crop production
In-State Upstream GHGs		27,136	
Total		**(119,713)**	

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

Table B2. Descriptive statistics: Biochar - carbon sequestration in soils

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

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

Table B3. Descriptive dtatistics: Biochar – N_2O

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

Table B4. Descriptive statistics: Biochar – CH_4

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

Appendix C. Split fertilizer application

Table C1. Split fertilizer application: Emissions-avoided [a]

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres) [a]	Counterfactual
N_2O-direct	soils	(13,125)	single application
N_2O-indirect volatilization	indirect emission-Nitrogen volatilization, redeposition	108	single application
N_2O-indirect leaching	indirect emission-Nitrogen leaching or runoff	(1,006)	single application
CH_4	soils	not known	single application
CO_2	carbon accumulation in soils	-	single application
CO_2	cultivated soils from lime or urea use	-	single application
GHGs-energy	fossil fuel and electricity use in crop production	568	single application
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	-	single application
Total		**(13,455)**	

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

Table C2. Descriptive statistics: Split fertilizer application - N_2O

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

Table C3. Descriptive statistics: Split fertilizer application - CH_4

	emissions: % change in emissions per hectare	number of studies	change in emissions, ratio positive-to-negative: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	-4%	8	3/5	9%	-22%	14%

Appendix D. Subsurface fertilizer placement

Table D1. Subsurface fertilizer placement: Emissions-avoided [a]

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres) [a]	Counterfactual
N_2O-direct	soils	36,750	surface or shallow fertilizer placement
N_2O-indirect	redeposition	(1,187)	fertilizer placement
N_2O-indirect leaching	indirect emission-Nitrogen leaching or runoff	(4,999)	surface or shallow fertilizer placement
CH_4	soils	not known	surface or shallow fertilizer placement
CO_2	carbon accumulation in soils	-	surface or shallow fertilizer placement
CO_2	cultivated soils from lime or urea use	-	surface or shallow fertilizer placement
GHGs-energy	fossil fuel and electricity use in crop production	405	surface or shallow fertilizer placement
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	90	surface or shallow fertilizer placement
Total		**31,060**	

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

Table D2. Descriptive statistics: Subsurface fertilizer placement – N_2O

	emissions: % change in emissions per hectare	number of studies	change in emissions, ratio positive-to-negative: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	58%	7	5/2	37%	-15%	130%
meta-analyses (synthetic nitrogen-only)	10%	2	1/1	20%	-29%	49%
empirical site studies	61%	53	38/15	18%	25%	97%
modeling studies	21%	5	4/1	20%	-19%	61%
expert judgment/literature reviews	100%	1	1/0	NA	NA	NA
synthetic nitrogen	30%	35	22/13	16%	-1%	61%
manure nitrogen	125%	25	23/2	33%	60%	189%
conventional tillage	99%	13	8/5	66%	-30%	227%
reduced tillage	26%	7	5/2	14%	-1%	53%
no till tillage	7%	12	7/5	12%	-17%	30%
surface versus deep application	78%	52	40/12	20%	40%	117%
shallow versus deep application	21%	18	13/5	11%	1%	42%
annual flux monitoring/modeling	41%	16	11/5	17%	7%	74%
growing season and subgrowing season flux monitoring/modeling	75%	43	33/10	23%	30%	121%

Table D3. Descriptive statistics: Subsurface fertilizer placement – CH_4

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

Appendix E. Spring fertilizer placement

Table E1. Spring fertilizer application: Emissions-avoided [a]

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres) [a]	Counterfactual
N_2O-direct	soils	2,236	crop production
N_2O-indirect	redeposition	116	crop production
N_2O-indirect leaching	indirect emission-Nitrogen leaching or runoff	(237)	crop production
CH_4	soils	not known	crop production
CO_2	carbon accumulation in soils	-	crop production
CO_2	cultivated soils from lime or urea use	-	crop production
GHGs-energy	fossil fuel and electricity use in crop production	-	crop production
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	-	crop production
Total		2,115	

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

Table E2. Descriptive statistics: Spring fertilizer application - N_2O

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

Appendix F. Controlled release fertilizers

Table F1. Controlled release fertilizers: Emissions-avoided [a]

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(21,152)	urea
N_2O-indirect	redeposition	(1,475)	urea
N_2O-indirect leaching	indirect emission-Nitrogen leaching or runoff	(4,743)	urea
CH_4	soils	not known	urea
CO_2	carbon accumulation in soils	-	urea
CO_2	cultivated soils from lime or urea use	-	urea
GHGs-energy	fossil fuel and electricity use in crop production	-	urea
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	-	urea
Total		(27,369)	

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

Table F2. Descriptive statistics: Controlled release fertilizer - N_2O

	emissions: % change in emissions per hectare	number of studies	change in emissions, ratio positive-to-negative: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses	-33%	9	0/9	10%	-53%	-13%
modeling studies	-7%	1	0/1	NA	NA	NA
empirical site studies	-10%	54	15/39	8%	-26%	6%
surface nitrogen application	6%	18	5/13	16%	-25%	38%
subsurface nitrogen application	-6%	23	9/14	12%	-34%	22%
single nitrogen application	6%	29	11/18	13%	-18%	31%
split nitrogen application	-23%	16	4/15	10%	-43%	-3%
<1 to 2 years of observations or simulations	-1%	32	12/20	11%	-22%	19%
3 years-plus of observations or simulations	-13%	2,120	3/18	12%	-36%	10%
annual flux monitoring/modeling	2%	11	4/7	17%	-31%	35%
growing season and subgrowing season flux monitoring/modeling	-13%	44	12/32	9%	-31%	5%

Table F 3. Descriptive statistics: Controlled release fertilizer – CH_4

	emissions: % change in emissions per hectare	number of studies	change in emissions, ratio positive-to-negative: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
all studies	44%	7	3/4	107%	-165%	253%

Appendix G. Nitrification and urease inhibitors

Table G1. Nitrification and urease inhibitors: Emissions-avoided [a]

Greenhouse Gas	Emission Source or Sink	Emission (CO_2-e short tons per 100,000 acres per year) [a]	Counterfactual
N_2O-direct	soils	(20,415)	no inhibitors
N_2O-indirect	redeposition	(995)	no inhibitors
N_2O-indirect leaching	indirect emission-Nitrogen leaching or runoff	(2,012)	no inhibitors
CH_4	soils	(612)	no inhibitors
CO_2	carbon accumulation in soils	-	no inhibitors
CO_2	cultivated soils from lime or urea use	-	no inhibitors
GHGs-energy	fossil fuel and electricity use in crop production	-	no inhibitors
Out-of-State Upstream GHGs	upstream agricultural chemicals and fossil fuel production	-	no inhibitors
Total		**(24,033)**	

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

Table G2. Descriptive statistics: Nitrification and urease inhibitors - N_2O

	emissions: % change in emissions per hectare or acre	number of studies	change in emissions, ratio positive-to-negative: study numbers	standard error of mean (+/-)	lower 95% confidence interval	upper 95% confidence interval
meta-analyses and other derivative statistical studies	-32%	23	2/21	5%	-41%	-23%
empirical site studies	-31%	130	18/112	2%	-35%	-26%
modeling studies	-17%	4	0/4	9%	-35%	2%
expert judgment/literature reviews	-26%	4	0/4	7%	-40%	-12%
nitrification inhibitors	-39%	88	5/83	3%	-44%	-34%
urease inhibitors	-15%	28	8/20	5%	-25%	-4%
nitrification plus urease inhibitors	-24%	42	6/36	3%	-30%	-18%
synthetic nitrogen	-28%	108	16/91/1	3%	-33%	-23%
manure/urine nitrogen	-36%	36	2/34	3%	-42%	-29%
surface nitrogen application	-33%	71	9/62	4%	-40%	-26%
subsurface nitrogen application	-27%	27	4/22/1	4%	-35%	-18%
growing season and subgrowing season flux monitoring/modeling	-31%	86	9/77	3%	-37%	-26%
annual flux monitoring/modeling	-25%	43	9/34	3%	-31%	-20%

Table G 3. Descriptive statistics: Nitrification and urease inhibitors – CH_4

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

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

Avoided-emissions = N_2O emissions from cropland fertilizer use * -0.15

Endnotes

K. Abdalla, *et al*., "No-tillage Lessens Soil CO_2 Emissions under Arid and Sandy Soil Conditions: Results from a Meta-Analysis," *Biogeosciences 13* (2016): 3,619-3,633

M. Abdalla, *et al*., "Critical Review of the Impacts of Cover Crops on Nitrogen Leaching, Net Greenhouse Gas Balance and Crop Productivity," *Global Change Biology 25* (2019): 2,530-2,543

M. Adviento-Borbe, *et al*., "Soil Greenhouse Gas Fluxes and Global Warming Potential in Four High-Yielding Maize Systems," *Global Change Biology 13* (2007): 1,972-1,988

M. Al-Kaisi, *et al*. "Soil Carbon and Nitrogen Changes as Affected by Tillage System and Crop Biomass in a Corn-Soybean Rotation," *Applied Soil Ecology 30* (2005): 174-191

M. Al-Kaisi, *et al*., "Tillage and Crop Rotation Effects on Corn Agronomic Response and Economic Return at Seven Iowa Locations," *Agronomy Journal 107* (2015): 1,411-1,424

D. Allen, *et al*., "Nitrous Oxide and Methane Emissions from Soil are Reduced Following Afforestation of Pastureland in Three Contrasting Climatic Zones," *Australian Journal of Soil Research 47* (2009): 443-458

R. Allmaras, *et al*., "Corn-Residue Transformations into Root and Soil Carbon as Related to Nitrogen, Tillage, and Stover Management," *Soil Science Society of America Journal 68* (2004): 1,366-1,375

F. Alluvione, *et al.* "Nitrogen Tilllage and Crop Rotation Effects on Carbon Dioxide and Methane Fluxes from Irrigated Cropping Systems," *Journal Environmental Quality 38* (2009): 2,023-2,033

J. Almaraz, *et al*., "Carbon Dioxide and Nitrous Oxide Fluxes in Corn Grown under Two Tillage Systems in Southwestern Quebec," *Soil Science Society of America Journal 73* (2009): 113-119

R. Alvarez, "A Review of Fertilizer and Conservation Tillage Effects on Soil Organic Carbon Storage," *Soil Use and Management 21* (2005): 38-52

J. Alvaro-Fuentes, *et al*., "Tillage Effects on Soil Organic Carbon Fractions in Mediterranean Dryland Agroecosystems," *Soil Science Society of America Journal 72* (2008): 541-547

C. Amadi*, et al*., "Greenhouse Gas Mitigation Potential of Shelterbelts: Estimating Farm-Scale Emission Reductions Using the Holos Model," *Canadian Journal of Soil Science 97* (2017): 353-367

P. Ambus and S. Christensen, "Spatial and Seasonal Nitrous Oxide Fluxes in Danish Forest, Grassland, and Agroecosystems," *Journal of Environmental Quality 24* (1995): 993-1,001

B. Amichev, *et al*., "Carbon Sequestration by White Spruce Shelterbelts in Saskatchewan, Canada: 3PG and CBM-CFS3 Model Simulations," *Ecological Modeling 325* (2016): 35-46

B. Amichev, et *al.*, "Carbon Sequestration and Growth of Six Common Tree and Shrub Shelterbelts in Saskatchewan, Canada," *Canadian Journal of Soil Science 97* (2017): 368-381

J. Anderson, *et al*., *The Potential for Terrestrial Carbon Sequestration in Minnesota: A Report to the Department of Natural Resources from the Minnesota Terrestrial Carbon Sequestration Initiative*, University of Minnesota, February 2008

D. Angers and N. Eriksen-Hamel, "Full Inversion Tillage and Organic Carbon Distribution in Soil Profiles: A Meta-analysis," *Soil Science Society of America Journal 72* (2008): 1,370-1,374

D. Angers, *et al*., "Dynamics of Soil Organic Matter and Corn Residues Affected by Tillage Practices," *Soil Science Society of America Journal 59* (1995): 1,311-1,315

D. Archer and A. Halvorson, "Greenhouse Gas Mitigation Economics for Irrigated Cropping System in Northeastern Colorado," *Soil Science Society of America Journal 74* (2010): 446-452

E. Aronson and B. Helliker, "Methane Flux in Non-Wetland Soils in Response to Nitrogen Addition: A Meta-Analysis," *Ecology 9* (2010): 3,242-3,251

E. Aronson, *et al*. (2013) "Environmental Impacts on the Diversity of Methane-Cycling Microbes and Their Resultant Function," *Frontiers in Microbiology* vol 4, article 225. Doi:10.3389/fmicb.2013.00225

E. Austin, *et al*., "Cover Crop Root Contributions to Soil Carbon in a No-Till Corn Bioenergy Cropping System," *Global Change Biology-Bioenergy 9* (2017): 1,252-1,263

E. Baggs., *et al.,* "The Fate of Nitrogen from Incorporated Cover Crop and Green Manure Residues," *Nutrient Cycling in Agroecosystems 56* (2000): 153-163

Z. Bai, *et al*., "Effects of Agricultural Management Practices on Soil Quality: A Review of Long-term Experiments for Europe and China," *Agriculture, Ecosystems and Environment 265* (2018): 1-7

J. Baker and T. Griffis, "Examining Strategies to Improve the Carbon Balance of Corn-Soybean Agriculture Using Eddy Covariance and Mass Balance Techniques," *Agricultural and Forest Meteorology 128* (2005): 163-177

J. Balesdent, *et al*., “Effect of Tillage on Soil Organic Carbon Mineralization Estimated from ^{13}C Abundance in Maize Fields,” *Journal of Soil Science 41* (1990): 587-596

J. Balesdent, *et al*., “Relationship of Soil Organic Matter Dynamics to Physical Protection and Tillage,” *Soil and Tillage Research 53* (2000): 215-230

B. Ball, *et al*., "Seasonal Nitrous Oxide Emissions from Field Soils under Reduced Tillage, Compost Application or Organic Farming," *Agriculture, Ecosystems and Environment 189* (2014): 171-180

M. Baranski, *et al*., *Agricultural Conservation on Working Lands: Trends from 2004 to Present*, Technical Bulletin 1950, Office of the Chief Economist, US Department of Agriculture, November 2018, 127 pages.

J. Barsotti, *et al*., "Net Greenhouse Gas Emissions Affected by Sheep Grazing in Dryland Cropping Systems," *Soil Science Society of America Journal 77* (2012): 1,012-1,025

A. Basche, *et al*., "Do Cover Crops Increase or Decrease Nitrous Oxide Emissions? A Meta-Analysis," *Journal of Soil and Water Conservation 69* (2014): 471-481

A. Basche, *et al*., "Simulating Long-term Impacts of Cover Crops and Climate Change on Crop Production and Environmental Outcomes in the Midwestern United States," *Agriculture, Ecosystems and Environment 218* (2016): 95-106

C. Bayer, *et al*., “Methane Emissions from Soil under Long-Term No-Till Cropping Systems,” *Soil and Tillage Research 124* (2012): 1-7

C. Bayer, *et al*., “Soil Nitrous Oxide Emissions as Affected by Long-term Tillage, Cropping Systems and Nitrogen Fertilization in Southern Brazil,” *Soil and Tillage Research 46* (2015): 213-222

G. Behnke, *et al*., "Long-term Crop Rotation and Tillage Effects on Soil Greenhouse Gas Emissions and Crop Production in Illinois, USA," *Agriculture, Ecosystems and Environment 261* (2018): 62-70

L. Bell, *et al*., "Soil Profile Carbon and Nutrient Stocks under Long-term Conventional and Organic Crop and Alfalfa Crop-rotations and Re-established Grassland," *Agriculture, Ecosystems and Environment 158* (2012): 156-163

M. Benoit, *et al*., "Nitrous Oxide Emissions and Nitrate Leaching in an Organic and a Conventional Cropping System (Seine Basin, France)," *Agriculture, Ecosystems and Environment 213* (2015): 131-141

P. Bierman, *et al*., “Survey of Nitrogen Fertilizer Use on Corn in Minnesota,” *Agricultural Systems 109* (2012): 42-53

H. Blanco-Canqui, *et al*., “Addition of Cover Crops Enhances No-Till Potential for Improving Soil Physical Properties,” *Soil Science Society of America Journal 75* (2011): 1,471-1,481

H. Blanco-Canqui, *et al*., "Soil Carbon Accumulation under Switchgrass barriers," *Agronomy Journal 106* (2014): 2,185-2,192

H. Blanco-Canqui, *et al*., “Cover Crops and Ecosystem Services: Insights from Studies in Temperate Soils,” *Agronomy Journal 107* (2015): 2,449-2,474

A. Bouwman, *et al*., “A Global High-Resolution Emission Inventory for Ammonia,” *Global Biogeochemical Cycles 11* (1997): 561-587

N. Brouchard, *et al*., "The Capacity of Vegetative Filter Strips and Swales to Sequester Carbon," *Ecological Engineering 54* (2013): 227-232

D. Butman, *et al*., "Aquatic Carbon Cycling in the Coterminous United States and Implications for Terrestrial Carbon Accounting," *Proceedings of the National Academy of Sciences 113* (2016): 58-63

G. Camargo, *et al*., “Energy Use and Greenhouse Gas Emissions from Crop Production Using the Farm Energy Analysis Tool,” *Bioscience 63* (2013): 263-273

C. Cambardella, *et al*., “Soil Carbon Sequestration in Central US Agroecosystems, chapter 4 in M. Liebig, *et al*., eds., *Managing Agricultural Greenhouse Gases* (Amsterdam: Elsevier Publisher, 2012), pp. 41-58

A. Chambers, *et al*., "Soil Carbon Sequestration Potential of US Croplands and Grasslands: Implementing the 4 per Thousand Initiative," *Journal of Soil and Water Conservation 71* (2016): 68A-74A

C. Clapp, *et al*., "Soil Organic Carbon and ^{13}C Abundance as Related to Tillage, Crop Residue, and Nitrogen Fertilization under Continuous Corn Management in Minnesota," *Soil and Tillage Research 55* (2000): 127-142

D. Clay, *et al*., “Tillage and Corn Residue Harvesting Impact Surface and Subsurface Carbon Sequestration,” *Journal of Environmental Quality 44* (2015): 803-809

R. Conant, *et al*., “Impacts of Periodic Tillage on Soil C Stocks: A Synthesis,” *Soil and Tillage Research 95* (2007): 1-10

R. Conant, *et al*., "Grassland Management Impacts on Soil Carbon Stocks: A New Synthesis," *Ecological Applications 27* (2017): 662-668

K. Congreves, *et al*., "Soil Organic Carbon and Land Use: Processes and Potential in Ontario’s Long-term Agro-Ecosystem Research Sites," *Canadian Journal of Soil Science 94* (2014): 317-336

J. Coulter, *et al*., "Soil Organic Matter Response to Cropping System and Nitrogen Fertilization," *Agronomy Journal 101* (2009): 592-599

R. Dalal and D. Allen, "Greenhouse Gas Fluxes from Natural Systems," *Australian Journal of Botany 56* (2008): 396-407

M. David, *et al*., “Modeling Denitrification in a Tile-Drained, Corn and Soybean Agroecosystem of Illinois,” *Biogeochemistry 93* (2009): 7-30

E. Davidson and I. Ackerman, “Changes in Soil Carbon Inventories Following Cultivation of Previously Untilled Soils,” *Biogeochemistry 20 (*1993): 161-193

E. Davidson, “Fluxes of Nitrous Oxide and Nitric Oxide from Terrestrial Ecosystems,” in J. Rogers and W. Whitman, eds., *Microbial Production and Consumption of Greenhouse Gases: Methane, Nitrogen Oxides and Halomethanes* (Washington, D.C.: American Society of Microbiology, 1991), pp. 219-235

C. Decock, "Mitigating Nitrous Oxide Emissions from Corn Cropping Systems in the Midwestern US: Potential and Data Gaps," *Environmental Science and Technology 48* (2014): 4,247-4,256

W. Deen and P. Kataki, "Carbon Sequestration in a Long-term, Conventional versus Conservation Tillage Experiment," *Soil and Tillage Research 74* (2003): 143-150

S. DeGryze, *et al*., “Assessing the Potential for Greenhouse Gas Mitigation in Intensively Managed Annual Cropping Systems at the Regional Scale,” *Agriculture, Ecosystems and Environment 144* (2010): 150-158

S. DeGryze, *et al*., “Simulating Greenhouse Gas Budgets of Four California Cropping Systems under Conventional and Alternative Management,” *Ecological Applications 20* (2010): 1,805-1,819

S. Del Grosso, *et al*., "Simulated Effects of Dryland Cropping Intensification on Soil Organic Matter and Greenhouse Gas Exchanges Using the DAYCENT Ecosystem Model," *Environmental Pollution 116* (2002): S75-S83

S. Del Grosso, *et al*., "DAYCENT Model Analysis of Past and Contemporary Soil N_2O and Net Greenhouse Gas Flux for Major Crops in the USA," *Soil and Tillage Research 83* (2005): 9-24

L. Dendooven, *et al*., “Global Warming Potential of Agricultural Systems with Contrasting Tillage and Residue Management in the Central Highlands of Mexico,” *Agriculture, Ecosystems and Environment 152* (2012): 50-58

K. Denef, *et al*., "Carbon Sequestration in Microaggregates of No-Tillage Soils with Different Clay Mineralogy," *Soil Science Society of America Journal 68* (2004): 1,935-1,944

R. Desjardins, *et al*., "Management Strategies to Sequester Carbon in Agricultural Soils and to Mitigate Greenhouse Gas Emissions," *Climatic Change 70* (2005): 283-297

B. Dimassi, *et al*., "Changes in Soil Carbon and Nitrogen Following Tillage Conversion in a Long-term Experiment in Northern France," *Agriculture, Ecosystems and Environment 169* (2013): 12-20

B. Dimassi, *et al*., "Long-term Effect of Contrasted Tillage and Crop Management on Soil Carbon Dynamics during 41 years," *Agriculture, Ecosystems and Environment 188* (2014): 134-146

A. Dobermann, *et al*., "Global Warming Potential of High Yielding Continuous Corn and Corn-Soybean Systems," *Better Crops 91* (2007): 16-19

M. Dolan, *et al*., "Soil Organic Carbon and Nitrogen in a Minnesota Soil as Related to Tillage, Residue and Nitrogen Management," *Soil and Tillage Research 89* (2006): 221-231

A. Don, *et al*., “Conversion of Cropland into Grassland: Implications for Soil Organic-Carbon Stocks in Two Sols with Different Texture,” *Journal of Plant Nutrition 172* (2009): 53-62

C. Drury, *et al*., "Nitrous Oxide and Carbon Dioxide Emissions from Monoculture and Rotational Cropping of Corn, Soybeans and Winter Wheat," *Canadian Journal of Soil Science 88* (2008): 163-174

Z. Du, *et al*., "The Effect of No-Till on Organic C Storage in Chinese Soils Should not be Overemphasized: A Meta-Analysis," *Agriculture, Ecosystems and Environment 236* (2017): 1-11

A. Dunmola, *et al*., "Pattern of Greenhouse Gas Emissions from a Prairie Pothole Agricultural Landscape in Manitoba, Canada," *Canadian Journal of Soil Science 90* (2010): 243-256

L. Dutaur and L. Verchott, "A Global Inventory of the Soil CH_4 Sink," *Global Biogeochemical Cycles 21* (2007): 1-9

K. Dybala, *et al*., "Carbon Sequestration in Riparian Forests: A Global Synthesis and Meta-analysis," *Global Change Biology 25* (2019: 57-67

A. Eagle, *et al*., *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States: A Synthesis of the Literature*, 3rd edition, Nicholas Institute, Duke University, January 2012

B. Ellert and H. Janzen, "Nitrous Oxide, Carbon Dioxide and Methane Emissions from Irrigated Cropping Systems as Influenced by Legumes, Manure and Fertilizer," *Canadian Journal of Soil Science 88* (2008): 207-217

M. Eve, *et al*., "Predicted Impact of Management Changes on Soil Carbon Storage for Each Cropland Region of the Coterminous United States," *Journal of Soil and Water Conservation 57* (2002): 196-204

P. Falloon, *et al*., "Managing Field Margins for Biodiversity and Carbon Sequestration: A Great Britain Case Study," *Soil Use and Management 20* (2004): 240-247

J. Fargione, *et al*. (2018) “Natural Climate Solutions for the United States,” *Science Advances.* 4. eaat1869. DOI: 10.1126/sciadv.aat1869

J. Feng, *et al*. (2018) "Impact of Agronomy Practices on the Effects of Reduced Tillage Systems on CH_4 and N_2O Emissions from Agricultural Fields: A Global Meta-analysis," *PLoS ONE* 13(5): e0196703. https//doi,org/10.1371/journal.pone.0196703

K. Fisher, *et al*., "Nitrous Oxide Emission from Cropland and Adjacent Riparian Buffers in Contrasting Hydrogeomorphic Settings," *Journal of Environmental Quality 43* (2014): 338-348

S. Fisher and R. Moore, 2007 *Tillage Transect Survey. Final Report*, Water Resources Center, University of Minnesota Mankato, October 2008

C. Fissore, *et al*., "Limited Potential for Terrestrial Carbon Sequestration to Offset Fossil-Fuel Emissions in the Upper Midwestern USA," *Frontiers in Ecology and the Environment 8* (2010): 409-413

R. Follett, *et al*., “The Potential of US Grazing Land to Sequester Soil Carbon,” in R. Follett, *et al*., eds., *The Potential of US Grazing Lands to Sequester Carbon and to Mitigate the Greenhouse Effect*, chapter 16 (Boca Raton, Florida: CRC Press, 2001), pp. 401-431

R. Follett, “US Agriculture’s Relationship to Soil Carbon,” *Journal of Soil and Water Conservation 64* (2009): 159A-165A

J. Fortier, *et al*., "Biomass Carbon, Nitrogen and Phosphorus Stocks in Hybrid Poplar Buffers, Herbaceous Buffers and Natural Woodlots in the Riparian Zone on Agricultural Land," *Journal of Environmental Management 154* (2015): 333-345

A. Gal, *et al*., "Soil Carbon and Nitrogen Accumulation with Long-term No-Till versus Moldboard Plowing Overestimated with Tilled-Zone Sampling Depths," *Soil and Tillage Research 96* (2007): 42-51

Y. Gan, *et al*., "Strategies for Reducing the Carbon Footprint of Field Crops for Semiarid Areas. A Review," *Agronomy for Sustainable Development 31* (2011): 643-656

Y. Gan (2014) "Improving Farming Practices Reduces the Carbon Footprint of Spring Wheat Production," *Nature Communications 5*, 5012. doi:10.1038/ncomms6012

I. Gelfand and G. Robertson, "Mitigation of Greenhouse Gases in Agricultural Ecosystems," in S. Hamilton, *et al*., eds., *The Ecology of Agricultural Landscapes: Long-term Research on the Path to Sustainability* (New York: Oxford University Press, 2015) pp. 310-339

I. Gelfand, *et al*., "Carbon Debt of Conservation Reserve Program (CRP) Grasslands Converted to Bioenergy Production," *Proceedings of the National Academy of Sciences 108* (2011): 13,864-13,869

I. Gelfand, *et al*., "Long-term Nitrous Oxide Fluxes in Annual and Perennial Agricultural and Unmanaged Ecosystems in the Upper Midwest, USA," *Global Change Biology 22* (2016): 3,594-3,607

K. Gillette, *et al*., "N Loss to Drain Flow and N_2O Emissions from a Corn-Soybean Rotation with Winter Rye," *Science of the Total Environment 618* (2018): 982-997

J. Gomes, *et al*., "Soil Nitrous Oxide Emissions in Long-term Cover Crop-based Rotations under Subtropical Climate," *Soil and Tillage Research 106* (2009): 36-44

B. Govaerts, *et al*., "Conservation Agriculture and Soil Carbon Sequestration: Between Myth and Farmer Reality," *Critical Reviews in Plant Science 28* (2009): 97-122

B. Grant, *et al*., "Estimated N_2O and CO_2 Emissions as Influenced by Agricultural Practices in Canada," *Climatic Change 65* (2004): 315-332

E. Gregorich, *et al*., "Tillage Effects on N_2O Emissions from Soils under Corn and Soybeans in Eastern Canada," *Canadian Journal of Soil Science 88* (2008): 153-161

E. Gregorich, *et al*., "Nitrogenous Gas Emissions from Soils and Greenhouse Gas Effects," *Advances in Agronomy 132* (2015): 39-74

T. Groh, *et al*., "Nitrous Oxide Emissions from Saturated Riparian Buffers: Are We Trading a Water Quality Problem for an Air Quality Problem," *Journal of Environmental Qua*lity *48* (2018): 261-269

I. Guo and R. Gifford, "Soil Carbon Stocks and Land Use Change: A Meta-Analysis," *Global Change Biology 8* (2002): 345-360

G. Guardia, *et al*., "Effect of Cover Crops on Greenhouse Gas Emissions in an Irrigated Field under Integrated Soil Fertility Management," *Biogeosciences 13* (2016): 5,245-5,257

J. Guzman and M. Al-Kaisi, “Soil Carbon Dynamics and Carbon Budget of Newly Reconstructed Tall-Grass Prairies in South Central Iowa,” *Journal of Environmental Quality 39* (2010): 136-146

J. Hassink, “The Capacity of Soils to Preserve Organic C and N by Their Association with Clay and Silt Particles,” *Plant Soil 191* (1997): 77-87

J. Havlin, *et al*., “Crop Rotation and Tillage Effects on Soil Organic Carbon and Nitrogen,” *Soil Science Society of America Journal 54* (1990): 148-152

M. Hefting, *et al*., "Spatial Variation in Denitrification and N_2O Emission in Relation to Nitrate Removal Efficiency in an N-Stressed Riparian Buffer Zone," *Ecosystems 9* (2006): 550-563

G. Hernandez-Ramirez, *et al*., "Greenhouse Gas Fluxes in an Eastern Corn Belt Soil: Weather, Nitrogen Source, and Rotation," *Journal of Environmental Quality 38* (2009): 841-854

S. Hinshaw and R. Dahlgren, "Nitrous Oxide Fluxes and Dissolved N Gases (N_2 and N_2O) Within Riparian Zones along the Agriculturally Impacted San Joaquin River," *Nutrient Cycling in Agroecosystems 105* (2016): 85-102

Y. Huang, *et al*., "Greenhouse Gas Emissions and Crop Yield in No-Tillage Systems: A Meta-Analysis," *Agriculture, Ecosystems and Environment 268* (2018): 144-153

D. Huggins, *et al*., "Corn-Soybean Sequence and Tillage Effects on Soil Carbon Dynamics and Storage," *Soil Science Society of America Journal 71* (2007): 145-154

J. Iqbal, *et al*., "Denitrification and Nitrous Oxide Emissions in Annual Cropland, Perennial Grass Buffers, and Restored Perennial Grasslands," *Soil Science Society of America Journal 79* (2015): 231-244

Intergovernmental Panel on Climate Change (IPCC), *2006 IPCC Guidelines for National Greenhouse Gas Inventories. Vol. 4. Agriculture, Forestry and Other Land Use* (Hayama, Japan: Institute for Global Environmental Strategies, 2006)

Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2007: The Physical Science Basis*. *Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press, 2007)

Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2012: The Physical Science Basis. Working Group 1 Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press, 2013)

P. Jacinthe and R. Lal, “Labile Carbon and Methane Uptake as Affected by Tillage Intensity in a Mollisol,” *Soil and Tillage Research 80* (2005): 35-45

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

P. Jacinthe, *et al*., "Nitrous Oxide Emission from Riparian Buffers in Relation to Vegetation and Flood Frequency," *Journal of Environmental Quality 41* (2012): 95-105

S. Jagadamma, *et al*., "Nitrogen Fertilization and Cropping Systems effects on Soil Organic Carbon and Total Nitrogen Pools Under Chisel-Plow in Illinois," *Soil and Tillage Research 95* (2007): 348-356

J. Jastrow, *et al*., “Carbon Dynamics of Aggregate Associated Organic Matter Estimated by Carbon-13 Natural Abundance,” *Soil Science Society of America Journal 60* (1996): 801-807

J. Jastrow, *et al.,* “Contributions of Interacting Biological Mechanisms to Soil Aggregate Stabilization in Restored Prairie,” *Soil Biology and Biochemistry 30* (1998): 905-915

J. Johnson, *et al*., "Do Mitigation Strategies Reduce Global Warming Potential in the Northern U.S. Corn Belt," *Journal of Environmental Quality 40* (2011): 1,551-1,559

M. Jones and A. Donnelly, “Carbon Sequestration in Temperate Grassland Ecosystems and the Influence of Management, Climate and Elevated CO_2,” *New Phytologist 164* (2004): 423-439

D. Kane, *Carbon Sequestration Potential on Agricultural Lands: A Review of Current Science and Available Practices*, National Sustainable Agricultural Coalition/Breakthrough Strategies and Solutions, November 2015

J. Kaye and M. Quemada, "Using Cover Crops to Mitigate and Adapt to Climate Change: A Review," *Agronomy of Sustainable Development* (2017) 37: 4. https://doi.org/10.1007/s13593-016-0410-x

S. Kim and B. Dale, “Economics of Nitrogen Fertilizer Application on Greenhouse Gas Emissions and Economics of Corn Production,” *Environmental Science and Technology 42* (2008): 6,028-6,033

D. Kim and M. Kirschbaum, "The Effect of Land-Use Change on the Net Exchange of Greenhouse Gases: A compliation of Estimates," *Agriculture, Ecosystems and Environment 208* (2015): 114-126

D. Kim, *et al*., "Nitrous Oxide Emissions from Riparian Forest Buffers, Warm-Season and Cool-Season Grass Filters, and Crop Fields," *Biogeosciences Discussions 6* (2009): 607-650

J. Knops and K. Bradley, “Soil Carbon and Nitrogen Accumulation and Vertical Distribution Across a 74-Year Chronosequence,” *Soil Science Society of America Journal 73* (2009): 2,096-2,104

M. Krauss, *et al*., "Impact of Reduced Tillage on Greenhouse Gas Emissions and Soil Carbon Stocks in an Organic Grass-Clover Ley - Winter Wheat Cropping Sequence," *Agriculture, Ecosystems and Environment 239* (2017): 324-333

A. Kravchenko and G. Robertson, “Whole-Profile Soil Carbon Stocks: The Danger of Assuming Too Much from Analyses of Too Little,” *Soil Science Society of America Journal 75* (2011): 235-240

B. Kustermann, *et al*., "Modeling Carbon Cycles and Estimation of Greenhouse Gas Emissions from Organic and Conventional Farming Systems," *Renewable Agriculture and Food Systems 23* (2008): 38-52

H. Kwon, *et al*., "Modeling State-level Soil Carbon Emission Factors under Various Scenarios for Direct Land Use Change Associated with United States Biofuel Feedstock Production," *Biomass and Bioenergy 55* (2013): 299-310

S. Kuo, *et al*., “Winter Cover Crop Effect on Soil Organic Carbon and Carbohydrate in Soil,” *Soil Science Society of America Journal 61* (1997): 145-152

R. Lal, *et al*., *The Potential of US Cropland to Sequester Carbon and Mitigate the Greenhouse Effect* (Ann Arbor: Ann Arbor Press, 1998)

W. Larson, *et al*., "Effects of Increasing Amounts of Organic Residues on Continuous Corn: I. Organic Carbon, Nitrogen, Phosphorus, and Sulfur," *Agronomy Journal 64* (1972): 204-208

J. Le Mer and P. Roger, "Production, Oxidation and Consumption of Methane: A Review," *European Journal of Soil Biology 37* (2001): 25-50

N. Lenka, *et al*., "Soil Carbon Sequestration and Soil Erosion Control Potential of Hedgerows and Grass Filter Strips in Sloping Agricultural Lands of Eastern India," *Agriculture, Ecosystems and Environment 158* (2012): 31-40

U. Levine, *et al*., "Agriculture's Impact on Microbial Diversity and Associated Fluxes of Carbon Dioxide and Methane," *ISME Journal 5* (2011): 1,683-1,691

M. Liebig, *et al*., "Grazing Management Contributions to Net Global Warming Potential: A Long-term Evaluation in the Northern Great Plains," *Journal of Environmental Quality 39* (2010): 799-809

M. Liebig, *et al*. (2019) "Net Global Warming Potential of Spring Wheat Cropping Systems in a Semi-arid Region," *Land* 8,32; doi.10.3390/land 8020032

X. Liu, *et al*., "Tillage and Nitrogen Application Effects on Nitrous and Nitric Oxide Emissions from Irrigated Corn Fields," *Plant and Soil 276* (2005): 235-249

X. Liu, *et al*., "Dinitrogen and N_2O Emissions in Arable Soils: Effect of Tillage, N Source and Soil Moisture," *Soil Biology and Biochemistry 39* (2007): 2,362-2,370

G. Luo, *et al*., "Effects of Soil Temperature and Moisture on Methane Uptake and Nitrous Oxide Emissions across Different Ecosystem Types," *Biogeosciences 10* (2013): 3,205-3,219

L. Luo, *et al*., "Can No-tillage Stimulate Carbon Sequestration in Agricultural Soils? A Meta-Analysis of Paired Experiments," *Agriculture, Ecosystems and Environment 139* (2010): 224-231

S. Machefert, *et al*., "Nitrous Oxide Emissions from a Range of Land Uses Across Europe," *Hydrology and Earth System Sciences 6* (2002): 323-337

A. MacKenzie, *et al*., "Nitrous Oxide Emission as Affected by Tillage, Corn-Soybean-Alfalfa Rotations, and Nitrogen Fertilization," *Canadian Journal of Soil Science 77* (1997): 145-152

L. Mann, "Changes in Soil Carbon Storage after Cultivation," *Soil Science 142* (1986): 279-287

G. Marland, *et al*., "Managing Soil Organic Carbon in Agriculture: The Net Effect on Greenhouse Gas Emissions," *Tellus 55B* (2003): 613-621

C. Marquez, *et al*., "Assessing Soil Quality in a Riparian Buffer by Testing Organic Matter Fractions in Central Iowa, USA," *Agroforestry Systems 44* (1999): 133-140

C. Marquez, *et al.,* "Assessment of Soil Degradation through Soil Aggregation and Particulate Organic Matter Following Conversion of Riparian Buffers to Continuous Cultivation," *European Journal of Soil Science 68* (2017): 295-304

L. Mbuthia, *et al*., "Long-term Tillage, Cover Crop, and Fertilization Effects on Microbial Community Structure, Activity: Implications for Soil Quality," *Soil Biology and Biochemistry 89* (2015): 24-34

K. Mei, *et al*.,"Stimulation of N_2O Emission by Conservation Tillage Management in Agricultural Lands: A Meta-Analysis," *Soil and Tillage Research 182* (2018): 86-93

L. Merbold, *et al*., "Greenhouse Gas Budget (CO_2, CH_4 and N_2O) of Intensively Managed Grassland Following Restoration," *Global Change Biology 20* (2014): 1,913-1,928

K. Metevier, *et al*., “Using the *Ecosys* Mathematical Model to Simulate Temporal Variability of Nitrous Oxide Emissions from a Fertilized Agricultural Soil,” *Soil Biology and Biochemistry 41* (2009): 2,370-2,386

A. Meyer-Aurich, *et al*., “Cost-Efficient Rotation and Tillage Options to Sequester Carbon and Mitigate GHG Emissions from Agriculture in Eastern Canada,” *Agriculture, Ecosystems and Environment 117* (2006): 119-127

S. Miao, *et al*., "Conversion of Cropland to Grassland and Forest Mitigated Global Warming Potential in Northeast China," *Polish Journal of Environmental Studies 24* (2015): 1,195-1,203

B. Minasny, *et al*., "Soil Carbon 4 per Mille," *Geoderma 292* (2017): 59-86

Minnesota Pollution Control Agency, *Minnesota Nutrient Reduction Strategy*, St. Paul, MN, September 2014

D. Mitchell, *et al*., "Cover Crop Effects on Nitrous Oxide Emissions: Role of Mineralizable Carbon," *Soil Science Society of America Journal 77* (2013): 1,765-1,773

E. Moore, *et al*., “Rye Cover Crop Effects on Soil Quality in No-Till Corn Silage-Soybean Cropping Systems,” *Soil Science Society of America Journal 78* (2013): 968-976

A. Mosier, *et al.*, "Measurement of Net Global Warming Potential in Three Agroecosystems," *Nutrient Cycling in Agroecosystems 72* (2005): 67-76

A. Mosier, *et al*., "Net Global Warming Potential and Greenhouse Gas Intensity in Irrigated Cropping Systems in Northeastern Colorado," *Journal of Environmental Quality 35* (2006): 1,584-1,598

P. Nair, *et al*., “Carbon Sequestration in Agroforestry Systems,” *Advances in Agronomy 108* (2010): 237-306

National Agricultural Statistics Service, Agricultural Chemical Use Surveys, https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/

M. Necpalova, *et al*., "Potentials to Mitigate Greenhouse Gas Emissions from Swiss Agriculture," *Agriculture, Ecosystems and Environment 265* (2018): 84-102

X. Niu and S. Duiker, “Carbon Sequestration by Afforestation of Marginal Agricultural Land in the Midwestern US,” *Forest Ecology and Management 223* (2006): 415-427

S. Ogle, *et al*., "Agricultural Management Impacts on Soil Organic Carbon Storage under Moist and Dry Climatic Conditions of Temperate and Tropical Regions," *Biogeochemistry 72* (2005): 87-121

S. Ogle, *et al*., *Report on GHG Mitigation Literature Review for Agricultural Systems*," prepared for USDA Climate Change Office, Natural Resource Ecology Laboratory, Colorado State University, 2010; data reported in Swan, *et al*. (2015)

S. Ogle, *et al*., “No-Till Management Impacts on Crop Productivity, Carbon Input and Soil Carbon Sequestration,” *Agriculture, Ecosystems and Environment 149* (2012): 37-49

K. Olson, *et al*., "Effects of 24 Years of Conservation Tillage Systems on Soil Organic Carbon and Soil Productivity," *Applied and Environmental Soil Science* vol 2013 article ID 617504 10 pages (2013) https://dx.doi.org/10.155/2013/617504

K. Olson, *et al*., "Long-term Effects of Cover Crops on Crop Yields, Soil Organic Carbon Stocks and Sequestration," *Open Journal of Soil Science 4* (2014): 282-292

R. Omonode and T. Vyn, "Vertical Distribution of Soil Organic Carbon and Nitrogen under Warm-Season Native Grasses Relative to Croplands in West-Central Indiana, USA," *Agriculture, Ecosystems and Environment 117* (2006): 159-170

R. Omonode, *et al*., "Soil Nitrous Oxide Emission in Corn Following Three Decades of Tillage and Rotation Treatments," *Soil Science Society of America Journal 75* (2011): 152-163

W. Osterholz, *et al*., "Seasonal Nitrous Oxide and Methane Fluxes from Grain- and Forage-Based Production Systems in Wisconsin USA," *Journal of Environmental Quality 43* (2014): 1,833-1,843

B. Pan, *et al*., “Ammonia Volatilization from Synthetic Fertilizers and Its Mitigation Strategies: A Global Synthesis,” *Agriculture, Ecosystems and Environment 232* (2016): 283-289

K. Paustian, *et al*., “Agricultural Soils as a Sink to Mitigate CO_2 Emissions,” *Soil Use and Management 13* (1997): 230-244

A. Perego, *et al*., "Field Evaluation Combined with Modeling Analysis to Study Fertilizer and Tillage Factors Affecting N_2O Emissions: A Case Study in the Po Valley (Northern Italy)," *Agriculture, Ecosystems and Environment 225* (2016): 72-85

M. Perez-Suarez, *et al*., "Nitrogen and Carbon Dynamics in Prairie Vegetation Strips across Topographical Gradients in Mixed Central Iowa Agroecosystems," *Agriculture, Ecosystems and Environment 188* (2014): 1-11

S. Petersen, *et al*., "Tillage Effects on N_2O Emissions as Influenced by a Winter Cover Crop," *Soil Biology and Biochemistry 43* (2011): 1,509-1,517

J. Pikul, *et al*., "Change in Surface Soil Carbon under Rotated Corn in Eastern South Dakota," *Soil Science Society of America Journal 72* (2008): 1,738-1,744

D. Plaza-Bonilla, *et al*., "Tillage and Nitrogen Fertilization Effects on Nitrous Oxide Yield-Scaled Emissions in a Rainfed Mediterranean Area," *Agriculture, Ecosystems and Environment 189* (2014): 43-52

C. Poeplau and A. Don, "Carbon Sequestration in Agricultural Soil via Cultivation of Cover Crops - A Meta-Analysis," *Agriculture, Ecosystems and Environment 2000* (2015): 33-41

C. Poeplau, *et al*., “Temporal Dynamics of Soil Organic Carbon after Land-Use Change in the Temperate Zone – Carbon Response Functions as a Model Approach,” *Global Change Biology 17* (2011): 2,415-2,427

C. Poeplau, *et al*., “Effects of Perennial Ryegrass Cover Crop on Soil Organic Carbon Stocks in Southern Sweden,” *Geoderma Regional 4* (2015): 126-133

W. Post and K. Kwon, “Soil Carbon Sequestration and Land-Use Change: Processes and Potential,” *Global Change Biology 6* (2000): 317-328

P. Puget and R. Lal, "Soil Organic Carbon and Nitrogen in a Mollisol in Central Ohio as Affected by Tillage and Land Use," *Soil and Tillage Research 80* (2005): 201-213

K. Regina and L. Alukukku, "Greenhouse Gas Fluxes in Varying Soil Types Under Conventional and No-Tillage Practices," *Soil and Tillage Research 109* (2010): 144-152

R. Rheinhardt, *et al*., "Carbon Storage of Headwater Riparian Zones in an Agricultural Landscape," *Carbon Balance and Management 7* (2012): 1-4

I. Rieger, *et al*., "A Novel Dendrochronological Approach Reveals Drivers of Carbon Sequestration in Tree Species of Riparian Forests across Spatiotemporal Scales," *Science of the Total Environment 574* (2017): 1,261-1,275

G. Robertson, *et al*., "Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere," *Science 289* (2000): 1,922-1,925

G. Robertson, *et al*., "The Biogeochemistry of Bioenergy Landscapes: Carbon, Nitrogen, and Water Considerations," *Ecological Applications 21* (2011): 1,055-1,067

P. Rochette, *et al*., “No-Till Increase N_2O Emissions in Poorly Aerated Soils,” *Soil and Tillage Research 101* (2008a): 97-100

P. Rochette, *et al*., “Estimation of N_2O Emissions from Agricultural Soils in Canada. I. Development of a Country-Specific Methodology,” *Canadian Journal of Soil Science 88* (2008b): 641-654

S. Ruis and H. Blanco-Canqui, "Cover Crop Could Offset Crop Residue Removal Effects on Soil Carbon and Other Properties," *Agronomy Journal 109* (2017): 1-21

M. Russelle, "Survey Results of Forage Nutrient Management on Minnesota Farms," USDA, ARS-dairy cluster, 1997 https://fyi.uwex.edu/forages/survey-results-of-forage-nutrient-management-of-mn-farms/

U. Sainju, (2016) "A Global Meta-analysis on the Impact of Management Practices on Net Global Warming Potential and Greenhouse Gas Intensity from Cropland Soils," *PLoS ONE* 11(2): e0148527. doi:10.1371/journal.pone.0148527

U. Sainju, *et al*., “Cover Crops and Nitrogen Fertilization Effects on Soil Aggregation and Carbon and Nitrogen Pools,” *Canadian Journal of Soil Science 83* (2003): 155-165

U. Sainju, *et al*., "Net Global Warming Potential and Greenhouse Gas Intensity Influenced by Irrigation, Tillage, Crop Rotation, and Nitrogen Fertilization," *Journal of Environmental Quality 43* (2014): 777-788

U. Sainju, *et al*., “Cover Crop and Nitrogen Fertilization Influence Soil Carbon and Nitrogen under Bioenergy Sweet Sorghum,” *Agronomy Journal 110* (2018): 463-471

J. Sarkodie-Addo, *et al*., "Nitrous Oxide Emissions after Application of Inorganic Fertilizer and Incorporation of Green Manure Residues," *Soil Use and Management 19* (2003): 331-339

T. Sauer, *et al*., "Soil Carbon and Tree Litter Dynamics in a Red Cedar-Scotch Pine Shelterbelt," *Agroforestry Systems 71* (2007): 163-174

K. Schelde, *et al*., "Spatial and Temporal Variability of Nitrous Oxide Emissions in a Mixed Farming Landscape in Denmark," *Biogeosciences 9* (2012): 2,989-3,002

S. Shafer and E. Thompson, *A New Comparison of Greenhouse Gas Emissions from California Agricultural and Urban Land Uses,* American farmland Trust, 2015

X. Shi, *et al*., “Impact of Ridge Tillage on Soil Organic Carbon and Selected Physical Properties of a Clay Loam in Southwestern Ontario,” *Soil and Tillage Research 120* (2012): 1-7

J. Six, *et al*., “Aggregate and Sol Organic Matter Dynamics under Conventional and No-Tillage Systems,” *Soil Science Society of America Journal 63* (1999): 1,350-1,358

J. Six, *et al*., “Stabilization Mechanisms of Soil Organic Matter: Implications for C-Saturation of Soils,” *Plant and Soil 241* (2002a): 155-176

J. Six, *et al*., “Soil Organic Matter, Biota and Aggregation in Temperate and Tropical Soils – Effects of No-Tillage,” *Agronomie 22* (2002b): 755-775

J. Six, *et al*., "The Potential to Mitigate Global Warming with No-Tillage Management is Only realized When Practiced in the Long-Term," *Global Change Biology 10* (2004): 155-160

P. Smith, *et al*., "Carbon Sequestration Potential in European Croplands Has Been Overestimated," *Global Change Biology 11* (2005): 2,153-2,163

P. Smith, *et al*., "Greenhouse Gas Mitigation in Agriculture," *Philosophical Transactions of the Royal Society B 363* (2008): 789-813

J. Soussana, *et al*., “Full Accounting of Greenhouse Gas (CO_2, N_2O, CH_4) Budget of Nine European Grassland Sites,” *Agriculture, Ecosystems and Environment 121* (2007): 121-134

C. Stewart, *et al*., “Soil Carbon Saturation: Implications for Measureable Carbon Pool Dynamics in Long-Term Incubations,” *Soil Biology and Biochemistry 41* (2009): 357-366

N. Sutfin, *et al*., “Banking Carbon: A Review of Organic Carbon Storage and Physical Factors Influencing Retention in Floodplains and Riparian Ecosystems,” *Earth System Processes and Landforms 41* (2016): 38-60

M. Sulaiman, *et al*., "Greenhouse Gas Mitigation Potential of Annual and Perennial Dairy Feed Crop," *Agriculture, Ecosystems and Environment 245* (2017): 52-62

P. Suwanwaree and G. Robertson, “Methane Oxidation in Forest, Successional and No-Till Agricultural Ecosystems: Effects of Nitrogen and Soil Disturbance,” *Soil Science Society of America Journal 69* (2005): 1,722-1,729

A. Swan, *et al*., *COMET-Planner: Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning: A Companion Report to www.comet-planner.com*, NRCS-USDA and Colorado State, 2015

K. Tate, “Soil Methane Oxidation and Land-Use Change – from Process to Mitigation,” *Soil Biology and Biochemistry 80* (2015): 260-272

A. Tellez, *et al*., “Conservation Agriculture Practices Reduce the Global Warming Potential of Rainfed Low-Input Semi-Arid Agriculture,” *European Journal of Agronomy 84* (2017): 95-104

A. Tufekcioglui, *et al*., "Biomass, Carbon and Nitrogen Dynamics of Multi-Species Riparian Buffers within an Agricultural Watershed in Iowa," *Agroforestry Systems 57* (2003): 187-198

R. Udawatta and S. Jose, "Carbon Sequestration Potential of Agroforestry Practices in Temperate North America," in B. Kumar and P. Nair, eds., *Carbon Sequestration Potential of Agroforestry Systems, Advances in Agroforestry 8 (*Dordrecht: Springer, 2011) pp. 17-42

US Department of Agriculture, Farm Service Agency, “CRP Years Enrolled by State as of September 30, 2017,” https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/Conservation/PDF/CRP%20Years%20Enrolled%20by%20State%20Sep%202017.pdf

US Department of Agriculture, *2017 Census of Agriculture: Minnesota, State and County Data. Volume 3, Geographical Area Series, Part 23*, AC-17-A-23, Washington, DC, 2019

US Environmental Protection Agency, *Inventory of US Greenhouse Gas Emissions and Sinks, 1990-2016* EPA 430-R-18-001, April 2018

US Global Change Research Program, *Second State of the Carbon Cycle Report: A Sustained Assessment Report*, USGCRP, Washington, D.C., 2018

D. Ussiri, *et al*., "Nirtous Oxide and Methane Emissions from Long-term Tillage under a Continuous Corn Cropping System in Ohio," *Soil and Tillage Research 104* (2009): 247-255

C. van Kessel, *et al*., "Climate, Duration, and N Placement Determine N_2O Emissions in Reduced Tillage Systems: A Meta-analysis," *Global Change Biology 19* (2013): 33-44

G. Varvel, "Rotation and Nitrogen Fertilization Effects on Changes in Soil Carbon and Nitrogen," *Agronomy Journal 86* (1994): 319-325

R. Venterea and J. Coulter, "Split Application of Urea Does Not Decrease and May Increase Nitrous Oxide Emissions in Rainfed Corn," *Agronomy Journal 107* (2015): 337-348

R. Venterea and A. Stanenas, “Profile Analysis and Modeling of Reduced Tillage Effects on Soil Nitrous Oxide Flux,” *Journal of Environmental Quality 37* (2008): 1,360-1,367

R. Venterea, *et al*., "Nitrogen Oxide and Methane Emissions under Varying Tillage and Fertilizer Management," *Journal of Environmental Quality 34* (2005): 1,467-1,477

R. Venterea, *et al*., "Carbon and Nitrogen Storage are Greater under Biennial Tillage in a Minnesota Corn-Soybean Rotation," *Soil Science Society of America Journal 70* (2006): 1,752-1,762

R. Venterea, *et al*., “Challenges and Opportunities for Mitigating Nitrous Oxide Emissions from Fertilized Cropping Systems,” *Frontiers in Ecology 10* (2012): 562-570

S. Verma, *et al*., "Annual Carbon Dioxide Exchange in Irrigated and Rainfed Maize-Based Agroecosystems," *Agricultural and Forest Meteorology 131* (2005): 77-96

G. Vilain, *et al*., "Effect of Slope Position and Land Use on Nitrous Oxide (N_2O) Seine Basin, France," *Agricultural and Forest Meteorology 150* (2010): 1,192-1,020

I. Virto, *et al*., "Carbon Input Differences as the Main Factor Explaining the Variability in Soil Organic C Storage in No-Tilled Compared to Inversion Tilled Agrosystems," *Biogeochemistry 108* (2012): 17-26

von Lutzow, *et al*., “Stabilization of Organic Matter in Temperate Soils: Mechanisms and Their Relevance under Different Soil Conditions – a Review,” *European Journal of Soil Science 75* (2006): 426-445

N. Vuichard, *et al*. (2008) "Carbon Sequestration Due to the Abandonment of Agriculture in the Former USSR Since 1990," *Global Biogeochemical Cycles 22* GB4018, doi:10.1029/2008GB003212

D. Walters, *et al.,* "Closing the Corn Yield Gap: Management Practices that Improve Soil Quality and Net Productivity but Reduce Global Warming Potential," *2007 Indiana CCA Conference Proceedings, Indianapolis, December, 2007*

Q. Wang, *et al*., “Cover Crops in Mono- and Biculture for Accumulation of Biomass and Soil Organic Carbon,” *Journal of Sustainable Agriculture 36* (2012): 423-439

T. West and W. Post, "Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation: A Global Data Analysis," *Soil Science Society of America Journal 66* (2002): 1,930-1,946

T. West and J. Six, “Considering the Influence of Sequestration Duration and Carbon Saturation on Estimates of Soil Carbon Capacity,” *Climatic Change 80* (2007): 25-41

T. West, *et al*., “Regional Uptake and Release of Crop Carbon in the United States,” *Biogeosciences 8* (2011): 2,037-2,046

C. Wortmann, *et al*., “One-Time Tillage of No-Till Crop Land Five Years Post-Tillage,” *Agronomy Journal 102* (2010): 1,302-1,307

X. Yang, *et al*., “Impacts of Long-Term and Recently Imposed Tillage Practices on the Vertical Distribution of Soil Organic Carbon,” *Soil and Tillage Research 100* (2008): 120-124

X. Yang and M. Wander, “Tillage Effects on Soil Organic Carbon Distribution and Storage in a Silt Loam Soil in Illinois,” *Soil and Tillage Research 52* (1999): 1-9

Database bibliography

Cropland retirement to grasslands or forested land–N_2O

M. Abraha, *et al*., "Legacy Effects of Land Use on Soil Nitrous Oxide Emissions in Annual Crop and Perennial Grassland Ecosystems," *Ecological Applications 28* (2018): 1,362-1,369

M. Adviento, *et al*., "Soil Greenhouse Gas Fluxes and Global Warming Potential in Four High-Yielding Maize Systems," *Global Change Biology 13* (2007): 1,972-1,988

D. Allen, *et al*., "Nitrous Oxide and Methane Emissions from Soil Are Reduced Following Afforestation of Pasture Lands in Three Contrasting Climatic Zones," *Australian Journal of Soil research 47* (2009): 443-458

C. Amadi, *et al*., "Soil-Atmosphere Exchange of Carbon Dioxide, Methane and Nitrous Oxide in Shelterbelts Compared to Adjacent Cropped Fields," *Agriculture, Ecosystems and Environment 223* (2016): 123-134

C. Amadi, *et al*., "Greenhouse Gas Emissions Along a Shelterbelt-Cropped Field Transect," *Agriculture, Ecosystems and Environment 241* (2017): 110-120

C. Amadi, *et al*., "Greenhouse Gas Mitigation Potential of Shelterbelts: Estimating Farm-Scale Emission Reductions Using the Holos Model," *Canadian Journal of Soil Science 97* (2017): 353-367

P. Ambus and S. Christensen, "Spatial and Seasonal Nitrous Oxide and Methane Fluxes in Danish Forest, Grassland and Agroecosystems, "*Journal of Environmental Quality 24* (1995): 993-1001

P. Ambus and G. Robertson, "The Effect of Increased N Deposition on Nitrous Oxide, Methane and Carbon Dioxide Fluxes from Unmanaged Forest and Grassland Communities in Michigan," *Biogeochemistry 79* (2006): 315-337

M. Baah-Acheamfour, *et al*., "Forest and Grassland Cover Types Reduce Net Greenhouse Gas Emission from Agricultural Soils," *Science of the Total Environment 571* (2016): 1,115-1,127

B. Ball, *et al*., "Influence of Organic Ley-Arable Management and Afforestation in Sandy Loam to Clay Loam Soils on Fluxes of N_2O and CH_4 in Scotland," *Agriculture, Ecosystems and Environment 90* (2002): 305-317

M. Baranski and S. Del Grosso, *US Agriculture and Forestry Greenhouse Gas Inventory 1990-2013*, Technical Bulletin 1943, Office of the Chief Economist, US Department of Agriculture, September 2016

R. Bowden, *et al*., "Annual Nitrous Oxide Fluxes from Temperate Forest Soils in the Northeastern United States," *Journal of Geophysical Research 95D* (1990): 13,997-14,005

R. Bowden, *et al*., "Soil Fluxes of Carbon Dioxide, Nitrous Oxide, and Methane at a Productive Temperate Deciduous Forest," *Journal of Environmental Quality 29* (2000): 268-276

R. Brummer, *et al*., "Hierarchical Control on Nitrous Oxide in Forest Ecosystems," *Global Biogeochemical Cycles 13* (1999) 1,137-1,148

W. Burchill, *et al*., "Interannual Variation in Nitrous Oxide Emissions from Perennial Ryegrass/White Clover Grassland Used for Dairy Production," *Global Change Biology 20* (2014): 3,137-3,146

K. Butterbach-Bahl, *et al*., "Regional Inventory of Nitric Oxide and Nitrous Oxide Emissions for Forest Soils of Southeast Germany Using the Biogeochemical Model PnET-N-DNDC," *Journal of Geophysical Research 106* (2001): 34,155-34,166

K. Butterbach-Bahl, *et al*., "Quantifying the Regional Source Strength of N-Trace Gases Across Agricultural and Forest Ecosystems with Process-Based Models," *Plant and Soil 260* (2004): 311-329

J. Chamberlain, *et al*., "Using DAYCENT to Quantify On-Farm GHG Emissions and N Dynamics of Land Use Conversion to N-Managed Switchgrass in the Southern US," *Agriculture, Ecosystems and Environment 141* (2011): 332-341

R. Dalal and D. Allen, "Greenhouse Gas Fluxes from Natural Systems," *Australian Journal of Botany 56* (2008): 396-407

S. Del Grosso, *et al*., "Simulated Effects of Dryland Cropping Intensification on Soil Organic Matter and Greenhouse Gas Exchanges Using the DAYCENT Ecosystem Model," *Environmental Pollution 116* (2002): S75-S83

S. Del Grosso, *et al*., "DAYCENT Model Analysis of Past and Contemporary Soil N_2O and Net Greenhouse Gas Flux for Major Crops in the USA," *Soil and Tillage Research 83* (2005): 9-24

Y. Dong, *et al*., "Fluxes of CO_2, CH_4 and N_2O from a Temperate Forest Soil: the Effects of Leaves and Humus Layers," *Tellus 50B* (1998): 245-252

B. Duran, *et al*. (2016) "Nitrogen Fertilization Effects on Productivity and Nitrogen Loss in Three Grass-based Perennial Bioenergy Cropping Systems," *PLoS One 11*(3):e015919. doi:10.1371/journal.pone.0151919

C. Flechard, *et al*., "Effects of Climate and Management Intensity on Nitrous Oxide Emissions in Grassland Systems across Europe," *Agriculture, Ecosystems and Environment 121* (2007): 135-152

I. Gelfand, *et al*., "Carbon Debt of Conservation Reserve Program (CRP) Grasslands Converted to Bioenergy Production," *Proceedings of the National Academy of Sciences 108* (2011): 13,864-13,869

I. Gelfand, *et al*., "Long-term Nitrous Oxide Fluxes in Annual and Perennial Agricultural and Unmanaged Ecosystems in the Upper Midwest, USA," *Global Change Biology 22* (2016): 3594-3,607

I. Gelfand and G. Robertson, "Mitigation of Greenhouse Gases in Agricultural Ecosystems," in S. Hamilton, *et al*., eds., *The Ecology of Agricultural Landscapes: Long-term Research on the Path to Sustainability* (New York: Oxford University Press, 2015) pp. 310-339

S. Glatzel and K. Stahr, "Methane and Nitrous Oxide Exchange in Differently Fertilized Grassland in Southern Germany," *Plant and Soil 231* (2001): 21-35

L. Goodroad and D. Keeney, "Nitrous Oxide Emission from Forest, Marsh and Prairie Ecosystems," *Journal of Environmental Quality 13* (2004): 448-452

B. Grant, *et al*., "Estimated N_2O and CO_2 Emissions as Influenced by Agricultural Practices in Canada," *Climatic Change 65* (2004): 315-332

P. Groffman, et al., "Snow Depth, Soil Freezing, and Fluxes of Carbon Dioxide, Nitrous Oxide and Methane in a Northern Hardwood Forest," *Global Change Biology 12* (2006): 1,748-1,760

P. Groffman and C. Turner, "Plant Productivity and Nitrogen Gas Fluxes in a Tallgrass Prairie Landscape," *Landscape Ecology 10* (1995): 255-266

P. Gundersen, *et al*., "The Response of Methane and Nitrous Oxide Fluxes to Forest Change in Europe," *Biogeosciences 9* (2012): 3,999-4,012

G. Hernandez-Ramirez, *et al*., "Greenhouse Gas Fluxes in an Eastern Corn Belt Coil: Weather, Nitrogen Source, and Rotation," *Journal of Environmental Quality 38* (2009): 841-854

T. Hudiburg, *et al*., "Bioenergy Crop Greenhouse Gas Mitigation Potential under a Range of Management Practices," *Global Change Biology-Bioenergy 7* (2015): 366-374

J. Iqbal, *et al*., "Denitrification and Nitrous Oxide Emissions in Annual Cropland, Perennial Grass Buffers, and Restored Perennial Grasslands," *Soil Science Society of America Journal 79* (2014): 239-250

M. Kesik, *et al*., "Inventories of N_2O and NO Emissions from European Forest Soils," *Biogeosciences 2* (2005): 353-375

A. Kessavalou, *et al*., "Fluxes of Carbon Dioxide, Nitrous Oxide, and Methane in Grass Sod and Winter Wheat-Fallow Tillage Management," *Journal of Environmental Quality 27* (1998): 1,094-1,104

D. Kim, *et al*., "The Effect of Land-use Change on the Net Exchange Rates of Greenhouse Gases: A Compilation of Estimates," *Agriculture, Ecosystems and Environment 208* (2015): 114-126

D. Kim, *et al*., "Carbon Sequestration and Net Emissions of CH_4 and N_2O Under Agroforestry: Synthesizing Available Data and Suggestions for Future Studies," *Agriculture, Ecosystems and Environment 226* (2016): 65-78

D. Li, *et al*. (2011) "Measured and Simulated Nitrous Oxide Emissions from Ryegrass and Ryegrass/White Clover-Based Grasslands in a Moist Temperate Climate," *Plos One 6*(10): e26176. doi:10.1371/journal.pone.0026176

S. Liu, *et al*., "Baseline and Projected Future Carbon Storage, Carbon Sequestration, and Greenhouse Gas Fluxes in Terrestrial Ecosystems of the Eastern United States," in Z. Zhu and B. Reed, eds., *Baseline and Projected Future Carbon Storage and Greenhouse Gas Fluxes in Ecosystems of the Eastern United States*, Professional Paper 1804 (Washington, D.C.: US Geological Service, 2014)

A. Merino, *et al*., "Responses of Soil Organic Matter and Greenhouse Gas Fluxes to Soil Management and Land Use in a Humid Temperate Region of Southern Europe," *Soil Biology and Biochemistry 36* (2004): 917-925

A. Mosier, *et al*., "CH_4 and N_2O Fluxes in the Colorado Shortgrass Steppe 2. Long-term Impact of Land Use Change," *Global Biogeochemical Cycles 11* (1997): 29-42

A. Mosier, *et al*., "Soil-Atmosphere Exchange of CH_4, CO_2, NO_x and N_2O in the Colorado Shortgrass Steppe under Elevated CO_2," *Plant and Soil 240* (2002): 201-211

A. Mosier, *et al*., "Mitigating Net Global Warming Potential (CO_2, CH_4 and N_2O) in Upland Crop Production," Coalbed Methane Conference, 2005 http://www.coalinfo.net.cn/coalbed/meeting/2203/papers/agriculture/AG005.pdf

L. Oates, *et al*., "Nitrous Oxide Emissions During Establishment of Eight Alternative Cellulosic Bioenergy Cropping Systems in the North Central United States," *Global Change Biology-Bioenergy 8* (2016): 539-549

M. Peichl, *et al*., "Carbon Dioxide, Methane and Nitrous Oxide Exchanges in an Age-Sequence of Temperate Pine Forests," *Global Change Biology 6* (2010): 2198-2212

M. Peichl, *et al*., "Carbon and Greenhouse Gas Balances in an Age Sequence of Temperate Pine Plantations," *Biogeosciences 11* (2014): 5,399-5,410

K. Pilegaard, *et al*., "Factors Controlling Regional Differences in Forest Soil Emission of Nitrogen Oxides (NO and N_2O)," *Biogeosciences 3* (2006): 651-661

C. Potter, *et al*., "Process Modeling of Controls on Nitrogen Trace Gas Emissions from Soils Worldwide," *Journal of Geophysical Research 101* (1996): 1,361-1,377

A. Prieme and S. Christensen, "Natural Perturbations, Drying - Wetting and Freezing - Thawing Cycles, and the Emission of Nitrous Oxide, Carbon Dioxide and Methane from Farmed Organic Soils," *Soil Biology and Biochemistry 33* (2001): 2083-2091

G. Robertson, *et al*., "Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere," *Science 289* (2000): 1,922-1,925

G. Robertson, *et al*., "The Biochemistry of Bioenergy Landscapes: Carbon, Nitrogen and Water Considerations," *Ecological Applications 21* (2011): 1,055-1,066

B. Roth, *et al*., "The Effects of Land-Use Change from Grassland to *Miscanthus x giganteus* on Soil N_2O Emissions," *Land 2* (2013): 437-451

L. Ruan and G. Robertson, "Initial Nitrous Oxide, Carbon Dioxide and Methane Cost of Converting Conservation Reserve Program Grassland to Row Crops under No-Till vs. Conventional Tillage," *Global Change Biology 19* (2013): 2,478-2,489

R. Ruser, *et al*., "Effect of Crop-specific Field Management and N Fertilization on N_2O Emissions from a Fine-Loamy Soil," *Nutrient Cycling in Agroecosystems 59* (2001): 177-191

D. Saha, *et al*., "Landscape Control of Nitrous Oxide Emissions During the Transition from Conservation Reserve Program to Perennial Grasses for Bioenergy," *Global Change Biology-Bioenergy 9* (2017): 783-795

H. Schulte-Bisping, *et al*. (2003) "Nitrous Oxide Emission Inventory of German Forest Soils," *Journal of Geophysical Research 108*(D4), 4132, doi:10:1029/2002JD002292

R. Shrestha, *et al*., "Greenhouse Gas Emissions and Global Warming Potential of Reclaimed Forest and Grassland Soils," *Journal of Environmental Quality 38* (2009): 426-436

F. Sgourdis and S. Ullah, "Soil Greenhouse Gas Fluxes, Environmental Controls, and the Partitioning of N_2O Sources in UK Natural and Seminatural Land Use Types," *Journal of Geophysical Research-Biosciences 122* (2017): 2,617-2,633

C. Smith, *et al*., "Reduced Nitrogen Losses after Conversion of Row Crop Agriculture to Perennial Biofuel Crops," *Journal of Environmental Quality 42* (2013): 219-228

D. Smith, *et al*., "Fertilizer and Tillage Management Impacts on Non-Carbon Dioxide Greenhouse Gas Emissions," *Soil Science Society of America Journal 75* (2011): 1,070-1,082

P. Smith, *et al*., "Greenhouse Gas Mitigation in Agriculture," *Philosophical Transactions of the Royal Society B 363* (2008): 789-813

E. Stehfest and L. Bouwman, "N_2O and NO Emission from Agricultural Fields and Soils under Natural Vegetation: Summarizing Available Measurement Data and Modeling of Global Annual Emissions," *Nutrient Cycling in Agroecosystems 74* (2006): 207-228

B. Tangen, *et al*., "Effects of Land Use on Greenhouse Gas Fluxes and Soil Properties of Wetland Catchments in the Prairie Pothole Region of North America," *Science of the Total Environment 533* (2015): 391-409

H. Tian, *et al*., "Spatial and Temporal Patterns of CH_4 and N_2O Fluxes in Terrestrial Ecosystems of North America During 1979-2008: Application of a Global Biogeochemistry Model," *Biogeosciences 7* (2010): 2,673-2,694

S. Ullah and T. Moore (2011) "Biogeochemical Controls on Methane, Nitrous Oxide and Carbon Dioxide Fluxes from Deciduous Soils in Eastern Canada," *Journal of Geophysical Research 116* G03010, doi:10.1029/2010JG001525

G. Vilain, *et al*., "Effect of Slope Position and Land Use on Nitrous Oxide (N_2O) Emissions (Seine Basin, France)," *Agricultural and Forest Meteorology 150* (2010): 1,192-1,202

K. Von Arnold, *et al*., "Fluxes of CO_2, CH_4 and N_2O from Drained Coniferous Forests on Organic Soils," *Forest Ecology and Management 210* (2005): 239-254

A. Wile, *et al*., "Effect of Nitrogen Fertilization Rate on Yield, Methane and Nitrous Oxide Emissions from Switchgrass (*Panicum virgatum L*.) and Reed Canary Grass (*Phalaris arundinacea*)," *Canadian Journal of Soil Science 94* (2014): 129-137

X. Xu, *et al*., "Convergence in the Relationship of CO_2 and N_2O Exchanges Between Soil and Atmosphere within Terrestrial Ecosystems," *Global Change Biology 14* (2008): 1,651-1,660

Xu-Ri, *et al*., "Modelling Terrestrial Nitrous Oxide Emissions and Implications for Climate Feedback," *New Phytologist 196* (2012): 472-488

X. Yang, *et al*., "Nitrous Oxide Emissions from an AgroPastoral Ecotone of Northern China Depending on Land Uses," *Agriculture, Ecosystems and Environment 213* (2015): 241-251

Q. Yang, *et al*., "Enhancing the Soil and Water Assessment Tool Model for Simulating N_2O Emissions of Three Agricultural Systems," *Ecosystem Health and Sustainability 3* (2017): 1-12

S. Zechmeister-Boltenstern, *et al*., "Nitrous Oxide Emissions and Nitrate Leaching in Relation to Microbial Biomass Dynamics in a Beech Forest Soil," *Soil Biology and Biochemistry 34* (2002): 823-832

Q. Zhuang, *et al*., "An Inventory of Global N_2O Emissions from the Soils of Natural terrestrial Ecosystems," *Atmospheric Environment 47* (2012): 66-75

Cropland retirement to grasslands or forested land–CH_4

D. Allen, *et al*., "Nitrous Oxide and Methane Emissions from Soil Are Reduced Following Afforestation of Pasture Lands in Three Contrasting Climatic Zones," *Australian Journal of Soil Research 47* (2009): 443-458

C. Amadi, *et al*., "Soil-Atmosphere Exchange of Carbon Dioxide, Methane and Nitrous Oxide in Shelterbelts Compared to Adjacent Cropped Fields," *Agriculture, Ecosystems and Environment 223* (2016): 123-134

C. Amadi, *et al*., "Greenhouse Gas Emissions along a Shelterbelt-Cropped Field Transect," *Agriculture, Ecosystems and Environment 241* (2017): 110-120

C. Amadi, *et al*., "Greenhouse Gas Mitigation Potential of Shelterbelts: Estimating Farm-Scale Emission Reductions Using the Holos Model," *Canadian Journal of Soil Science 97* (2017): 353-367

P. Ambus and G. Robertson, "The Effect of Increase N Deposition on Nitrous Oxide, Methane and Carbon Dioxide Fluxes from Unmanaged Forest and Grassland Communities in Michigan," *Biogeochemistry 79* (2006): 315-337

E. Aronson and B. Helliker, "Methane Flux in Non-Wetland Soils in Response to Nitrogen Addition: A Meta-Analysis," *Ecology 9* (2010): 3,242-3,251

M. Baah-Acheamfour, *et al*., "Forest and Grassland Cover Types Reduce Net Greenhouse Gas Emission from Agricultural Soils," *Science of the Total Environment 571* (2016): 1,115-1,127

B. Ball, *et al*., "Influence of Organic Ley-Arable Management and Afforestation in Sandy Loam to Clay Loam Soils on Fluxes of N_2O and CH_4 in Scotland," *Agriculture, Ecosystems and Environment 90* (2002): 305-317

J. Blankinship, *et al*. (2010) "Effects of Interactive Global Changes on Methane Uptake in an Annual Grassland," *Journal of Geophysical Research 115,* G02008, doi:10.1029/2009JG001097

P. Crill, "Seasonal Patterns of Methane Uptake and Carbon Dioxide Release by a Temperate Woodland Soil," *Global Biogeochemical Cycles 5* (1991): 319-334

C. Curry, "Modeling the Soil Consumption of Atmospheric Methane at the Global Scale," *Global Biogeochemical Cycles 21* (2007): 1-15

R. Dalal and D. Allen, "Greenhouse Gas Fluxes from Natural Systems," *Australian Journal of Botany 56* (2008): 396-407

S. Del Grosso, *et al*., "Simulated Effects of Dryland Cropping Intensification on Soil Organic Matter and Greenhouse Gas Exchanges Using the DAYCENT Ecosystem Model," *Environmental Pollution 116* (2002): S75-S83

S. Del Grosso, *et al*., "DAYCENT Model Analysis of Past and Contemporary Soil N_2O and Net Greenhouse Gas Flux for Major Crops in the USA," *Soil and Tillage Research 83* (2005): 9-24

F. Dijkstra, *et al*., "Climate Change Reduces the Net Sink of CH_4 and N_2O in a Semiarid Grassland," *Global Change Biology 19* (2013): 1,816-1,826

K. Dobbie, *et al*., "Effect of Land Use on the Rate of Methane Uptake by Surface Soils in Northern Europe," *Atmospheric Environment 30* (1996): 1,005-1,011

K. Dobbie and K. Smith, "Comparison of CH_4 Oxidation Rates in Woodland, Arable and Set Aside Soils," *Soil Biology and Biochemistry 10/11* (1996): 1,357-1,365

Y. Dong, *et al*., "Fluxes of CO_2, CH_4 and N_2O from a Temperate Forest Soil: the Effects of Leaves and Humus Layers," *Tellus 50B* (1998): 245-252

L. Dutaur and L. Verchott, "A Global Inventory of the Soil CH_4 Sink," *Global Biogeochemical Cycles 21* (2007): 1-9

I. Gelfand, *et al*., "Carbon Debt of Conservation Reserve Program (CRP) Grasslands Converted to Bioenergy Production," *Proceedings of the National Academy of Sciences 108* (2011): 13,864-13,869

I. Gelfand and G. Robertson, "Mitigation of Greenhouse Gases in Agricultural Ecosystems," in S. Hamilton, *et al*., eds., *The Ecology of Agricultural Landscapes: Long-term Research on the Path to Sustainability* (New York: Oxford University Press, 2015) pp. 310-339

S. Glatzel and K. Stahr, "Methane and Nitrous Oxide Exchange in Differently Fertilized Grassland in Southern Germany," *Plant and Soil 231* (2001): 21-35

P. Groffman, *et al*., "Snow Depth, Soil Freezing, and Fluxes of Carbon Dioxide, Nitrous Oxide and Methane in a Northern Hardwood Forest," *Global Change Biology 12* (2006): 1,748-1,760

P. Gundersen, *et al*., "The Response of Methane and Nitrous Oxide Fluxes to Forest Change in Europe," *Biogeosciences 9* (2012): 3,999-4,012

G. Hernandez-Ramirez, *et al*., "Greenhouse Gas Fluxes in an Eastern Corn Belt Soil: Weather, Nitrogen Source, and Rotation," *Journal of Environmental Quality 38* (2009): 841-854

P. Jacinthe and R. Lal, "Labile Carbon and Methane Uptake as Affected by Tillage Intensity in a Mollosol," *Soil and Tillage Research 80* (2005): 35-45

A. Kessavalou, *et al*., "Fluxes of Carbon Dioxide, Nitrous Oxide, and Methane in Grass Sod and Winter Wheat-Fallow Tillage Management," *Journal of Environmental Quality 27* (1998): 1,094-1,104

D. Kim, *et al*., "The Effect of Land-use Change on the Net Exchange Rates of Greenhouse Gases: A Compilation of Estimates," *Agriculture, Ecosystems and Environment 208* (2015): 114-126

D. Kim, *et al*., "Carbon Sequestration and Net Emissions of CH_4 and N_2O under Agroforestry: Synthesizing Available Data and Suggestions for Future Studies," *Agriculture, Ecosystems and Environment 226* (2016): 65-78

J. LeMer and P. Roger, "Production, Oxidation, Emission and Consumption of Methane by Soils: A Review," *European Journal of Soil Biology 37* (2001): 25-50

U. Levine, *et al*., "Agriculture's Impact on Microbial Diversity and Associated Fluxes of Carbon Dioxide and Methane," *ISME Journal 5* (2011): 1,683-1,691

S. Liu, *et al*., "Baseline and Projected Future Carbon Storage, Carbon Sequestration, and Greenhouse-Gas Fluxes in Terrestrial Ecosystems of the Eastern United States," in Z. Zhu and B. Reed, eds., *Baseline and Projected Future Carbon Storage and Greenhouse Gas Fluxes in Ecosystems of the Eastern United States*, Professional Paper 1804 (Washington, D.C.: US Geological Service, 2014)

A. Merino, *et al*., "Responses of Soil Organic Matter and Greenhouse Gas Fluxes to Soil Management and Land Use in a Humid Temperate Region of Southern Europe," *Soil Biology and Biochemistry 36* (2004): 917-925

A. Mosier, *et al*., "CH_4 and N_2O Fluxes in the Colorado Shortgrass Steppe 2. Long-term Impact of Land Use Change," *Global Biogeochemical Cycles 11* (1997): 29-42

A. Mosier, *et al*., "Soil-Atmosphere Exchange of CH_4, CO_2, NO_x and N_2O in the Colorado Shortgrass Steppe under Elevated CO_2," *Plant and Soil 240* (2002): 201-211

A. Mosier, et al., "Mitigating Net Global Warming Potential (CO_2, CH_4 and N_2O) in Upland Crop Production," Coalbed Methane Conference, 2005 http://www.coalinfo.net.cn/coalbed/meeting/2203/papers/agriculture/AG005.pdf

M. Peichl, *et al*., "Carbon Dioxide, Methane and Nitrous Oxide Exchanges in an Age-Sequence of Temperate Pine Forests," *Global Change Biology 6* (2010): 2198-2212

M. Peichl, *et al*., "Carbon and Greenhouse Gas Balances in an Age Sequence of Temperate Pine Plantations," *Biogeosciences 11* (2014): 5,399-5,410

A. Prieme, *et al*., "Slow Increase in Rate of Methane Oxidation in Soils with Time Following Land Use Change from Arable Agriculture to Woodland," *Soil Biology and Biochemistry 29* (1997): 1,269-1,273

A. Ridgwell, *et al*., "Consumption of Atmospheric Methane by Soils: a Process-Based Model," *Global Biogeochemical Cycles 13* (1999): 59-70

G. Robertson, *et al*., "Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere," *Science 289* (2000): 1,922-1,925

L. Ruan and G. Robertson, "Initial Nitrous Oxide, Carbon Dioxide and Methane Cost of Converting Conservation Reserve Program Grassland to Row Crops under No-Till vs. Conventional Tillage," *Global Change Biology 19* (2013): 2,478-2,489

F. Sgourdis and S. Ullah, "Soil Greenhouse Gas Fluxes, Environmental Controls, and the Partitioning of N_2O Sources in UK Natural and Seminatural Land Use Types," *Journal of Geophysical Research-Biosciences 122* (2017): 2,617-2,633

R. Shrestha, *et al*., "Greenhouse Gas Emissions and Global Warming Potential of Reclaimed Forest and Grassland Soils," *Journal of Environmental Quality 38* (2009): 426-436

D. Smith, *et al*., "Fertilizer and Tillage Management Impacts on Non-Carbon Dioxide Greenhouse Gas Emissions," *Soil Science Society of America Journal 75* (2011): 1,070-1,082

K. Smith, *et al*., "Oxidation of Atmospheric Methane in Northern European Soils, Comparison with Other Ecosystems, and Uncertainties in the Global Terrestrial Sink," *Global Change Biology 6* (2000): 791-803

P. Smith, *et al*., "Greenhouse Gas Mitigation in Agriculture," *Philosophical Transactions of the Royal Society B 363* (2008): 789-813

P. Sumanwaree and G. Robertson. "Methane Oxidation in Forest, Successional, and No-Till Agricultural Ecosystems: Effects of Nitrogen and Soil Disturbance," *Soil Science Society of America Journal 69* (2005): 1,722-1,729

B. Tangen, *et al*., "Effects of Land Use on Greenhouse Gas Fluxes and Soil Properties of Wetland Catchments in the Prairie Pothole Region of North America," *Science of the Total Environment 533* (2015): 391-409

C. Tate and R. Striegl, "Methane Consumption and Carbon Dioxide Emission in Tallgrass Prairie: Effects of Biomass Burning and Conversion to Agriculture," *Global Biogeochemical Cycles 7* (1993): 735-784

H. Tian, *et al*., "Spatial and Temporal Patterns of CH_4 and N_2O Fluxes in Terrestrial Ecosystems of North America During 1979-2008: Application of a Global Biogeochemistry Model," *Biogeosciences 7* (2010): 2673-2694

S. Ullah and T. Moore (2011) "Biogeochemical Controls on Methane, Nitrous Oxide and Carbon Dioxide Fluxes from Deciduous Soils in Eastern Canada," *Journal of Geophysical Research 116* G03010, doi:10.1029/2010JG001525

K. Von Arnold, *et al*., "Fluxes of CO_2, CH_4 and N_2O from Drained Coniferous Forests on Organic Soils," *Forest Ecology and Management 210* (2005): 239-254

A. Wile, *et al*., "Effect of Nitrogen Fertilization Rate on Yield, Methane and Nitrous Oxide Emissions from Switchgrass (*Panicum virgatum L*.) and Reed Canary Grass (*Phalaris arundinacea*)," *Canadian Journal of Soil Science 94* (2014): 129-137

L. Yu, et al., "Methane Uptake in Global Forests and grassland Soils from 1981 to 2010," *Science of the Total Environment 607/608* (2017): 1,163-1,172

Cropland retirement to grasslands-live biomass, SOC/CO_2

D. Arrouays, *et al*., *Mitigation of the Greenhouse Effect: Increasing Carbon Stocks in French Agricultural Soils? Synthesis of an Assessment Report by the French Institute for Agricultural Research (INRA) on Request of the French Ministry for Ecology and Sustainable Development*, INRA, October 2002

M. Abraha, *et al*., "Ecosystem Carbon Exchange on Conversion of Conservation Reserve Program Grasslands to Annual and Perennial Cropping Systems," *Agricultural and Forest Meteorology 253/254* (2018): 151-160

K. Anderson-Teixeira, *et al*., "Changes in Soil Organic Carbon under Biofuels Crops," *Global Change Biology 1* (2009): 75-96

C. Arevalo*, et al*., "Ecosystem Carbon Stocks and Distribution under Different Land-Uses in North Central Alberta, Canada," *Forest Ecology and Management 257* (2009): 1,776-1,785

W. Amelung, *et a*l., "Restoration of Microbial Residues in Soils of the Conservation Reserve Program," *Soil Science Society of America Journal 65* (2001): 1,704-1,709

M. Ampleman, *et al*., "Differential Soil Organic Carbon Storage at Forb- and Grass-Dominated Plant Communities, 33 years after Tallgrass Prairie Restoration," *Plant Soil 374* (2014): 899-913

J. Anderson, *et al*., *The Potential for Terrestrial Carbon Sequestration in Minnesota: A Report to the Department of Natural Resources from the Minnesota Terrestrial Carbon Sequestration Initiative*, University of Minnesota, February 2008

S. Baer, *et al*., "Assessment of Soil Quality in Fields with Short and Long Term Enrollment in the CRP," *Journal of Soil and Water Conservation 55* (2000): 142-146

M. Baranski and S. Del Grosso, *US Agriculture and Forestry Greenhouse Gas Inventory 1990-2013*, Technical Bulletin 1943, Office of the Chief Economist, US Department of Agriculture, September 2016

J. Barker, *et al*., "Potential Carbon Benefits of the Conservation Reserve Program of the United States," *Journal of Biogeography 22* (1995): 743-751

J. Barker, *et al*., "Carbon Dynamics of the Conservation and Wetland reserve Programs," *Journal of Soil and Water Conservation 51* (1996): 340-346

L. Bell, *et al*., "Soil Profile Carbon and Nutrient Stocks under Long-term Conventional and Organic Crop and Alfalfa Crop-Rotations and Re-established Grassland," *Agriculture, Ecosystems and Environment 158* (2012): 156-163

R. Bowman and R. Anderson, "Conservation Reserve Program: Effects on Soil Organic Carbon and Preservation When Converting Back to Cropland in Northeastern Colorado," *Journal of Soil and Water Conservation 57* (2002): 121-126

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 Resources Ecology Laboratory and USDA-NRCS, 2001

L. Breuer, *et al*., "Impact of a Conversion from Cropland to Grassland on C and N Storage and Related Soil Properties: Analysis of a 60-Year Chronosequence," *Geoderma 113* (2006): 6-18

K. Bronson, *et al*., "Carbon and Nitrogen Pools of Southern High Plains Cropland and Grassland Soils," *Soil Science Society of America Journal 68* (2004): 1,695-1,704

J. Bruce, *et al*., "Carbon Sequestration in Soils," *Journal of Soil and Water Conservation 54* (1999): 382-389

K. Brye, *et al*., "Carbon Budgets for a Prairie and Agroecosystems: Effects of Land-Use and Interannual Variability," *Ecological Applications 12* (2002): 962-979

K. Brye and C. Kucharik, "Carbon and Nitrogen Sequestration in Two Prairie Chronosequences on Contrasting Soils in Southern Wisconsin," *American Midland Naturalist 149* (2003): 90-103

I. Burke, *et al*., "Soil Organic Matter Recovery in Semiarid Grasslands: Implications for the Conservation Reserve Program," *Ecological Applications 5* (1995): 793-801

K. Cahill, *et al*., "Prairie Restoration and Carbon Sequestration: Difficulties Quantifying C Sources and Sinks Using a Biometric Approach," *Ecological Applications 19* (2009): 2,185-2,201

C. Cambardella, *et al*., *Soil Carbon in Reconstructed Tallgrass Prairies*, poster, annual meeting of the American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, November 15-18, 2015, Minneapolis, MN

D. Cameron, *et al*., "Ecosystem Management and Land Conservation Can Substantially Contribute to California's Climate Mitigation Goals," *Proceedings of the National Academy of Sciences 114* (2017): 12,833-12,838

J. Chamberlain, *et al*., "Using DAYCENT to Quantify On-Farm GHG Emissions and N Dynamics of Land Use Conversion to N-Managed Switchgrass in the Southern US," *Agriculture, Ecosystems and Environment 141* (2011): 332-341

A. Chambers, *et al*., "Soil Carbon Sequestration Potential of US Croplands and Grasslands: Implementing the 4 per Thousand Initiative," *Journal of Soil and Water Conservation 71* (2016): 68A-74A

R. Conant, *et al*., "Grassland Management Impacts on Soil Carbon Stocks: A New Synthesis," *Ecological Applications 27* (2017): 662-668

S. DeGryze, *et al*., "Soil Organic Carbon Pool Changes Following Land-Use Conversions," *Global Change Biology 10* (2004): 1,120-1,132

S. Del Grosso, *et al*., "Simulated Effects of Dryland Cropping Intensification on Soil Organic Matter and Greenhouse Gas Exchanges Using the DAYCENT Ecosystem Model," *Environmental Pollution 116* (2002): S75-S83

K. Denef, *et al*., *Greenhouse Gas Emissions from U.S. Agriculture and Forestry: A Review of Emission Sources, Controlling factors, and Mitigation Potential*. Interim Report to USDA under contract #G-23F-8182H, ICF International, 2011

L. Deng, *et al*., "Global Patterns of the Effects of Land-Use Changes on Soil Carbon Stocks," *Global Ecology and Conservation 5* (2016): 127-138

A. Don, *et al*., "Conversion of Cropland to Grassland: Implications for Soil Organic-Carbon Stocks in Two Soils with Different Texture," *Journal of Plant Nutrition and Soil Science 172* (2009): 53-62

A. Eagle, *et al*., *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States: A Synthesis of the Literature*, 3rd edition, Nicholas Institute, Duke University, January 2012

Environmental Protection Agency, *Greenhouse Gas Mitigation Potential in US Forestry and Agriculture*, EPA-430-R-06-006, November 2005

Environmental Protection Agency, "CroplandGrassland_Carbon_1990-2015_CRF_Final (1).xlsx," state-level spreadsheet provided upon request (received February 2017)

M. Eve, *et al*., "Predicted Impact of Management Changes on Soil Carbon Storage for Each Cropland Region of the Coterminous United States," *Journal of Soil and Water Conservation 57* (2002): 196-204

FAPRI-University of Missouri, *Estimating the Water Quality, Air Quality and Soil Carbon Benefits of the Conservation Reserve Program*, FAPRI-UMC Report 01-07, January 2007

J. Fargione, *et al*. (2018) "Natural Climate Solutions for the United States," *Science Advances*.4. eaat1869. DOI: 10.1126/sciadv.aat1869

C. Fissore, *et al*., "Limited Potential for Terrestrial Carbon Sequestration to Offset Fossil-Fuel Emissions in the Upper Midwestern USA," *Frontiers in Ecology and the Environment 8* (2010): 409-413

R. Follett, "Soil Management Concepts and Carbon Sequestration in Cropland Soils," *Soil and Tillage Research 61* (2001): 77-92

R. Follett, *et al*., "The Potential of US Grazing Lands to Sequester Soil Carbon," chapter 16 in R. Follett, *et al.,* eds., *The Potential of US Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect* (Boca Raton: CRC Press, 2001)

R. Follett, *et al*., "Carbon Sequestration Under the Conservation Reserve Program in the Historic Grassland Soils of the United States of America," chapter 3 in R. Lal and R. Follett, eds., *Soil Carbon Sequestration and the Greenhouse Effect* (Madison, WI: Soil Science Society of America, Special Publication 57), pp. 27-40

R. Follett, *et al*., *Carbon Sequestration and Greenhouse Gas Fluxes in Agriculture: Challenges and Opportunities*, Council on Agricultural Science and Technology (CAST), Task Force Report 142, Ames, Iowa, October 2011

D. Gebhart, *et al*., "The CRP Increases Soil Organic Carbon," *Journal of Soil and Water Conservation 49* (1994): 488-492

I. Gelfand, *et al*., "Carbon Debt of Conservation Reserve Program (CRP) Grasslands Converted to Bioenergy Production," *Proceedings of the National Academy of Sciences 108* (2011): 13,864-13,869

I. Gelfand and G. Robertson, "Mitigation of Greenhouse Gases in Agricultural Ecosystems," in S. Hamilton, *et al*., eds., *The Ecology of Agricultural Landscapes: Long-term Research on the Path to Sustainability* (New York: Oxford University Press, 2015) pp. 310-339

T. Gilmanov, *et al*., "Integration of CO_2 Flux and Remotely-Sensed Data for Primary Production and Ecosystem Respiration Analysis in the Northern Great Plains: Potential for Quantitative Spatial Extrapolation," *Global Ecology and Biogeography 14* (2005): 271-292

T. Gilmanov, *et al*., "Partitioning European Grassland Net Ecosystem CO_2 Exchange into Gross Primary Productivity and Ecosystem Respiration Using Light Response Function Analysis," *Agriculture, Ecosystems and Environment 28* (2007): 93-120

T. Gilmanov, *et al*., "Productivity, Respiration, and Light-Response Parameters of World Grassland and Agroecosystems Derived from Flux-Tower Measurements," *Rangeland Ecology and Management 63* (2010): 16-39

R. Gleason, *et al*., *Ecosystem Services Derived from Wetland Conservation Practices in the United States Prairie Pothole Region with an Emphasis on the US Department of Agriculture Conservation Reserve and Wetlands Reserve Programs*, USGS Professional Paper 1745, US Geological Service, 2008

P. Gosling, *et al*. (2017) "Converting Highly Productive Arable Cropland in Europe to Grassland - A Poor Candidate for Carbon Sequestration," *Scientific Reports* 7: 10493 DOI:10.1038/s41598-017-11083-6

A. Grandy and G. Robertson, "Land-use Intensity Effects on Soil Organic Carbon Accumulation Rates and Mechanisms," *Ecosystems 10* (2007): 58-73

J. Guzman and M. Al-Kaisi, "Soil Carbon Dynamics and Carbon Budget of Newly Reconstructed Tall-Grass Prairies in South Central Iowa," *Journal of Environmental Quality 39* (2010): 136-146

D. Hernandez, *et al*., "Rapid Accumulation of Soil Carbon and Nitrogen in a Prairie Restoration Chronosequence," *Soil Science Society of America Journal 77* (2012): 2,029-2,038

T. Hudiburg, *et al*., "Bioenergy Crop greenhouse Gas Mitigation Potential Under a Range of Management Practices," *Global Change Biology-Bioenergy 7* (2015): 366-374

D. Huggins, *et al*., "Enhancing Carbon Sequestration in CRP-Managed Land," chapter 22 in R. Lal, *et al*., eds., *Management of Carbon Sequestration in Soil* (Boca Raton: CRC Press, 1997)

T. Hurisso, *et al*., "Soil Profile Carbon and Nitrogen in Prairie, Perennial Grass-Legume Mixture and Wheat-Fallow Production in the Central High Plains, USA," *Agriculture, Ecosystems and Environment 181* (2013): 179-187

S. Hyberg, "Role of Science in Guiding Conservation Reserve Program: Past and Future," in USGS, *Proceedings of the Conservation Reserve Program-Planting for the Future Conference, Fort Collins, Colorado*, June 6-9, 2004

ICF International, *Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States*, report prepared for Climate Change Office, US Department of Agriculture, February 2013

Intergovernmental Panel on Climate Change, *IPCC Special Report: Land Use, Land Use Change, and Forestry* (Cambridge, UK: Cambridge University Press, 2000)

T. Ihori, *et al*., "Effects of Cultivation and Abandonment on Soil Organic Matter in Northeastern Colorado," *Soil Science Society of America Journal 59* (1995): 1,112-1,119

R. Izaurrralde, *et al*., "Simulating Soil C Dynamics with EPIC: Model Description and Testing Against Long Term Data," *Ecological Modeling 192* (2006): 362-384

M. Jarecki and R. Lal, "Crop Management for Soil Carbon Sequestration," *Critical Reviews in Plant Sciences 22* (2003): 471-502

J. Jastrow, *et al*., "Contributions of Interacting Biological Mechanisms to Soil Aggregate Stabilization in Restored Prairie," *Soil Biology and Biochemistry 30* (1998): 905-916

N. Jelinski and C. Kucharik, "Land-Use Effects on Soil Carbon and Nitrogen on a Midwestern Floodplain," *Soil Science Society of America Journal 73* (2009): 217-224

J. Johnson, *et al*., "Greenhouse Gas Contributions and Mitigation Potential of Agriculture in the Central USA," *Soil and Tillage Research 83* (2005): 73-94

E. Joo, *et al*., "The Influence of Drought and Heat Stress on Long-term Carbon Fluxes of Bioenergy Crops Grown in the Midwestern USA," *Plant, Cell and Environment 39* (2016): 1,928-1,940

I. Kampf, *et al*., "Potential of Temperate Agricultural Soils for Carbon Sequestration: A Meta-Analysis of Land-Use Effects," *Science of the Total Environment 566/567* (2016): 428-435

D. Karlen, *et al*., "Conservation Reserve Program Effects on Soil Quality Indicators," *Journal of Soil and Water Conservation 54* (1999): 439-444

D. Kim, *et al*., "The Effect of Land-use Change on the Net Exchange Rates of Greenhouse Gases: A Compilation of Estimates," *Agriculture, Ecosystems and Environment 208* (2015): 114-126

J. Knops and D. Tilman, "Dynamics of Soil Nitrogen and Carbon Accumulation for 16 Years after Agricultural Abandonment," *Ecology 8* (2000): 88-98

J. Knops and K. Bradley, "Soil Carbon and Nitrogen Accumulation and Vertical Distribution Across a 74-Year Chronosequence," *Soil Science Society of America Journal 73* (2009): 2,096-2,104

C. Kucharik, "Impact of Prairie Age and Soil Order on Carbon and Nitrogen Sequestration," *Soil Science Society of America Journal 71* (2007): 430-441

C. Kucharik, *et al*., "Measurements and Modeling of Carbon and Nitrogen Cycling in Agroecosystems of Southern Wisconsin: Potential for SOC Sequestration During the Next 50 Years," *Ecosystems 4* (2001): 237-258

C. Kucharik, *et al*., "Statistical Assessment of a Paired-Site Approach for Verification of Carbon and Nitrogen Sequestration on Wisconsin Conservation Reserve Program Land," *Journal of Soil and Water Conservation 58* (2003): 58-67

R. Lal, *et al*., *The Potential of US Cropland to Sequester Carbon and Mitigate the Greenhouse Effect* (Ann Arbor, Michigan: Ann Arbor Press, 1998)

R. Lal, *et al*., "Achieving Soil Carbon Sequestration in the United States: A Challenge to the Policy Makers," *Soil Science 168* (2003): 827-845

J. Lewandrowski, *et al*., *Economics of Sequestering Carbon in the US Agricultural Sector*, ERS Technical Bulletin 1909, Economic Research Service, US Department of Agriculture, 2004

C. Li, *et al*., "Carbon Sequestration Potential in Semi-Arid Grasslands in the Conservation Reserve Program," *Geoderma 294* (2017): 80-90

M. Liebig, *et al*., "Greenhouse Gas Contributions and Mitigation Potential of Agricultural Practices in Northwestern USA and Western Canada," *Soil Tillage and Research 83* (2005): 25-52

D. Martens, *et al*., "Atmospheric Carbon Mitigation Potential of Agricultural Management in the Southwestern United States," *Soil and Tillage Research 83* (2005): 95-119

R. Matamala, *et al*., "Temporal Changes in C and N Stocks of Restored Prairie: Implications for C Sequestration Strategies," *Ecological Applications 18* (2008): 1,470-1,488

K. McLauchlan, *et al*., "Conversion from Agriculture to Grassland Builds Soil Organic Matter on Decadal Timescales," *Ecological Applications 16* (2006): 143-153

F. Mensah, *et al*., "Soil Carbon Changes in Cultivated and Excavated Land Converted to Grasses in East-Central Saskatchewan," *Biogeochemistry 63* (2003): 85-92

J. Nelson, *et al*., "Soil Organic Carbon Changes and Distribution in Cultivated and Restored Grassland Soils in Saskatchewan," *Nutrient Cycling in Agroecosystems 82* (2008): 137-148

S. Nyawira, *et al*., "Soil Carbon Response to Land-Use Change: Evaluation of a Global Vegetation Model Using Observational Meta-Analyses," *Biogeosciences 13* (2016): 5,661-5,675

Office of the Chief Economist, US Department of Agriculture, *USDA Agriculture and Forest Greenhouse Gas Inventory: 1990-2008*, Technical Bulletin 1930, June 2011

S. Ogle, *et al*., "Agricultural Management Impacts on Soil Organic Carbon Storage Under Moist and Dry Climatic Conditions of Temperate and Tropical Regions," *Biogeochemistry 72* (2005): 87-121

R. Omonode and T. Vyn, "Vertical Distribution of Soil Organic Carbon and Nitrogen Under Warm-Season Native Grasses Relative to Croplands in West-Central Indiana, USA," *Agriculture, Ecosystems and Environment 117* (2006): 159-170

K. Paustian, *et al*., "Modeling and regional Assessment of Soil Carbon: A Case Study of the Conservation Reserve Program," in R. Lal, *et al*., eds., *Soil Management for Enhancing Carbon Sequestration, Soil Science Society of America Journal Special Publication* (Madison, Wisconsin: Soil Science Society of America, 2001), pp. 207-223

J. Pereira, *et al*., "Net Ecosystem Exchange in Three Contrasting Mediterranean Ecosystems - the Effect of Drought," *Biogeosciences 4* (2007): 791-802

R. Phillips and O. Beeri, "Scaling-Up Knowledge of Growing Season Net Ecosystem Exchange for Long-term Assessment of North Dakota Grasslands under the Conservation Reserve Program," *Global Change Biology 14* (2008): 1,008-1,017

R. Phillips, *et al*., "Soil Organic Carbon Beneath Croplands and Re-established Grasslands in the North Dakota Prairie Pothole Region," *Environmental Management 55* (2015): 1,191-1,199

G. Pineiro, *et al*., "Set Asides Can Be Better Climate Investment that Corn Ethanol," *Ecological Applications 19* (2009): 277-282

C. Poeplau, *et al*., "Temporal Dynamics of Soil Organic Carbon after Land-use Change in the Temperate Zone-Carbon Response Functions as a Model Approach," *Global Change Biology 17* (2011): 2,415-2,427

C. Poeplau and A. Don, "Sensitivity of Soil Organic Carbon Stocks and Fractions to Different Land-Use Changes Across Europe," *Geoderma 192* (2013): 189-201

W. Post and K. Kwon, "Soil Carbon Sequestration and Land-Use Change: Processes and Potential," *Global Change Biology 6* (2000): 317-328

K. Potter, *et al*., "Carbon Storage after Long-term Grass Establishment on Degraded Soils," *Soil Science 164* (1999): 718-725

K. Potter, "Soil Carbon Content After 55 years of Management of a Vertisol in Central Texas," *Journal of Soil and Water Conservation 61* (2006): 338-343

K. Potter and J. Derner, "Soil Carbon Pools in Central Texas: Prairies, Restored Grasslands, and Cropland," *Journal of Soil and Water Conservation 61* (2006): 124-128

T. Purakayastha, *et al*., "Carbon Sequestration in Native Prairie, Perennial Grass, No-Till, and Cultivated Palouse Silt Loam," *Soil Science Society of America Journal 72* (2008): 534-540

J. Reeder, *et al*., "Soil C and N Changes on Conservation reserve Program Lands in the Central Great Plains," *Soil and Tillage Research 47* (1998): 339-349

M. Robles and I. Burke, "Soil Organic Matter Recovery on Conservation Reserve Program Fields in Southeastern Wyoming," *Soil Science Society of America Journal 62* (1998): 725-730

U. Sainju, *et al*., "Tillage and Crop Rotation Effects on Dryland Soil and Residue Carbon and Nitrogen," *Soil Science Society of America Journal 70* (2006): 668-678

M. Schmitt, *et al*., "Land Use Affects the Net Ecosystem CO_2 Exchange and Its Components in Mountain Grasslands," *Biogeosciences 7* (2010): 2,297-2,309

G. Schuman, *et al*., "Soil Carbon Dynamics and Potential Carbon Sequestration by Rangelands," *Environmental Pollution 116* (2002): 391-396

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 Resources Ecology Laboratory and USDA- NRCS, 2002

P. Smith, *et al*., "Carbon Sequestration Potential in European Croplands Has Been Overestimated," *Global Change Biology 11* (2005): 2,153-2,163

P. Smith, *et al*., "Greenhouse Gas Mitigation in Agriculture," *Philosophical Transactions of the Royal Society B 363* (2008): 789-813

J. Soussana, *et al*., "Carbon Cycling and Sequestration Opportunities in Temperate Grasslands," *Soil Use and Management 20* (2004): 219-230

M. Sperow, "Estimating the Economic Value of temporary and Permanent Carbon Sequestration Activities on Agricultural Land," paper presented at the Southern Agricultural Economics Association Annual Meeting, Little Rock, Arkansas, February 5-8, 2005

M. Sperow, *et al*., "Potential Soil C Sequestration on US Agricultural Soils," *Climatic Change 57* (2003): 319-339

M. Sperow, "An Enhanced Method for Using the IPCC Approach to Estimate Soil Organic Carbon Storage Potential on US Agricultural Soils," *Agriculture, Ecosystems and Environment 193* (2014): 96-107

A. Suyker and S. Verma, "Year-Round Observations of the Net Ecosystem Exchange of Carbon Dioxide in a Native Tallgrass Prairie," *Global Change Biology 7* (2001): 279-289

A. Swan, *et al*., *COMET-Planner: Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning: A Companion Report to www.comet-planner.com*, NRCS-USDA and Colorado State, 2015

C. Turner, *et al*., *Assessing Forestation Opportunities for Carbon Sequestration in Minnesota*, report prepared the Minnesota Forest Resources Council, January 2010

US State Department, *2016 Second Biennial Report of the United States of American Under the United Nations Framework Convention on Climate Change*, 2016

A. VandenBygaart, *et al*., "Soil Carbon Factors for the Canadian Agriculture National Greenhouse Gas Inventory," *Canadian Journal of Soil Science 88* (2008): 671-680

L. Vleeshouwers and A. Verhagen, "Carbon Emission and Sequestration by Agricultural Land Use: A Model Study for Europe," *Global Change Biology 8* (2002): 519-530

N. Vuichard, *et al*., "Carbon Sequestration Due to the Abandonment of Agriculture in the former USSR Since 1990," *Global Biogeochemical Cycles 22* GB4018, doi:10.1029/2008GB003212 (2008)

X. Wang, *et al*., "Land Management History of Canadian Grassland and the Impact on Soil Carbon Storage," *Rangeland Ecology and Management 67* (2014): 333-343

L. Xu and D. Baldocchi, "Seasonal Variation in Carbon Dioxide Exchange Over Mediterranean Annual Grassland in California," *Agricultural and Forest Meteorology 123* (2004): 79-96

T. Zenone, *et al*., "From Set-Aside Grassland to Annual and Perennial Cellulosic Biofuel Crops: Effects of Land Use Change on a Carbon Balance," *Agricultural and Forest Meteorology 182-183* (2013): 1-12

M. Zeri, *et al*., "Carbon Exchange by Establishing Biofuels Crops in Central Illinois," *Agriculture, Ecosystems and Environment 144* (2011): 319-329

L. Zhang, *et al*., "Upscaling Carbon Fluxes Over the Great Plains Grasslands: Sinks and Sources," *Journal of Geophysical Research-Biogeosciences 116* (2011): 1-16

C. Zilverberg, *et al*., "Landscape Dependent Changes in Soil Properties Due to Long-Term Cultivation and Subsequent Conversion to Native Grass Agriculture," *Catena 160* (2018): 282-297

Cropland retirement to forestland-live biomass, litter, SOC/CO_2

F. Agostini, *et al*., "Carbon Sequestration by Perennial Energy Crops: Is the Jury Still Out?" *Bioenergy Research 8* (2015): 1,057-1,080

C. Amadi, *et al*., "Soil-Atmosphere Exchange of Carbon Dioxide, Methane and Nitrous Oxide in Shelterbelts Compared with Adjacent Cropped Fields," *Agriculture, Ecosystems and Environment 223* (2016): 123-134

C. Amadi, *et al*., "Greenhouse Gas Mitigation Potential of Shelterbelts: Estimating Farm-Scale Emission Reductions Using the Holos Model," *Canadian Journal of Soil Science 97* (2017): 353-367

B. Amichev, *et al*., "Carbon Sequestration by White Spruce Shelterbelts in Saskatchewan, Canada: 3PG and CBM-CFS3 Model Simulations," *Ecological Modeling 325* (2016): 35-46

B. Amichev, *et al*., "Carbon Sequestration and Growth of Six Common Tree and Shrub Shelterbelts in Saskatchewan, Canada," *Canadian Journal of Soil Science 97* (2017): 368-381

J. Anderson, *et al*., *The Potential for Terrestrial Carbon Sequestration in Minnesota: A Report to the Department of Natural Resources from the Minnesota Terrestrial Carbon Sequestration Initiative*, University of Minnesota, February 2008

C. Arevalo, *et al*., "Ecosystem Carbon Stocks and Distribution under Different Land-Uses in North Central Alberta, Canada," *Forest Ecology and Management 257* (2009): 1,776-1,785

C. Arevalo, *et al*., "Land Use Change Effects on Ecosystem Carbon Balance: From Agricultural to Hybrid Poplar Plantation," *Agriculture, Ecosystems and Environment 141* (2011): 342-349

D. Arrouays, *et al*., *Mitigation of the Greenhouse Effect: Increasing Carbon Stocks in French Agricultural Soils? Synthesis of an Assessment Report by the French Institute for Agricultural Research (INRA) on Request of the French Ministry for Ecology and Sustainable Development*, INRA, October 2002

W. Ballesteros-Possu, *et al*., "Estimating Carbon Storage in Windbreaks on US Agricultural Lands," *Agroforestry Systems 90* (2016): 889-904

J. Barker, *et al*., "Potential Carbon Benefits of the Conservation Reserve Program of the United States," *Journal of Biogeography 22* (1995): 743-751

J. Barker, *et al*., "Carbon Dynamics of the Conservation and Wetland Reserve Programs," *Journal of Soil and Water Conservation 51* (1996): 340-346

J. Brandle, *et al*., "Opportunities to Increase Tree Planting in Shelterbelts and the Potential Impacts on Carbon Storage and Conservation," chapter 9, in R. Sampson and D. Hair, eds., *Forests and Global Change, Vol. 1: Opportunities for Increasing Forest Cover* (Washington, D.C.: American Forests, 1992)

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 Resources Ecology Laboratory and USDA-NRCS, 2001

J. Bruce, *et al*., "Carbon Sequestration in Soils," *Journal of Soil and Water Conservation 54* (1999): 382-389

M. Callaway and S. Ragland, *An Analysis of Opportunities to Increase Carbon Sequestration on Timberland and Agricultural Land in the United States, 1993-2035*, report prepared for the Climate Change Division, US Environmental Protection Agency, RCG Hagler/Bailly, 1993

R. Chang, *et al*. (2014) "Soil Carbon and Nitrogen Changes Following Afforestation of Marginal Cropland Across a Precipitation Gradient in Loess Plateau of China," *PLoS ONE 9*(1): e85426. doi:10.1371/journal.pone.0085426

Y. Chendev, *et al*., "Accumulation of Organic Carbon in Chernozems (Mollisols) under Shelterbelts in Russia and the United States," *Eurasian Soil Science 48* (2015): 43-53

M. Coleman, *et al*., "Comparing Soil Carbon of Short Rotation Poplar Plantations with Agricultural Crops and Woodlots in North Central United States," *Environmental Management 33* (2004): S299-S308

P. Curtis, *et al*., "Biometric and Eddy-Covariance Based Estimates of Annual Carbon Storage in Five Eastern North American Deciduous Forests," *Agricultural and Forest Meteorology 113* (2002): 3-19

S. DeGryze, *et al*., "Soil Organic Carbon Pool Changes Following Land-Use Conversions," *Global Change Biology 10* (2004): 1,120-1,132

L. Deng, *et al*., "Global Patterns of the Effects of Land-Use Changes on Soil Carbon Stocks," *Global Ecology and Conservation 5* (2016): 127-138

S. Fang, *et al*., "Biomass Production and Carbon Sequestration Potential in Poplar Plantations with Different Management Patterns," *Journal of Environmental Management 85* (2007): 672-679

C. Fissore, *et al*., "Limited Potential for Terrestrial Carbon Sequestration to Offset Fossil-Fuel Emissions in the Upper Midwestern USA," *Frontiers in Ecology and the Environment 8* (2010): 409-413

C. Garten, "Soil Carbon Storage Beneath Recently Established Tree Plantations in Tennessee and South Carolina, USA," *Biomass and Bioenergy 23* (2002): 93-102

I. Gelfand and G. Robertson, "Mitigation of Greenhouse Gases in Agricultural Ecosystems," in S. Hamilton, *et al*., eds., *The Ecology of Agricultural Landscapes: Long-term Research on the Path to Sustainability* (New York: Oxford University Press, 2015) pp. 310-339

L. Guo and M. Gifford, "Soil Carbon Stocks and Land Use Change: A Meta Analysis," *Global Change Biology 8* (2002): 345-360

L. Heath, *et al*., "The Potential of US Forest Soils to Sequester Carbon," chapter 23 in J. Kimble, *et al*., eds., *The Potential of US Forest Soils to Sequester Carbon and to Mitigate the Greenhouse Effect* (Boca Raton: CRC Press, 2003) pp. 385-394

G. Hernandez-Ramirez, *et al*., "Carbon Sources and Dynamics in Afforested and Cultivated US Corn Belt Soils." *Soil Science Society of America Journal 75* (2010): 216-225

T. Hooker and J. Compton, "Forest Ecosystem Carbon and Nitrogen Accumulation during the First Century after Agricultural Abandonment," *Ecological Applications 13* (2003): 299-313

ICF International, *Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States*, report prepared for Climate Change Office, US Department of Agriculture, February 2013

M. Johnson, *et al*., "Changes in Ecosystem Carbon Storage Over 40 Years on an Old-Field/Forest Landscape in East-Central Minnesota," *Forest Ecology and Management 83* (1996): 17-26

D. Kim, *et al*., "The Effect of Land-use Change on the Net Exchange Rates of Greenhouse Gases: A Compilation of Estimates," *Agriculture, Ecosystems and Environment 208* (2015): 114-126

D. Kim, *et al*., "Carbon Sequestration and Net Emissions of CH_4 and N_2O under Agroforestry: Synthesizing Available Data and Suggestions for Future Studies," *Agriculture, Ecosystems and Environment 226* (2016): 65-78

J. Kort and J. Turnock, "Carbon Reservoir and Biomass in Canadian Prairie Shelterbelts," *Agroforestry Systems 44* (1999): 175-186

J. Laganiere, *et al*., "Carbon Accumulation in Agricultural Soils after Afforestation: A Meta-analysis," *Global Change Biology 16* (2010): 439-453

J. Lewandrowski, *et al*., *Economics of Sequestering Carbon in the US Agricultural Sector*, ERS Technical Bulletin 1909, Economic Research Service, US Department of Agriculture, 2004

D. Li and Y. Luo, "Global Patterns of the Dynamics of Soil Carbon and Nitrogen Stocks Following Afforestation: A Meta-Analysis," *New Phytologist 195* (2012): 172-181

D. McKinley, *et al*., "Woody Plant Encroachment by *Juniperus Virginiana* in a Mesic Native Grassland Promotes Rapid Carbon and Nitrogen Accrual," *Ecosystems 11* (2008): 454-468

A. Merino, *et al*., "Responses of Soil Organic Matter and Greenhouse Gas Fluxes to Soil Management and Land Use in a Humid Temperate Region of Southern Europe," *Soil Biology and Biochemistry 36* (2004): 917-925

B. Minasny, *et al*., "Soil Carbon 4 Per Mille," *Geoderma 292* (2017): 59-86

S. Morris, *et al*., "Evaluation of Carbon Accrual in Afforested Agricultural Soils," *Global Change Biology 13* (2007): 1,145-1,156

L. Nave, *et al*., "Afforestation Effects on Soil Carbon Storage in the United States: A Synthesis," Soil *Science Society of America Journal 77* (2013): 1,035-1,047

X. Niu and S. Duiker, "Carbon Sequestration Potential by Afforestation of Marginal Agricultural Land in the Midwestern US," *Forest Ecology and Management 223* (2006): 415-427

M. Norris, *et al*., "Assessing Changes in Biomass, Productivity, and C and N Stores Following *Juniperus Virginiana* Forest Expansion into Tallgrass Prairie," *Canadian Journal of Forest Resources 31* (2001): 1,940-1,946

S. Nyawira, *et al*., "Soil Carbon Response to Land-Use Change: Evaluation of a Global Vegetation Model Using Observational Meta-Analyses," *Biogeosciences 13* (2016): 5,661-5,675

P. Pardon, *et al*., "Trees Increase Soil Organic Carbon and Nutrient Availability in Temperate Agroforestry Systems," *Agriculture, Ecosystems and Environment 247* (2017): 98-111

E. Paul, *et al*., "Interpretation of Soil Carbon and Nitrogen Dynamics in Agricultural and Afforested Soils," *Soil Science Society of America Journal 67* (2003): 1,620-1,628

K. Paul, *et al*., "Change in Soil Carbon Following Afforestation," *Forest Ecology and Management 168* (2002): 241-257

M. Peichl, *et al*., "Carbon and Greenhouse Gas Balances in an Age Sequence of Temperate Pine Plantations," *Biogeosciences 11* (2014): 5,399-5,410

S. Pellerin, *et al*., "Identifying Cost-Competitive Greenhouse Gas Mitigation Potential of French Agriculture," *Environmental Science and Policy 77* (2017): 130-139

C. Poeplau and A. Don, "Sensitivity of Soil Organic Carbon Stocks and Fractions to Different Land-Use Changes Across Europe," *Geoderma 192* (2013): 189-201

C. Poeplau, *et al*., "Temporal Dynamics of Soil Organic Carbon after Land-use Change in the Temperate Zone-Carbon Response Functions as a Model Approach," *Global Change Biology 17* (2011): 2,415-2,427

P. Poulton, *et al*., "Accumulation of Carbon and Nitrogen by Old Arable Land Reverting to Woodland," *Global Change Biology 9* (2003): 945-955

K. Pregitzer and E. Euskirchen, "Carbon Cycling and Storage in World's Forests: Biome Patterns Related to Forest Age," *Global Change Biology 10* (2004): 2,052-2,077

D. Richter, *et al*., "Rapid Accumulation and Turnover of Soil Carbon in a Re-establishing Forest," *Nature 400* (1999): 56-57

G. Robertson, *et al*., "Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere," *Science 289* (2000): 1,922-1,925

T. Sauer, *et al*., "Soil Properties Following Reforestation or Afforestation of Marginal Cropland," *Plant Soil 360* (2012): 375-390

B. Scharenbroch, *et al*., "Tree Encroachment Impacts Carbon Dynamics in a Sand Prairie in Wisconsin," *Soil Science Society of America Journal 74* (2010): 956-968

M. Schoeneberger, "Agroforestry: Working Trees for Sequestering Carbon on Agricultural Lands," *Agroforestry Systems 75* (2009): 27-37

S. Shi, *et al*., "A Synthesis of Change in Deep Soil Organic Carbon Stored with Afforestation of Agricultural Soils," *Forest Ecology and Management 296* (2013): 53-63

P. Smith, *et al*., "Meeting Europe's Climate Change Commitments: Quantitative Estimates of the Potential for Carbon Mitigation by Agriculture," *Global Change Biology 6* (2000): 525-539

P. Smith, *et al*., "Carbon Sequestration Potential in European Croplands Has Been Overestimated," *Global Change Biology 11* (2005): 2,153-2,163

J. Smith, *et al*., *Methods for Calculating Forest Ecosystems and Harvested Carbon with Standard Estimates for Forest Types of the United States*, General Technical Report NE-343, Northeastern Research Station, US Forest Service, 2005

S. Smukler, *et al*., "Biodiversity and Multiple Ecosystem Functions in an Organic Farmscape," *Agriculture, Ecosystems and Environment 139* (2010): 80-97

A. Swan, *et al*., *COMET-Planner: Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning: A Companion Report to www.comet-planner.com*, NRCS-USDA and Colorado State, 2015

B. Thiel, *et al*., "Using Hedgerow Biodiversity to Enhance Carbon Storage of Farmland in the Fraser River Delta of British Columbia," *Journal of Soil and Water Conservation 70* (2015): 247-256

C. Turner, *et al*., *Assessing Forestation Opportunities for Carbon Sequestration in Minnesota*, report prepared the Minnesota Forest Resources Council, January 2010

R. Udawatta and S. Jose, "Carbon Sequestration Potential of Agroforestry Practices in Temperate North America," in B. Kumar and P. Nair, eds., *Carbon Sequestration Potential of Agroforestry Systems*, *Advances in Agroforestry 8* (Dordrecht: Springer, 2001) pp. 17-42

K. Updegraff, *et al*., "Environmental Benefits of Cropland Conversion to Hybrid Poplar: Economic and Policy Considerations," *Biomass and Bioenergy 27* (2004): 411-428

US Climate Change Science Program, *First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle*, March 2007

D. Ussiri, *et al*., "Soil Properties and Carbon Sequestration of Afforested Pastures in Reclaimed Minesoils of Ohio," *Soil Science Society of America Journal 70* (2006): 1,797-1,806

L. Vesterdal, *et al*., "Change in Soil Organic Carbon Following Afforestation of Former Arable Land," *Forest Ecology and Management 169* (2003): 137-147

S. Walker, *et al*., *Terrestrial Carbon Sequestration in the Northeast: Quantities and Costs. Part 3A. Opportunities for Improving Carbon Storage through Afforestation of Agricultural Lands*, report to US DOE-NETL, Winrock International, 2007

D. Williamson, *et al*., *Carbon Sequestration, Greenhouse Gases and Nebraska Agriculture-Background and Potential, Report of the Carbon Sequestration Advisory Committee to the Nebraska Department of Natural Resources*, 2001

R. Zalesny and W. Heedlee, "Developing Woody Crops for the Enhancement of Ecosystem Services under Changing Climates in the North Central United States," *Journal of Forest and Environmental Science* 31 (2015): 78-90

Shelterbelts/Hedges–N_2O

C. Amadi, *et al*., "Soil-Atmosphere Exchange of Carbon Dioxide, Methane and Nitrous Oxide in Shelterbelts Compared to Adjacent Cropped Fields," *Agriculture, Ecosystems and Environment 223* (2016): 123-134

C. Amadi, *et al*., "Greenhouse Gas Emissions along a Shelterbelt-Cropped Field Transect," *Agriculture, Ecosystems and Environment 241* (2017): 110-120

C. Amadi, *et al*., "Greenhouse Gas Mitigation Potential of Shelterbelts: Estimating Farm-Scale Emission Reductions Using the Holos Model," *Canadian Journal of Soil Science 97* (2017): 353-367

C. Amadi, *et al*., "Dynamics of Soil-Derived Greenhouse Gas Emissions from Shelterbelts under Elevated Soil Moisture Conditions in a Semi-Arid Prairie Environment," *Agroforestry Systems 92* (2018): 321-334

M. Baah-Acheamfour, *et al*., "Forest and Grassland Cover Types Reduce Net Greenhouse Gas Emission from Agricultural Soils," *Science of the Total Environment 571* (2016): 1,115-1,127

A. Swan, *et al*., *COMET-Planner: Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning: A Companion Report to www.comet-planner.com*, NRCS-USDA and Colorado State, 2015

B. Thiel, *et al*., "Soil CO_2, CH_4 and N_2O Emissions from Production Fields with Planted and Remnant Hedgerows in the Fraser River Delta of British Columbia," *Agroforestry Systems 91* (2017): 1,139-1,156

Shelterbelts/Hedges–CH_4

C. Amadi, *et al*., "Soil-Atmosphere Exchange of Carbon Dioxide, Methane and Nitrous Oxide in Shelterbelts Compared to Adjacent Cropped Fields," *Agriculture, Ecosystems and Environment 223* (2016): 123-134

C. Amadi, *et al*., "Greenhouse Gas Emissions along a Shelterbelt-Cropped Field Transect," *Agriculture, Ecosystems and Environment 241* (2017): 110-120

C. Amadi, *et al*., "Greenhouse Gas Mitigation Potential of Shelterbelts: Estimating Farm-Scale Emission Reductions Using the Holos Model," *Canadian Journal of Soil Science 97* (2017): 353-367

C. Amadi, *et al*., "Dynamics of Soil-Derived Greenhouse Gas Emissions from Shelterbelts under Elevated Soil Moisture Conditions in a Semi-Arid Prairie Environment," *Agroforestry Systems 92* (2018): 321-334

M. Baah-Acheamfour, *et al*., "Forest and Grassland Cover Types Reduce Net Greenhouse Gas Emission from Agricultural Soils," *Science of the Total Environment 571* (2016): 1,115-1,127

B. Thiel, *et al*., "Soil CO_2, CH_4 and N_2O Emissions from Production Fields with Planted and Remnant Hedgerows in the Fraser River Delta of British Columbia," *Agroforestry Systems 91* (2017): 1,139-1,156

Shelterbelts/Hedges–living biomass, litter, SOC–CO_2

C. Amadi, *et al*., "Soil-Atmosphere Exchange of Carbon Dioxide, Methane and Nitrous Oxide in Shelterbelts Compared with Adjacent Cropped Fields," *Agriculture, Ecosystems and Environment 223* (2016): 123-134

C. Amadi, *et al*., "Greenhouse Gas Mitigation Potential of Shelterbelts: Estimating Farm-Scale Emission Reductions Using the Holos Model," *Canadian Journal of Soil Science 97* (2017): 353-367

B. Amichev, *et al*., "Carbon Sequestration by White Spruce Shelterbelts in Saskatchewan, Canada: 3PG and CBM-CFS3 Model Simulations," *Ecological Modeling 325* (2016): 35-46

B. Amichev, et *al.*, "Carbon Sequestration and Growth of Six Common Tree and Shrub Shelterbelts in Saskatchewan, Canada," *Canadian Journal of Soil Science 97* (2017): 368-381

D. Arrouays, *et al*., *Mitigation of the Greenhouse Effect: Increasing Carbon Stocks in French Agricultural Soils? Synthesis of an Assessment Report by the French Institute for Agricultural Research (INRA) on Request of the French Ministry for Ecology and Sustainable Development*, INRA, October 2002

W. Ballesteros-Possu, *et al*., "Estimating Carbon Storage in Windbreaks on US Agricultural Lands," *Agroforestry Systems 90* (2016): 889-904

J. Brandle, *et al*., "Opportunities to Increase Tree Planting in Shelterbelts and the Potential Impacts on Carbon Storage and Conservation," chapter 9, in R. Sampson and D. Hair, eds., *Forests and Global Change, Vol. 1: Opportunities for Increasing Forest Cover* (Washington, D.C.: American Forests, 1992)

Y. Chendev, *et al*., "Accumulation of Organic Carbon in Chernozems (Mollisols) under Shelterbelts in Russia and the United States," *Eurasian Soil Science 48* (2015): 43-53

J. Fargione, *et al*. (2018) "Natural Climate Solutions for the United States," *Science Advances.4.*eaat1869.DOI: 10.1126/sciadv.aat1869

L. Heath, *et al*., "The Potential of US Forest Soils to Sequester Carbon," chapter 23 in J. Kimble, *et al*., *The Potential of US Forest Soils to Sequester Carbon and to Mitigate the Greenhouse Effect* (Boca Raton: CRC Press) pp. 385-394

D. Kim, *et al*., "Carbon Sequestration and Net Emissions of CH_4 and N_2O under Agroforestry: Synthesizing Available Data and Suggestions for Future Studies," *Agriculture, Ecosystems and Environment 226* (2016): 65-78

J. Kort and J. Turnock, "Carbon Reservoir and Biomass in Canadian Prairie Shelterbelts," *Agroforestry Systems 44* (1999): 175-186

R. Lal, *et al*., "Achieving Soil Carbon Sequestration in the United States: A challenge to the Policymakers," *Soil Science 168* (2003): 827-845

N. Lenka, *et al*., "Soil Carbon Sequestration and Soil Erosion Control Potential of Hedgerows and Grass Filter Strips in Sloping Agricultural Lands of Eastern India," *Agriculture, Ecosystems and Environment 158* (2012): 31-40

F. Montagnini and P. Nair, "Carbon Sequestration: An Unexploited Environmental Benefit of Agroforestry Systems," *Agroforestry Systems 61* (2004): 281-295

P. Pardon, *et al*., "Trees Increase Soil Organic Carbon and Nutrient Availability in Temperate Agroforestry Systems," *Agriculture, Ecosystems and Environment 247* (2017): 98-111

S. Pellerin, *et al*., "Identifying Cost-Competitive Greenhouse Gas Mitigation Potential of French Agriculture," *Environmental Science and Policy 77* (2017): 130-139

T. Sauer, *et al*., "Soil Carbon and Tree Litter Dynamics in a Red Cedar-Scotch Pine Shelterbelt," *Agroforestry Systems 71* (2007): 163-174

M. Schoeneberger, "Agroforestry: Working Trees for Sequestering Carbon on Agricultural Lands," *Agroforestry Systems 75* (2009): 27-37

S. Smukler, *et al*., "Biodiversity and Multiple Ecosystem Functions in an Organic Farmscape," *Agriculture, Ecosystems and Environment 139* (2010): 80-97

A. Swan, *et al*., *COMET-Planner: Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning: A Companion Report to www.comet-planner.com*, NRCS-USDA and Colorado State, 2015

B. Thiel, *et al*., "Using Hedgerow Biodiversity to Enhance Carbon Storage of Farmland in the Fraser River Delta of British Columbia," *Journal of Soil and Water Conservation 70* (2015): 247-256

R. Udawatta and S. Jose, "Carbon Sequestration Potential of Agroforestry Practices in Temperate North America," in B. Kumar and P. Nair, eds., *Carbon Sequestration Potential of Agroforestry Systems, Advances in Agroforestry 8 (*Dordrecht: Springer, 2011) pp. 17-42

F. Wang, *et al*. (2013) "Biomass Accumulation and Carbon Sequestration in Four Different Aged Cauarina equisetifolia Coastal Shelterbelt Plantations in South China," *PLoS ONE 8*(10): e77449. doi:10.1371/journal.pone.0077449

D. Williamson, *et al*., *Carbon Sequestration, Greenhouse Gases and Nebraska Agriculture-Background and Potential,* Report of the Carbon Sequestration Advisory Committee to the Nebraska Department of Natural Resources, 2001

Field borders, filter strips, contour buffer strips, vegetated barriers–N_2O

J. Iqbal, *et al*., "Denitrification and Nitrous Oxide Emissions in Annual Cropland, Perennial Grass Buffers, and Restored Perennial Grasslands," *Soil Science Society of America Journal 79* (2015): 231-244

Grassland references above in “Cropland Retirement to Grasslands or Forested land – N_2O**”**

Field borders, filter strips, contour buffer strips, vegetated barriers–CH_4

Grassland references above in “Cropland Retirement to Grasslands or Forested land – CH_4**”**

Field borders, filter strips, contour buffer strips, vegetated barriers–SOC/CO_2

H. Blanco-Canqui, *et al*., "Soil Carbon Accumulation under Switchgrass barriers," *Agronomy Journal 106* (2014): 2,185-2,192

N. Brouchard, *et al*., "The Capacity of Vegetative Filter Strps and Swales to Sequester Carbon," *Ecological Engineering 54* (2013): 227-232

P. Falloon, *et al*., "Managing Field Margins for Biodiversity and Carbon Sequestration: A Great Britain Case Study," *Soil Use and Management 20* (2004): 240-247

N. Lenka, *et al*., "Soil Carbon Sequestration and Soil Erosion Control Potential of Hedgerows and Grass Filter Strips in Sloping Agricultural Lands of Eastern India," *Agriculture, Ecosystems and Environment 158* (2012): 31-40

P. Pardon, *et al*., "Trees Increase Soil Organic Carbon and Nutrient Availability in Temperate Agroforestry Systems," *Agriculture, Ecosystems and Environment 247* (2017): 98-111

M. Perez-Suarez, *et al*., "Nitrogen and Carbon Dynamics in Prairie Vegetation Strips across Topographical Gradients in Mixed Central Iowa Agroecosystems," *Agriculture, Ecosystems and Environment* 188 (2014): 1-11

A. Swan, *et al*., *COMET-Planner: Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning: A Companion Report to www.comet-planner.com*, NRCS-USDA and Colorado State, 2015

Grassland references above in “Cropland Retirement to Grasslands- live biomass, SOC/CO_2”

Riparian buffers–N_2O

P. Ambus and S. Christensen, "Spatial and Seasonal Nitrous Oxide and Methane Fluxes in Danish Forest, Grassland and Agroecosystems," *Journal of Environmental Quality 24* (1995): 993-1,001

P. Baas, *et al*., "Areas of Residential Development in the Southern Appalachian Mountains are Characterized by Low Riparian Zone Nitrogen Cycling and No Increase in Soil Greenhouse Gas Emissions," *Biogeochemistry 113* (2017): 113-125

T. Burt, *et al*., "Denitrification in Riparian Buffer Zones: The Role of Floodplain Hydrology," *Hydrological Processes 13* (1999): 1,451-1,463

I. Creed, *et al*., "Hydrological Profiling for Greenhouse Gas Effluxes from Natural Grasslands in the Prairie Pothole Region of Canada," *Journal of Geophysical Research- Biosciences* 118 (2013), 680-697

M. Davis, “Nitrous Oxide Emissions from Saturated Riparian Buffers: Are We Trading a Water Quality Problem for an Air Quality Problem," chapter 3, M. Davis, *Greenhouse Gas Emissions from Saturated Riparian Buffers and Woodchip BioReactors*, PhD Dissertation, Iowa State, 2018

K. Dhondt, *et al*., "Temporal and Spatial Patterns of Denitrification Enzyme Activity and Nitrous Oxide Fluxes in Three Adjacent Vegetated Riparian Buffer Zones," *Biology and Fertility of Soils 40* (2004): 243-251

A. Dunmola, *et al*., "Pattern of Greenhouse Gas Emissions from a Prairie Pothole Agricultural Landscape in Manitoba, Canada," *Canadian Journal of Soil Science 90* (2010): 243-256

A. Eagle, *et al*., *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States: A Synthesis of the Literature*, 3rd edition, Nicholas Institute, Duke University, January 2012

K. Fisher, *et al*., "Nitrous Oxide Emission from Cropland and Adjacent Riparian Buffers in Contrasting Hydrogeomorphic Settings," *Journal of Environmental Quality 43* (2014): 338-348

J. Gomez, *et al*., "Spatial and Temporal Patterns of CO_2, CH_4, and N_2O Fluxes at the Soil-Atmosphere Interface in a Northern Temperate Forested Watershed," *Insights of Forest Research 1* (2017): 1-12 G.

G. Gopalakrishnan, *et al*., "Modeling Biogeochemical Impacts of Bioenergy Buffers with Perennial Grass for a Row-Crop Field in Illinois," *Global Change Biology-Bioenergy 4* (2012): 739-750

M. Hefting, *et al*., "Nitrous Oxide Emission and Denitrification in Chronically Nitrate-Loaded Riparian Buffer Zones," *Journal of Environmental Quality 32* (2003): 1,194-1,203

M. Hefting, *et al*., "Spatial Variation in Denitrification and N_2O Emission in Relation to Nitrate Removal Efficiency in an N-Stressed Riparian Buffer Zone," *Ecosystems 9* (2006): 550-563

S. Hinshaw and R. Dahlgren, "Nitrous Oxide Fluxes and Dissolved N Gases (N_2 and N_2O) Within Riparian Zones along the Agriculturally Impacted San Joaquin River," *Nutrient Cycling in Agroecosystems 105* (2016): 85-102

K. Hopfensperger, *et al*., "Influence of Plant Communities and Soil Properties on Trace Gas Fluxes in Riparian Northern Harwood Forests," *Forest Ecology and Management 258* (2009): 2,076-2,082

P. Jacinthe, *et al*., "Nitrous Oxide Emission from Riparian Buffers in Relation to Vegetation and Flood Frequency," *Journal of Environmental Quality 41* (2012): 95-105

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

D. Kim, *et al*., "Nitrous Oxide Emissions from Riparian Forest Buffers, Warm-Season and Cool-Season Grass Filters, and Crop Fields," *Biogeosciences Discussions 6* (2009): 607-650

D. Kim, *et al*., "Background Nitrous Oxide Emissions in Agricultural and Natural Lands: a Meta-analysis," *Plant Soil 373* (2013): 17-30

D. Kim, *et al*., "Carbon Sequestration and Net Emissions of CH_4 and N_2O under Agroforestry: Synthesizing Available Data and Suggestions for Future Studies," *Agriculture, Ecosystems and Environment 226* (2016): 65-78

S. Machefert, *et al*., "Nitrous Oxide Emissions from Two Riparian Ecosystems: Key Controlling Variables," *Water, Air, and Soil Pollution 4* (2004): 427-436

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*

Catchments for Biomass Production, Water Quality, and Food Security, IAEA TechDOC 1784 (Geneva: IAEA, 2016) pp. 115-133

U. Mander, *et al*., "Isotopologue Ratios of N_2O and N_2 Measurements Underpin the Importance of Denitrification in Differently N-Loaded Riparian Alder Forests," *Environmental Science and Technology 48* (2014): 11,910-11,918

U. Mander, *et al*., "Gaseous Carbon and Nitrogen Fluxes in Riparian Alder Stands," *Boreal Environmental Research 13* (2008): 231-241

U. Mander, *et al*., "Emission of Greenhouse Gases from Constructed Wetlands for Wastewater Treatment and from Riparian Buffer Zones," *Water Science and Technology 52* (2005): 167-176

W. Merbach, *et al*., "Trace Gas Emissions from Riparian Areas of Small Eutrophic Waters in Northeast Germany," in G. Broil, *et al*.,eds., *Wetlands in Central Europe: Soil Organics, Soil Ecological Processes and Trace Gas Emissions* (London: Springer, 2012) pp. 235-244

D. Pennock, *et al*., "Landscape Controls on N_2O and CH_4 Emissions from Freshwater Mineral Soil Wetlands of the Canadian Prairie Pothole Region," *Geoderma 155* (2010): 308-319

S. Poblador, *et al*., "Soil Water Content Drives Spatiotemporal Patterns of CO_2 and N_2O Emissions from a Mediterranean Forest Soil," *Biogeosciences 14* (2017): 4,195-4,208

P. Saari, *et al*., "Emissions and Dynamics of N_2O in a Buffer Wetland Receiving Flows from a Forested Peatland," *Boreal Environmental Research 18* (2013): 164-180

K. Schelde, *et al*., "Spatial and Temporal Variability of Nitrous Oxide Emissions in a Mixed Farming Landscape in Denmark," *Biogeosciences 9* (2012): 2,989-3,002

K. Soosaar, *et al*., "Dynamics of Gaseous Nitrogen and Carbon Fluxes in Riparian Alder Forests," *Ecological Engineering 37* (2011): 40-53

A. Swan, *et al*., *COMET-Planner: Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning: A Companion Report to www.comet-planner.com*, NRCS-USDA and Colorado State, 2015

S. Teiter and U. Mander, "Emission of N_2O, N_2, CH_4 and CO_2 from Constructed Wetlands for Wastewater Treatment from Riparian Buffer Zones," *Ecological Engineering 25* (2005): 528-541

S. Ullah and T. Moore (2011) "Biogeochemical Controls on Methane, Nitrous Oxide and Carbon Dioxide Fluxes from Deciduous Soils in Eastern Canada," *Journal of Geophysical Research 116*, G03010, doi:10.1029/2010JG001525

P. Vidon and S. Serchan, "Landscape Geomorphic Characteristic Impacts on Greenhouse Gas Fluxes in Exposed Stream and Riparian Sediments," *Environmental Science Process & Impacts 18* (2016): 844-853

G. Vilain, *et al*., "Effect of Slope Position and Land Use on Nitrous Oxide (N_2O) Seine Basin, France," *Agricultural and Forest Meteorology 150* (2010): 1,192-1,020

J. Walker, *et al*., "Nitrogen Trace Gas Emissions from a Riparian Ecosystem in Southern Appalachia," *Chemosphere 49* (2002): 1,389-1,398

D. Weller, *et al*., "Denitrification in Riparian Forests Receiving Agricultural Discharges," in W. Mitsch, ed., *Global Wetlands: Old World and New* (London: Elsevier Science, 1994), pp 117-131

Riparian buffers–CH_4

P. Ambus and S. Christensen, "Spatial and Seasonal Nitrous Oxide and Methane Fluxes in Danish Forest, Grassland and Agroecosystems," *Journal of Environmental Quality 24* (1995): 993-1,001

E. Aronson, *et al*. (2012) "Methane Flux Response to Nitrogen Amendment in an Upland Pine Forest Soil and Riparian Zone," *Journal of Geophysical Research-Biogeosciences 117*, G03012, doi:10.1029/2012JG001962

P. Baas, *et al*., "Areas of Residential Development in the Southern Appalachian Mountains are Characterized by Low Riparian Zone Nitrogen Cycling and No Increase in Soil greenhouse Gas Emissions," *Biogeochemistry 113* (2017): 113-125

I. Creed, *et al*., "Hydrological Profiling for Greenhouse Gas Effluxes from Natural Grasslands in the Prairie Pothole Region of Canada," *Journal of Geophysical Research- Biosciences* 118 (2013), 680-697

A. Dunmola, *et al*., "Pattern of Greenhouse Gas Emissions from a Prairie Pothole Agricultural Landscape in Manitoba, Canada," *Canadian Journal of Soil Science 90* (2010): 243-256

A. Eagle, *et al*., *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States: A Synthesis of the Literature*, 3rd edition, Nicholas Institute, Duke University, January 2012

E. Friedman, *et al*., "Methane Emission in a Specific Riparian-Zone Sediment Decreased with Bioelectrochemical Manipulation and Corresponded to the Microbial Community Dynamics," *Frontiers in Microbiology 6* (2016): 1-11

J. Garnier, *et al*., "Budget of Methane Emissions from Soils, Livestock and the River Network at the Regional Scale of the Seine basin (France)," *Biogeochemistry 116* (2013): 199-214

Gomez, *et al*., "Spatial and Temporal Patterns of CO_2, CH_4, and N_2O Fluxes at the Soil-Atmosphere Interface in a Northern Temperate Forested Watershed," *Insights of Forest Research 1* (2017): 1-12

P. Jacinthe, *et al*., "Soil Methane and Carbon Dioxide Fluxes from Cropland and Riparian Buffers in Different Hydrogeomorphic Settings," *Journal of Environmental Quality 44* (2015): 1,080-1,090

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

K. Kaiser, *et al*., "Landscape Analysis of Soil Methane Flux across Complex Terrain," *Biogeosciences 15* (2018): 3,143-3,167

D. Kim, *et al*., "Methane Flux in Cropland and Adjacent Riparian Buffers with Different Vegetation Covers," *Journal of Environmental Quality 39* (2010): 97-105

D. Kim, *et al*., "Carbon Sequestration and Net Emissions of CH_4 and N_2O under Agroforestry: Synthesizing Available Data and Suggestions for Future Studies," *Agriculture, Ecosystems and Environment 226* (2016): 65-78

U. Mander, *et al*., "Emission of Greenhouse Gases from Constructed Wetlands for Wastewater Treatment and from Riparian Buffer Zones," *Water Science and Technology 52* (2005): 167-176

U. Mander, *et al*., "Gaseous Carbon and Nitrogen Fluxes in Riparian Alder Stands," *Boreal Environmental Research 13* (2008): 231-241

W. Merbach, *et al*., "Trace Gas Emissions from Riparian Areas of Small Eutrophic Waters in Northeast Germany," in G. Broil, *et al*., eds., *Wetlands in Central Europe: Soil Organics, Soil Ecological Processes and Trace Gas Emissions* (London: Springer, 2012) pp. 235-244

D. Pennock, *et al*., "Landscape Controls on N_2O and CH_4 Emissions from Freshwater Mineral Soil Wetlands of the Canadian Prairie Pothole Region," *Geoderma 155* (2010): 308-319

K. Soosaar, *et al*., "Dynamics of Gaseous Nitrogen and Carbon Fluxes in Riparian Alder Forests," *Ecological Engineering 37* (2011): 40-53

S. Teiter and U. Mander, "Emission of N_2O, N_2, CH_4, and CO_2 from Constructed Wetlands for Wastewater treatment and From Riparian Buffer Zones," *Ecological Engineering 25* (2005): 528-541

P. Vidon and S. Serchan, "Landscape Geomorphic Characteristic Impacts on Greenhouse Gas Fluxes in Exposed Stream and Riparian Sediments," *Environmental Science Process & Impacts 18* (2016): 844-853

Riparian buffers–living biomass, litter, SOC–CO_2

J. Bruce, *et al*., "Carbon Sequestration in Soils," *Journal of Soil and Water Conservation 54* (1999): 382-389

A. Chambers, *et al*., "Soil Sequestration Potential of US Croplands and Grassland: Implementing the 4 per Thousand Initiative," *Journal of Soil and Water Conservation 71* (2016): 68A-74A

K. Dybala, *et al*., "Carbon Sequestration in Riparian Forests: A Global Synthesis and Meta-analysis," *Global Change Biology 25* (2019): 57-67

A. Eagle, *et al*., *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States: A Synthesis of the Literature*, 3rd edition, Nicholas Institute, Duke University, January 2012

S. Fennessy and C. Craft, "Agricultural Conservation Practices Increase Wetland Ecosystem Services in the Glaciated Interior Plains," *Ecological Applications 21* (2011): S49-S64

J. Fortier, *et al*., "Nutrient Accumulation and Carbon Sequestration in 6-Year-Old Hybrid Poplars in Multiclonal Agricultural Riparian Buffer Strips," *Agriculture, Ecosystems and Environment 137* (2010): 276-287

J. Fortier, *et al*., "Biomass Carbon, Nitrogen and Phosphorus Stocks in Hybrid Poplar Buffers, Herbaceous Buffers and Natural Woodlots in the Riparian Zone in Agricultural Land," *Journal of Environmental Management 154* (2015): 333-345

J. Fortier, *et al*. (2016) "Potential for Hybrid Poplar Riparian Buffers to Provide Ecosystem Services in Three Watersheds with Contrasting Agricultural Land Use," *Forests* 7,37; doi:10.3390/f7020037

M. Hernandez, *et al*., *Carbon Sequestration Potential of Agroforestry Practices in the L'Omiere River Watershed in Quebec*, Agriculture and Agri-food Canada, 2008

ICF International, *Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States*, report prepared for the USDA, Climate Change Program Office, February 2013

D. Kim, *et al*., "Carbon Sequestration and Net Emissions of CH_4 and N_2O under Agroforestry: Synthesizing Available Data and Suggestions for Future Studies," *Agriculture, Ecosystems and Environment 226* (2016): 65-78

J. Kochendorfer, *et al*., "Net Ecosystem Exchange, Evapotranspiration and Canopy Conductance in a Riparian Forest," *Agricultural and Forest Meteorology 151* (2011): 544-553

R. Lal, *et al*., *The Potential of US Cropland to Sequester Carbon and Mitigate the Greenhouse Effect* (Ann Arbor: Ann Arbor Press, 1998)

R. Lal, *et al*., "Achieving Soil Carbon Sequestration in the United States: A Challenge to Policy Makers," *Soil Science 12* (2003): 827-845

J. Lewandrowski, *et al*., *Economics of Sequestering Carbon in the U.S. Agricultural Sector*, Technical Bulletin 1909, Economic Research Service, US Department of Agriculture, April 2004

D. Lewis, *et al*., *Creek Carbon: Mitigating Greenhouse Gas Emissions through Riparian Revegetation*, University of California Cooperative Extension, 2015

X. Ma, *et al*., "Carbon Dioxide Fluxes and Their Environmental Controls in a Riparian Forest in the Hyper-Arid Region of Northwest China," *Forests 8* (2017): 379

C. Marquez, *et al*., "Assessing Soil Quality in a Riparian Buffer by Testing Organic Matter Fractions in Central Iowa, USA," *Agroforestry Systems 44* (1999): 133-140

J. Marton, *et al*., "USDA Conservation Practices Increase Carbon Storage and Water Quality Improvement Functions: An Example from Ohio," *Restoration Ecology 22* (2014): 117-124

V. Matzek, *et al*., "Can Carbon Credits Fund Riparian Forest Restoration?" *Restoration Ecology 23* (2015): 7-14

V. Matzek, *et al*., "Development of a Carbon Calculator Tool for Riparian Forest Restoration," *Applied Vegetation Science 21* (2018): 585-594

F. Montagnini and P. Nair, "Carbon Sequestration: An Underexploited Environmental Benefit of Agroforestry Systems," *Agroforestry Systems 61* (2004): 281-295

J. McKay, *et al*., "Riparian Reforestation: Are There Changes in Soil Carbon and Soil Microbial Communities?" *Science of the Total Environment 566/567* (2016): 960-967

P. Nair and V. Nair, "Carbon Storage in North American Agroforestry Systems," chapt. 20, in J. Kimble, *et al.*, eds., *The Potential of US Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect* (Boca Raton: CRC Press, 2003), pp. 333-346

S. Pellerin, *et al*., "Identifying Cost-Competitive Greenhouse Gas Mitigation Potential of French Agriculture," *Environmental Science and Policy 77* (2017): 130-139

R. Rheinhardt, *et al*., "Carbon Storage of Headwater Riparian Zones in an Agricultural Landscape," *Carbon Balance and Management 7* (2012): 1-4

I. Rieger, *et al*., "Interplay of Sedimentation and Carbon Accretion in Riparian Forests," *Geomorphology 214* (2014): 157-167

I. Rieger, *et al*., "A Novel Dendrochronological Approach Reveals Drivers of Carbon Sequestration in Tree Species of Riparian Forests across Spatiotemporal Scales," *Science of the Total Environment 574* (2017): 1,261-1,275

R. Scott, *et al*., "Ecohydrological Impacts of Wood Plant Encroachment: Seasonal Patterns of Water and Carbon Dioxide Exchange within a Semiarid Riparian Environment," *Global Change Biology 1*2 (2006): 311-324

D. Shoch, *et al*., "Carbon Storage of Bottomland Hardwood Afforestation in the Lower Mississippi Valley, USA," *Wetlands 29* (2009): 535-542

J. Smith, *et al*., *Methods for Calculating Forest Ecosystems and Harvested Carbon with Standard Estimates for Forest Types of the United States*, General Technical Report NE-343, Northeastern Research Station, US Forest Service, 2005

S. Smukler, *et al*., "Biodiversity and Multiple Ecosystem Functions in an Organic Farmscape," *Agriculture, Ecosystems and Environment 139* (2010): 80-97

A. Swan, *et al*., *COMET-Planner: Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning: A Companion Report to www.comet-planner.com*, NRCS-USDA and Colorado State, 2015

A. Tufekcioglui, *et al*., "Biomass, Carbon and Nitrogen Dynamics of Multi-Species Riparian Buffers within an Agricultural Watershed in Iowa," *Agroforestry Systems 57* (2003): 187-198

R. Udawatta and S. Jose, "Agroforestry Strategies to Sequester Carbon in Temperate North America," *Agroforestry Systems 86* (2012): 225-242

D. Williamson, *et al*., *Carbon Sequestration, Greenhouse Gases and Nebraska Agriculture-Background and Potential*, Report of the Carbon Sequestration Advisory Committee to the Nebraska Department of Natural Resources, 2001

Winter cover crops/catch crops–N_2O

A. Basche, *et al*., "Do Cover Crops Increase or Decrease Nitrous Oxide Emissions? A Meta-Analysis," *Journal of Soil and Water Conservation 69* (2014): 471-481

E. Baggs, *et al*., "Nitrous Oxide Emissions Following the Application of Residues and Fertilizer under Zero and Conventional Tillage," *Plant Soil 254* (2003): 361-370

M. Cavigelli and T. Parkin, "Cropland Management Contributions to Greenhouse Gas Flux: Central and Eastern U.S.," chapter 9 in M. Liebig, *et al*., eds., *Managing Agricultural Greenhouse Gases* (London: Academic Press, 2012), pp. 129-165

N. Chirinda, *et al*., "Soil Properties, Crop Production and Greenhouse Gas Emissions from Organic and Inorganic Fertilizer-based Arable Cropping Systems," *Agriculture, Ecosystems and Environment 139* (2010): 584-594

N. Chrinda, *et al*., "Emissions of Nitrous Oxide from Arable Organic and Conventional Cropping Systems on Two Soil Types," *Agriculture, Ecosystems and Environment 136* (2010): 199-208

B. Davis, *et al*., "Nitrous Oxide Emissions Increase Exponentially with Organic N Rate from Cover Crops and Applied Turkey Litter," *Agriculture, Ecosystems and Environment 272* (2019): 165-174

S. De Gryze, *et al*., "Simulating Greenhouse Gas Budgets of Four California Cropping Systems under Conventional and Alternative Management," *Ecological Applications 20* (2010): 1805-1819

S. DeGryze, *et al*., "Assessing the Potential for Greenhouse Gas Mitigation in Intensively-Managed Annual Cropping Systems at the Regional Scale," *Agriculture, Ecosystems and Environment 144* (2011): 150-158

K. Denef, *et al*., *Greenhouse Gas Emissions from U.S. Agriculture and Forestry: A Review of Emission Sources, Controlling factors, and Mitigation Potential*. Interim Report to USDA under contract #G-23F-8182H, ICF International, 2011

A. Eagle, *et al*., *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States: A Synthesis of the Literature*, 3rd edition, Nicholas Institute, Duke University, January 2012

N. Farahbakhshazad, *et al*., "Modeling Biogeochemical Impacts of Alternative Management Practices for a Row-Crop Field in Iowa," *Agriculture, Ecosystems and Environment 123* (2008): 30-48

T. Fisher, *et al*., "Fluxes of Nitrous Oxide and Nitrate from Agricultural Fields on the Delmarva Peninsula: N Biogeochemistry and Economics of Field Management," *Agriculture, Ecosystems and Environment 254* (2018): 162-178

B. Fronning, *et al*., "Use of Manure, Compost, and Cover Crops to Supplant Crop Residue Carbon in Corn Stover Removed Cropping Systems," *Agronomy Journal 100* (2008): 1,703-1,710

I. Gelfand and G. Robertson, "Mitigation of Greenhouse Gases in Agricultural Ecosystems," in S. Hamilton, *et al*., eds., *The Ecology of Agricultural Landscapes: Long-term Research on the Path to Sustainability* (New York: Oxford University Press, 2015), pp. 310-339

K. Gillette, *et al*., "N Loss to Drain Flow and N_2O Emissions from a Corn-Soybean Rotation with Winter Rye," *Science of the Total Environment 618* (2018): 982-997

G. Guardia, *et al*., "Effect of Cover Crops on Greenhouse Gas Emissions in an Irrigated Field under Integrated Soil Fertility Management," *Biogeosciences 13* (2016): 5,245-5,257

Z. Han, *et al*., "N_2O Emissions from Grain Cropping Systems: A Meta-Analysis of the Impacts of Fertilizer-based and Ecologically-based Nutrient Management Strategies," *Nutrient Cycling in Agroecosystems 107* (2017): 335-355

J. Iqbal, *et al*., "Does Nitrogen Fertilizer Application Rate to Corn Affect Nitrous Oxide Emissions from Rotated Soybean Crop?" *Journal of Environmental Quality 44* (2015): 711-719

M. Jarecki, *et al*., "Cover Crop Effects on Nitrous Oxide Emission from a Manure-Treated Mollisol," *Agriculture, Ecosystems and Environment 134* (2009): 29-35

C. Kallenbach, *et al*., "Cover Cropping Affects Soil N_2O and CO_2 Emissions Differently Depending on Type of Irrigation," *Agriculture, Ecosystems and Environment 137* (2010): 251-260

J. Kaye and M. Quemada (2017) "Using Cover Crops to Mitigate and Adapt to Climate Change: A Review," *Agronomy of Sustainable Development 37*: 4. https://doi.org/10.1007/s13593-016-0410-x

E. Lugato, *et al*., "Mitigation Potential of Soil Carbon Management Overestimated by Neglecting N_2O Emissions," *Nature Climate Change 8* (2018): 219-223

D. Mitchell, *et al*., "Cover Crop Effects on Nitrous Oxide Emissions: Role of Mineralizable Carbon," *Soil Science Society of America Journal 77* (2013): 1,765-1,773

M. Necpalova, *et al*., "Potentials to Mitigate Greenhouse Gas Emissions from Swiss Agriculture," *Agriculture, Ecosystems and Environment 265* (2018): 84-102

W. Negassa, *et al*., "Cover Crop and Tillage Systems Effect on Soil CO_2 and N_2O Fluxes in Contrasting Topographical Positions," *Soil and Tillage Research 154* (2015): 64-74

J. Oleson, *et al*., "Effect of Climate Change on Greenhouse Gas Emissions from Arable Crop Rotations," *Nutrient Cycling in Agroecosystems 70* (2004): 147-160

V. Pappa, *et al*., "Nitrous Oxide Emissions and Nitrate Leaching in an Arable Rotation Resulting from the Presence of an Intercrop," *Agriculture, Ecosystems and Environment 141* (2011): 153-161

T. Parkin and T. Kaspar, "Nitrous Oxide Emissions from Corn-Soybean Systems in the Midwest," *Journal of Environmental Quality 35* (2006): 1,496-1,506

T. Parkin, *et al*., "Rye Cover Crop Effects on Direct and Indirect Nitrous Oxide Emissions," *Soil Science Society of America Journal 80* (2016): 1,551-1,559

S. Petersen, *et al*., "Tillage Effects on N_2O Emissions as Influenced by a Winter Cover Crop," *Soil Biology and Biochemistry 43* (2011): 1,509-1,517

C. Peyard, *et al*., "N_2O Emissions of Low Input Cropping Systems as Affected by Legume and Cover Crop Use," *Agriculture, Ecosystems and Environment 224* (2016): 145-156

G. Posse, *et al*., "Impact of Land Use During Winter on the Balance of Greenhouse Gases," *Soil Use and Management 34* (2018): 525-532

Z. Qin, *et al*., *Incorporating Agricultural Management Practices into the Assessment of Soil Carbon Change and Life-Cycle Greenhouse Gas Emissions of Corn Stover Ethanol Production*, ANL/ESD-15/26, Energy Systems Division, Argonne National Laboratory, 2015

G. Robertson, *et al*., "Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere," *Science 289* (2000): 1,922-1,925

S. Ruis, *et al*., “Impacts of Early- and Late-Terminated Cover Crops on Gas Fluxes,” *Journal of Environmental Quality 47* (2018): 1,426-1,435

A. Sanz-Cobena, *et al*., "Do Cover Crops Enhance N_2O, CO_2 or CH_4 Emissions from Soil in Mediterranean Arable Systems? *Science of the Total Environment 466/467* (2014): 164-174

J. Sarkodie-Addo, *et al*., "Nitrous Oxide Emissions after Application of Inorganic Fertilizer and Incorporation of Green Manure Residues," *Soil Use and Management 19* (2003): 331-339

D. Smith, *et al*., "Fertilizer and Tillage Management Impacts on Non-Carbon Dioxide Greenhouse Gas Emissions," *Soil Science Society of America Journal 75* (2011): 1,070-1,082

A. Swan, *et al*., *COMET-Planner: Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning: A Companion Report to www.comet-planner.com*, NRCS-USDA and Colorado State, 2015

H. Tribouillois, *et al*., “Cover Crops Mitigate Direct Greenhouse Gas Balance but Reduce Drainage under Climate Change Scenarios in Temperate Climates with Dry Summers,” *Global Change Biology 24* (2018): 2,513-2,529

P. Turner, *et al*., "Impact of Kura Clover Living Mulch on Nitrous Oxide Emissions in a Corn-Soybean System," *Journal of Environmental Quality 45* (2016): 1,782-1,787

B. Wegner, *et al*., “Response of Surface Greenhouse Gas Fluxes to Crop Residue Removal and Cover Crops under a Corn-Soybean Rotation,” *Journal of Environmental Quality 47* (2018): 1,146-1.154

Winter cover crops/catch crops–CH_4

S. De Gryze, *et al*., "Simulating Greenhouse Gas Budgets of Four California Cropping Systems under Conventional and Alternative Management," *Ecological Applications 20* (2010): 1,805-1,819

B. Fronning, *et al*., "Use of Manure, Compost, and Cover Crops to Supplant Crop Residue Carbon in Corn Stover Removed Cropping Systems," *Agronomy Journal 100* (2008): 1,703-1,710

I. Gelfand and G. Robertson, "Mitigation of Greenhouse Gases in Agricultural Ecosystems," in S. Hamilton, *et al*., eds., *The Ecology of Agricultural Landscapes: Long-term Research on the Path to Sustainability* (New York: Oxford University Press, 2015), pp. 310-339

G. Guardia, *et al*., "Effect of Cover Crops on Greenhouse Gas Emissions in an Irrigated Field under Integrated Soil Fertility Management," *Biogeosciences 13* (2016): 5,245-5,257

J. Kaye and M. Quemada, "Using Cover Crops to Mitigate and Adapt to Climate Change: A Review," *Agronomy of Sustainable Development* (2017) 37: 4. https://doi.org/10.1007/s13593-016-0410-x

M. Necpalova, *et al*., "Potentials to Mitigate Greenhouse Gas Emissions from Swiss Agriculture," *Agriculture, Ecosystems and Environment 265* (2018): 84-102

G. Robertson, *et al*.,"Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere," *Science 289* (2000): 1922-1925

A. Sanz-Cobena, *et al*., "Do Cover Crops Enhance N_2O, CO_2 or CH_4 Emissions from Soil in Mediterranean Arable Systems? *Science of the Total Environment 466/467* (2014): 164-174

D. Smith, *et al*., "Fertilizer and Tillage Management Impacts on Non-Carbon Dioxide Greenhouse Gas Emissions," *Soil Science Society of America Journal 75* (2011): 1,070-1,082

Winter cover crops/catch crops–SOC-CO_2

M. Abdalla, *et al*., “Critical Review of the Impacts of Cover Crops on Nitrogen Leaching, Net Greenhouse Gas Balance and Crop Productivity,” *Global Change Biology 25* (2019): 2,530-2.543

J. Acuna and M. Villamil, "Short-term Effects of Cover Crops and Compaction on Soil Properties and Soybean Production in Illinois," *Agronomy Journal 106* (2014): 860-870

J. Anderson, *et al*., *The Potential for Terrestrial Carbon Sequestration in Minnesota: A Report to the Department of Natural Resources from the Minnesota Terrestrial Carbon Sequestration Initiative*, University of Minnesota, February 2008

D. Arrouays, *et al*., *Mitigation of the Greenhouse Effect: Increasing Carbon Stocks in French Agricultural Soils? Synthesis of an Assessment Report by the French Institute for Agricultural Research (INRA) on Request of the French Ministry for Ecology and Sustainable Development*, INRA, October 2002

E. Austin, *et al*., "Cover Crop Root Contributions to Soil Carbon in a No-Till Corn Bioenergy Cropping System," *Global Change Biology-Bioenergy 9* (2017): 1,252-1,263

X. Bai, *et al*., “Responses of Soil Carbon Sequestration to Climate Smart Agricultural Practices: A Meta-analysis,” *Global Change Biology 25* (2019): 2,591-2,606

J. Baker and T. Griffis, "Examining Strategies to Improve the Carbon Balance of Corn-Soybean Agriculture Using Eddy Covariance and Mass Balance Techniques," *Agricultural and Forest Meteorology 128* (2005): 163-177

K. Balkcom, *et al*., "Conservation Systems to Enhance Soil Carbon Sequestration in the Southeast U.S. Coastal Plain," *Soil Science Society of America Journal 77* (2013): 1,774-1,783

A. Basche, *et al*., "Simulating Long-term Impacts of Cover Crops and Climate Change on Crop Production and Environmental Outcomes in the Midwestern United States," *Agriculture, Ecosystems and Environment 218* (2016): 95-106

H. Blanco-Canqui, *et al*., "Replacing Fallow with Cover Crops in a Semiarid Soil: Effects on Soil Properties," *Soil Science Society of America Journal 77* (2013): 1026-1034

H. Blanco-Canqui, *et al*., "Cover Crops and Ecosystem Services: Insights from Studies in Temperate Soils," *Agronomy Journal 107* (2015): 2,449-2,474

K. Blomback, *et al*., "Simulations of Soil Carbon and Nitrogen Dynamics during Seven Years in a Catch Crop Experiment," *Agricultural Systems 76* (2003): 95-114

A. Chambers, *et al*., "Soil Sequestration Potential of US Croplands and Grassland: Implementing the 4 per Thousand Initiative," *Journal of Soil and Water Conservation 71* (2016): 68A-74A

J. Constantin, *et al*., "Effects of Catch Crops, No Till and Reduced Nitrogen Fertilizer on Nitrogen Leaching and Balance in Three Long-Term Experiments," *Agriculture, Ecosystems and Environment 135* (2010): 268-278

K. Denef, *et al*., *Greenhouse Gas Emissions from U.S. Agriculture and Forestry: A Review of Emission Sources, Controlling factors, and Mitigation Potential*. Interim Report to USDA under contract #G-23F-8182H, ICF International, 2011

S. De Gryze, *et al*., "Simulating Greenhouse Gas Budgets of Four California Cropping Systems under Conventional and Alternative Management," *Ecological Applications 20* (2010): 1,805-1,819

S. DeGryze, *et al*., "Assessing the Potential for Greenhouse Gas Mitigation in Intensively Managed Annual Cropping Systems at the Regional Scale," *Agriculture, Ecosystems and Environment 144* (2011): 150-158

C. Dell, *et al*., "No-till and Cover Crop Impacts on Soil Carbon and Associated Properties on Pennsylvania Dairy Farms," *Journal of Soil and Water Conservation 63* (2008): 136-142

C. Dell, *et al*., "Implications of Observed and Simulated Soil Carbon Sequestration for Management Options in Corn-Based Rotations," *Journal of Environmental Quality 47* (2018): 617-624

B. Dimassi, *et al*., "Long-term Effect of Contrasted Tillage and Crop Management on Soil Carbon Dynamics during 41 years," *Agriculture, Ecosystems and Environment 188* (2014): 134-146

I. Dozier, *et al*., "Tillage and Cover Cropping Effects on Soil Properties and Crop Production in Illinois," *Agronomy Journal 109* (2017): 1,261-1,270

A. Eagle, *et al*., *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States: A Synthesis of the Literature*, 3rd edition, Nicholas Institute, Duke University, January 2012

C. Emmel, *et al*., "Integrated Management of a Swiss Cropland is Not Sufficient to Preserve its Soil Carbon Pool in the Long-Term," *Biogeosciences Discussion* http://doi.org/10.5194bg-2018-205

N. Farahbakhshazad, *et al*., "Modeling Biogeochemical Impacts of Alternative Management Practices for a Row-Crop Field in Iowa," *Agriculture, Ecosystems and Environment 123* (2008): 30-48

J. Fargione, *et al*. (2018) "Natural Climate Solutions for the United States," *Science Advances.4.* eaat1869. DOI: 10.1126/sciadv.aat1869

C. Fissore, *et al*., "Limited Potential for Terrestrial Carbon Sequestration to Offset Fossil-Fuel Emissions in the Upper Midwestern USA," *Frontiers in Ecology and the Environment 8* (2010): 409-413

A. Franzluebbers, "Soil Organic Carbon Sequestration and Agricultural Greenhouse Gas Emissions in the Southeastern USA," *Soil and Tillage Research* 83 (2005): 120-147

A. Franzluebbers, "Achieving Soil organic Carbon Sequestration with Conservation Agricultural Systems in the Southeastern United States," *Soil Science Society of America Journal 74* (2010): 347-357

B. Fronning, *et al*., "Use of Manure, Compost, and Cover Crops to Supplant Crop Residue Carbon in Corn Stover Removed Cropping Systems," *Agronomy Journal 100* (2008): 1,703-1,710

I. Gelfand and G. Robertson, "Mitigation of Greenhouse Gases in Agricultural Ecosystems," in S. Hamilton, *et al*., eds., *The Ecology of Agricultural Landscapes: Long-term Research on the Path to Sustainability* (New York: Oxford University Press, 2015), pp. 310-339

T. Higashi, *et al*., "Tillage and Cover Crop Species Affect Soil Organic Carbon in Andosol, Kanto, Japan," *Soil and Tillage Research 138* (2014): 64-72

M. Jarecki and R. Lal, "Crop Management for Soil Carbon Sequestration," *Critical Reviews in Plant Sciences 22* (2003): 471-502

C. Jones, *et al*., "Perennialization and Cover Cropping Mitigate Soil Carbon Loss from Residue Harvesting," *Journal of Environmental Quality 47* (2018): 710-717

T. Kaspar, *et al*., "Examining Changes in Soil Organic Carbon with Oat and Rye Cover Crops Using Terrain Covariates," *Soil Science Society of America Journal 70* (2006): 1,168-1,177

J. Kaye and M. Quemada, "Using Cover Crops to Mitigate and Adapt to Climate Change: A Review," *Agronomy of Sustainable Development* (2017) 37: 4. https://doi.org/10.1007/s13593-016-0410-x

A. Kong, *et al.,* "The Relationship between Carbon Input, Aggregation, and Soil Organic Carbon Stabilization in Sustainable Cropping Systems," *Soil Science Society of America Journal 69* (2005): 1,078-1,085

B. Kustermann, *et al*., "Modeling Carbon Cycles and Estimation of Greenhouse Gas Emissions from Organic and Conventional Farming Systems," *Renewable Agriculture and Food Systems 23* (2008): 38-52

R. Lal, *et al*., *The Potential of US Cropland to Sequester Carbon and Mitigate the Greenhouse Effect* (Ann Arbor: Ann Arbor Press, 1998)

R. Lal, *et al*., "Achieving Soil Carbon Sequestration in the United States: A Challenge to Policy Makers," *Soil Science 12* (2003): 827-845

R. Lal, "Soil Carbon Sequestration and Aggregation by Cover Cropping," *Journal of Soil and Water Conservation 70* (2015): 329-339

J. Lewandrowski, *et al*., *Economics of Sequestering Carbon in the U.S. Agricultural Sector*, Technical Bulletin 1909, Economic Research Service, US Department of Agriculture, April 2004

M. Liebig, *et al*., "Crop Sequence and Nitrogen Fertilization Effects on Soil Properties in the Western Corn Belt," *Soil Science Society of America Journal 66* (2002): 596-601

E. Lugato, *et al*., "Potential Carbon Sequestration of European Arable Soils Estimated By Modelling a Comprehensive Set of Management Practices," *Global Change Biology 20* (2015): 3,557-3,567

E. Lugato, *et al*., "Mitigation Potential of Soil Carbon Management Overestimated by Neglecting N_2O Emissions," *Nature Climate Change 8* (2018): 219-223

L. Mbuthia, *et al*., "Long-term Tillage, Cover Crop, and Fertilization Effects on Microbial Community Structure, Activity: Implications for Soil Quality," *Soil Biology and Biochemistry 89* (2015): 24-34

M. McDaniel, *et al*., "Does Agricultural Crop Diversity Enhance Soil Microbial Biomass and Organic Matter Dynamics? A Meta-analysis," *Ecological Applications 24* (2014): 560-570

J. Mitchell, *et al*., "Tillage and Cover Cropping Affect Crop Yields and Soil Carbon in the San Joaquin Valley, California," *Agronomy Journal 107* (2015): 588-596

A. Mukherjee and R. Lal, "Short-term Effects of Cover Cropping on the Quality of a Typic Argiaquolls in Central Ohio," *Catena 131* (2015): 125-129

M. Necpalova, *et al*., "Potentials to Mitigate Greenhouse Gas Emissions from Swiss Agriculture," *Agriculture, Ecosystems and Environment 265* (2018): 84-102

J. Olesen, *et al*., "Effect of Climate Change on Greenhouse Gas Emissions from Arable Crop Rotations," *Nutrient Cycling in Agroecosystems 70* (2004): 147-160

K. Olson, *et al*., "Cover Crop Effects on Crop Yields and Soil Organic Carbon Content," *Soil Science 175* (2010): 89-97

K. Olson, *et al*., "Long-term Effects of Cover Crops on Crop Yields, Soil Organic Carbon Stocks and Sequestration," *Open Journal of Soil Science 4* (2014): 282-292

S. Pellerin, *et al*., "Identifying Cost-Competitive Greenhouse Gas Mitigation Potential of French Agriculture," *Environmental Science and Policy 77* (2017): 130-139

C. Poeplau and A. Don, "Carbon Sequestration in Agricultural Soil via Cultivation of Cover Crops - A Meta-Analysis," *Agriculture, Ecosystems and Environment 2000* (2015): 33-41

C. Poeplau, *et al*., "Effect of Perennial Ryegrass Cover Crop on Soil Organic Carbon Stocks in Southern Sweden," *Geoderma Regional 4* (2015): 126-133

Z. Qin, *et al*., *Incorporating Agricultural Management Practices into the Assessment of Soil Carbon Change and Life-Cycle Greenhouse Gas Emissions of Corn Stover Ethanol Production*, ANL/ESD-15/26, Energy Systems Division, Argonne National Laboratory, 2015

Z. Qin, *et al*., "Land Management Change Greatly Impacts Biofuels' Greenhouse Gas Emissions," *Global Change Biology-Bioenergy 10* (2018): 370-381

G. Robertson, *et al*., "Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere," *Science 289* (2000): 1,922-1,925

J. Rorick and E. Kladivko, "Cereal Rye Cover Crop Effects on Soil Carbon and Physical Properties in Southeastern Indiana," *Journal of Soil and Water Conservation 72* (2017): 260-265

S. Ruis and H. Blanco-Canqui, "Cover Crop Could Offset Crop Residue Removal Effects on Soil Carbon and Other Properties," *Agronomy Journal 109* (2017): 1-21

U. Sainju, *et al*., "Long-term Effects of Tillage, Cover Crops, and Nitrogen Fertilization on Organic Carbon and Nitrogen Concentrations in Sandy Soils in Georgia, USA," *Soil and Tillage Research 63* (2002): 167-179

U. Sainju, *et al*., "Carbon Accumulation in Cotton, Sorghum, and Underlying Soil as Influenced by Tillage, Cover Crops, and Nitrogen Fertilization," *Plant and Soil 273* (2005): 219-234

U. Sainju, *et al*., "Carbon Supply and Storage in Tilled and Nontilled Soils as Influenced by Cover Crops and Nitrogen Fertilization," *Journal of Environmental Quality 35* (2006): 1,507-1,517

U. Sainju, *et al*., "Cover Crop Effects on Soil Carbon and Nitrogen under Bioenergy Sorghum Crops," *Journal of Soil and Water Conservation 70* (2015): 410-417

U. Sainju, *et al*., "Cover Crop and Nitrogen Influence Soil Carbon under Bioenergy Sweet Sorghum," *Agronomy Journal 110* (2018): 463-471

A. Sanz-Cobena, *et al*., "Strategies for Greenhouse Gas Emissions Mitigation in Mediterranean Agriculture: A Review," *Agriculture, Ecosystems and Environment 238* (2017): 5-24

M. Schipanski, *et al*., "A Framework for Evaluating Ecosystem Services Provided by Cover Crops in Agroecosystems," *Agricultural Systems 125* (2014): 12-22

S. Senthilkumar, *et al*., "Topography Influences Management System Effects on Total Carbon and Nitrogen," *Soil Science Society of America Journal 73* (2009): 2,059-2,067

S. Senthilkumar, *et al*., "Contemporary Evidence of Soil Carbon Loss in the US Corn Belt," *Soil Science Society of America Journal 73* (2009): 2,078-2,086

M. Sperow, *et al*., "Potential Soil C Sequestration on US Agricultural Soils," *Climatic Change 57* (2003): 319-339

M. Sperow, "An Enhanced Method for Using the IPCC Approach to Estimate Soil Organic Carbon Storage Potential on US Agricultural Soils," *Agriculture, Ecosystems and Environment 193* (2014): 96-107

M. Steele, *et al*., "Winter Annual Cover Crop Impacts on No-Till Soil Physical Properties and Organic Matter," *Soil Science Society of America Journal 76* (2012): 2,164-2,173

A. Swan, *et al*., *COMET-Planner: Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning: A Companion Report to www.comet-planner.com*, NRCS-USDA and Colorado State, 2015

A. Taghizadeh-Toosi, *et al*., "Changes in Carbon Stocks of Danish Agricultural Mineral Soils between 1986 and 2009," *European Journal of Soil Science 65* (2014): 730-740

H. Tribouillois, *et al*., "Cover Crops Mitigate Direct Greenhouse Gas Balance but Reduce Drainage under Climate Change Scenarios in Temperate Climates with Dry Summers," *Global Change Biology 24* (2018): 2,513-2,529

J. Veenstra, *et al*., "Tillage and Cover Cropping Effects on Aggregate-Protected Carbon in Cotton and Tomato," *Soil Science Society of America Journal 71* (2007): 362-371

F. Viera, *et al*., “Building Up Organic Matter in a Subtropical Paleudult under Legume Crop-based Rotations,” *Soil Science Society of America Journal 73* (2009): 1,699-1,706

M. Villamil, *et al*., "No-Till Corn/Soybean Systems Including Winter Cover Crops: Effects on Soil Properties," *Soil Science Society of America Journal 70* (2006): 1,936-1,944

X. Yang and B. Kay, "Rotation and Tillage Effects on Soil Organic Carbon Sequestration in a Typic Hapludalf in Southern Ontario," *Soil and Tillage Research 59* (2001): 107-114

No tillage and reduced tillage–N_2O

M. Abdalla, *et al*., "Application of the DNDC Model to Predict Emissions of N_2O from Irish Agriculture," *Geoderma 151* (2009): 327-337

M. Abdalla, *et al*., "Simulation of N_2O Fluxes from Irish Arable Soils: Effect of Climate Change and Management," *Biology and Fertility of Soils 46* (2010): 247-260

M. Abdalla, *et al*., "Emissions of Nitrous Oxide from Irish Arable Soils: Effects of Tillage and Reduced N Input," *Nutrient Cycling in Agroecosystems 86* (2010): 53-65

J. Almaraz, *et al*., "Carbon Dioxide and Nitrous Oxide Fluxes in Corn Grown under Two Tillage Systems in Southwestern Quebec," *Soil Science Society of America Journal 73* (2009): 113-119

C. Alvarez, *et al*., "Soil Nitrous Emissions under Different Management Practices in the Semi-arid Region of the Argentinian Pampas," *Nutrient Cycling in Agroecosystems 94* (2012): 209-220

D. Archer and A. Halvorson, "Greenhouse Gas Mitigation Economics for Irrigated Cropping System in Northeastern Colorado," *Soil Science Society of America Journal 74* (2010): 446-452

G. Badagliacca, *et al*., "Long-Term No-Tillage Application Increases Soil Organic Carbon, Nitrous Oxide Emissions and Faba Bean (*Vicia faba L*.) Yields under Rain-Fed Mediterranean Conditions," *Science of the Total Environment 639* (2018): 350-359

G. Badagliacca, *et al*., "Long-Term Effects of Contrasting Tillage on Soil Organic Carbon, Nitrous Oxide and Ammonia Emissions in a Mediterranean Vertisol under Different Crop Sequences," *Science of the Total Environment 619/620* (2018): 18-27

B. Ball, *et al*., "Seasonal Nitrous Oxide Emissions from Field Soils under Reduced Tillage, Compost Application or Organic Farming," *Agriculture, Ecosystems and Environment 189* (2014): 171-180

G. Behnke, *et al*., "Long-term Crop Rotation and Tillage Effects on Soil Greenhouse Gas Emissions and Crop Production in Illinois, USA," *Agriculture, Ecosystems and Environment 261* (2018): 62-70

A. Bhatia, *et al*., "Mitigating Nitrous Oxide Emission from Soil under Conventional and No-tillage in Wheat using Nitrification Inhibitors," *Agriculture, Ecosystems and Environment 136* (2010): 247-253

P. Boeckx, *et al*., "Short-term Effect of Tillage Intensity on N_2O and CO_2 Emissions," *Agronomy for Sustainable Development 31* (2011): 453-461

M. Cavigelli, *et al*., "Global Warming Potential of Organic and Conventional Grain Cropping Systems in the Mid-Atlantic Region of the US," in *Proceedings of the Farming System Design Conference, Monterey, California, 2009*

D. Chatskikh and J. Oleson, "Soil Tillage Enhanced CO_2 and N_2O Emissions from Loamy Soil under Spring Barley," *Soil and Tillage Research 97* (2007): 5-18

D. Chatskikh, *et al*., "Effects of Reduced Tillage on Net Greenhouse Gas Fluxes from Loamy Sand Soil under Winter Crops in Denmark," *Agriculture, Ecosystems and Environment 128* (2008): 117-126

S. Chen, *et al*., "Relationship between Nitrous Oxide Emission and Winter Wheat Production," *Biology and Fertility of Soils 44* (2008): 985-989

G. Chen, *et al*., "Can Conservation Tillage Reduce N_2O Emissions on Cropland Transitioning to Organic Vegetable Production," *Science of the Total Environment 618* (2018): 927-940

M. Choudhary, *et al*., "Nitrous Oxide Emissions from a New Zealand Cropped Soil: Tillage Effects, Spatial and Seasonal Variability," *Agriculture, Ecosystems and Environment 93* (2002): 33-43

K. Congreves, *et al*., "Differences in Field-Scale N_2O Flux Linked to Crop Residue Removal under Two Tillage Systems in Cold Climates," *Global Change Bioenergy 9* (2017): 666-680

B. Davis, *et al*., "Nitrous Oxide Emissions Increase Exponentially with Organic N Rate from Cover Crops and Applied Turkey Litter," *Agriculture, Ecosystems and Environment 272* (2019): 165-174

C. Decock, "Mitigating Nitrous Oxide Emissions from Corn Cropping Systems in the Midwestern US: Potential and Data Gaps," *Environmental Science and Technology 48* (2014): 4,247-4,256

S. de Gryze, *et al*., "Simulating Greenhouse Gas Budgets of Four California Cropping Systems under Conventional and Alternative Management," *Ecological Applications 20* (2010): 1,805-1,819

S. DeGryze, *et al*., "Assessing the Potential for Greenhouse Gas Mitigation in Intensively Managed Annual Cropping Systems at the Regional Scale," *Agriculture, Ecosystems and Environment 144* (2011): 150-158

S. Del Grosso, *et al*., "DAYCENT Model Analysis of Past and Contemporary Soil N_2O and Net Greenhouse Gas Flux for Major Crops in the USA," *Soil and Tillage Research 83* (2005): 9-24

S. Del Grosso, *et al*., "Testing DAYCENT Model Simulations of Corn Yields and Nitrous Oxide Emissions in Irrigated Tillage Systems in Colorado," *Journal of Environmental Quality 37* (2008): 1,383-1,389

Q. Deng, *et al*. (2015) "Corn Yield and Soil Nitrous Oxide Emissions under Different Fertilizer and Soil Management: a Three-Year Field Experiment in Middle Tennessee," *PLoS One 10*(4): e0125406. Doi:10.1371/journal.pone.0125406

Q. Deng, *et al*., "Assessing the Impacts of Tillage and Fertilization Management on Nitrous Oxide Emissions in a Cornfield Using the DNDC Model," *Journal of Geophysical Research Biogeosciences 121* (2016): 337-349

Q. Deng, *et al*., "Assessing the Short-Term Effects of Management Practices on N_2O Emissions from Diverse Mediterannean Agricultural Ecosystems using a Biogeochemical Model," *Journal of Geophysical Research Biogeosciences 123* (2018): 1,557-1,571

C. Drury, *et al*., "Emissions of Nitrous Oxide and Carbon Dioxide: Influence of Tillage Type and Nitrogen Placement Depth," *Soil Science Society of America Journal 70* (2006): 570-581

C. Drury, *et al*., "Nitrogen Source, Application Time, and Tillage Effects on Soil Nitrous Oxide Emissions and Corn Grain Yields," *Soil Science Society of America Journal 76* (2012): 1,268-1,279

M. Dusenbury, *et al*., "Nitrous Oxide Emissions from a Northern Great Plains Soil as Influenced by Nitrogen Management and Cropping Systems," *Journal of Environmental Quality 38* (2008): 542-550

A. Elmi, *et al*., "Long-Term Effect of Conventional and No-Tillage Production Systems on Nitrous Oxide Fluxes from Corn (*Zea mays L*) Field in Southwestern Quebec," *American Journal of Environmental Sciences 5* (2009): 238-246

N. Farahbakhshazad, *et al*., "Modeling Biogeochemical Impacts of Alternative Management Practices for a Row-Crop Field in Iowa," *Agriculture, Ecosystems and Environment 123* (2008): 30-48

J. Feng, *et al*., "Integrated Assessment of the Impact of Enhanced-Efficiency Nitrogen Fertilizer on N_2O Emission and Crop Yield," *Agriculture, Ecosystems and Environment 231* (2016): 218-228

J. Feng, *et al*. (2018) "Impact of Agronomy Practices on the Effects of Reduced Tillage Systems on CH_4 and N_2O Emissions from Agricultural Fields: A Global Meta-Analysis," PLoS ONE 13(5):e0196703. https//doi.org/10.1371/journal.pone.0196703

R. Fus, *et al*., "Pulse Emissions of N_2O and CO_2 from an Arable Field Depending on Fertiization and Tillage Practice," *Agriculture, Ecosystems and Environment 144* (2011): 61-68

W. Gao and X. Bian (2017) "Evaluation of the Agronomic Impacts on Yield-Scaled N_2O Emissions from Wheat and Maize Fields in China," *Sustainability* 9(7) 1201, doi: 10.3990/su9071201

S. Garcia-Marco, *et al*., "No Tillage and Liming Reduce Greenhouse Gas Emissions from Poorly Drained Agricultural Soils in the Mediterranean Regions," *Science of the Total Environment 566/567* (2016): 512-520

I. Gelfand, *et al*., "Long-term Nitrous Oxide Fluxes in Annual and Perennial Agricultural and Unmanaged Ecosystems in the Upper Midwest," *Global Change Biology 22* (2016): 3,594-3,607

K. Gillette, *et al*., “Simulating N_2O Emissions under Different Tillage Systems using the RZ-SHAW Model,” *Soil and Tillage Research 165* (2017): 268-278

A. Glenn, *et al*., "Nitrous Oxide Emissions from an Annual Crop Rotation on Poorly Drained Soil on the Canadian Prairies," *Agricultural and Forest Meteorology 166/167* (2012): 41-49

O. Grageda-Cabrera, *et al*., "Fertiizer Dynamics in Different Tillage and Crop Rotation Systems in a Vertisol in Central Mexico," *Nutrient Cycling in Agroecosystems 89* (2011): 125-134

A. Grandy, *et al*., "Long-term Trends in Nitrous Oxide Emissions, Soil Nitrogen, and Crop Yields of Till and No-Till Cropping Systems," *Journal of Environmental Quality 35* (2006): 1,487-1,495

B. Grant, *et al*., "Estimated N_2O and CO_2 Emissions as Influenced by Agricultural Practices in Canada," *Climatic Change 65* (2004): 315-332

E. Gregorich, *et al*., ""Greenhouse Gas Contributions of Agricultural Soils and Potential Mitigation Practices in Eastern Canada," *Soil and Tillage Research 83* (2005): 53-72

E. Gregorich, *et al*., "Tillage Effects on N_2O Emissions from Soils under Corn and Soybeans in Eastern Canada," *Canadian Journal of Soil Science 88* (2008): 153-161

J. Guzman, *et al*., "Greenhouse Gas Emissions Dynamics as Influenced by Corn Residue Removal in Continuous Corn System" *Soil Science Society of America Journal 79* (2015): 612-625

A. Halvorson, *et al*., "Nitrogen, Tillage, and Crop Rotation Effects on Nitrous Oxide Emissions from Irrigated Cropping Systems," *Journal of Environmental Quality 37* (2008): 1,337-1,344

A. Halvorson, *et al*., "Tillage and Inorganic Nitrogen Source Effects on Nitrous Oxide Emissions from Irrigated Cropping Systems," *Soil Science Society of America Journal 74* (2010): 436-445

Z. Han, *et al*., "N_2O Emissions from Grain Cropping Systems: A Meta-Analysis of the Impacts of Fertilizer-based and Ecologically-based Nutrient Management Strategies," *Nutrient Cycling in Agroecosystems 107* (2017): 335-355

B. Helgason, *et al*., "Toward Improved Coefficients for Predicting Direct N_2O Emissions from Soil in Canadian Agroecosystems," *Nutrient Cycling in Agroecosystems 72* (2005): 87-99

H. Heller, *et al*., "Effects of Manure and Cultivation on Carbon Dioxide and Nitrous Oxide Emissions from a Corn Field under Mediterranean Conditions," *Journal of Environmental Quality 39* (2010): 437-448

Y. Huang, *et al*., "Greenhouse Gas Emissions and Crop Yield in No-Tillage Systems: A Meta-Analysis," *Agriculture, Ecosystems and Environment 268* (2018): 144-153

D. Hunt, *et al*., "Effect of Polymer-Coated Urea on Nitrous Oxide Emission in Zero-till and Conventionally Tilled Silage Corn," *Canadian Journal of Soil Science 96* (2016): 12-22

V. Jin, *et al*., "Soil Greenhouse Gas Emissions in Response to Corn Stover Removal and Tillage Management across the US Corn Belt," *Bioenergy Research 7* (2014): 517-527

S. Kaharabata, *et al*., "Comparing Measured and Expert-N Predicted N_2O Emissions from Conventional Till and No-Till Corn Treatments," *Nutrient Cycling in Agroecosystems 66* (2003): 107-118

A. Kessavalou, *et al*., "Fluxes of Carbon Dioxide, Nitrous Oxide, and Methane in Grass Sod and Winter Wheat-Fallow Tillage Management," *Journal of Environmental Quality 27* (1998): 1,094-1,104

N. Koga, *et al*. (2004) "N_2O Emission and CH_4 Uptake in Arable Fields Managed Under Conventional and Reduced Tillage Cropping Systems in Northern Japan," *Global Biogeochemical Cycles 18*, GB4025, doi:10.1029/2004GB002260

A. Kong, *et al*., "Transitioning from Standard to Minimum Tillage: Tradeoffs between Soil Organic Matter Stabilization, Nitrous Oxide Emissions and N Availability in Irrigated Cropping Systems," *Soil and Tillage Research 104* (2009): 256-262

M. Krauss, *et al*., "Impact of Reduced Tillage on Greenhouse Gas Emissions and Soil Carbon Stocks in an Organic Grass-Clover Ley - Winter Wheat Cropping Sequence," *Agriculture, Ecosystems, and Environment 239* (2017): 324-333

S. Kumar, "Long-Term Tillage and Drainage Influences on Greenhouse Gas Fluxes from a Poorly Drained Soil of Central Ohio," *Journal of Soil and Water Conservation 69* (2014): 553-563

J. Lee, *et al*., "Tillage and Seasonal Emissions of CO_2, N_2O and NO across a Seed Bed and at Field Scale in a Mediterranean Climate," *Agriculture, Ecosystems and Environment 129* (2009): 378-390

R. Lemke, *et al*., "Tillage and N Source Influence Soil-Emitted Nitrous Oxide in the Alberta Parkland Region," *Canadian Journal of Soil Science 79* (1999): 15-24

C. Li, *et al*., "Carbon Sequestration in Arable Soils is Likely to Increase Nitrous Oxide Emissions, Offsetting Reductions in Climate Radiative Forcing," *Climatic Change 72* (2005): 321-338

G. Li, *et al*., "Tillage Does Not Increase Nitrous Oxide Emissions under Dryland Canola (*Brassica napus L.*) In a Semiarid Environment of South-Eastern Australia," *Soil Research 54* (2016): 512-522

H. Li, *et al*., "Estimates of N_2O Emissions and Mitigation Potential from a Spring Maize Field Based on DNDC Model," *Journal of Integrative Agriculture 11* (2012): 2,067-2,078

X. Liu, *et al*., "Tillage and Nitrogen Application Effects on Nitrous and Nitric Oxide Emissions from Irrigated Corn Fields," *Plant and Soil 276* (2005): 235-249

X. Liu, *et al*., "The Impact of Nitrogen Placement and Tillage on NO, N_2O, CH_4 and CO_2 Fluxes from a Clay Loam Soil," *Plant and Soil 280* (2006): 177-188

B. Ludwig, *et al*., "Modelling of Crop Yields and N_2O Emissions from Silty Arable Soils with Differing Tillage in Two Long-term Experiments," *Soil and Tillage Research 112* (2011): 114-121

A. MacKenzie, *et al*., "Nitrous Oxide Emission as Affected by Tillage, Corn-Soybean-Alfalfa Rotations, and Nitrogen Fertilization," *Canadian Journal of Soil Science 77* (1977): 145-152

B. Maharjan and R. Venterea, "Anhydrous Ammonia Injection Depth Does Not Affect nitrous Oxide Emissions in a Silt Loam Over Two Growing Seasons," *Journal of Environmental Quality 43* (2014): 1,527-1,535

S. Mahli, *et al*., "Tillage, Nitrogen and Crop Residue Effects on Crop Yield, Nutrient Uptake, Soil Quality and Greenhouse Gas Emissions," *Soil and Tillage Research 90* (2006): 171-183

S. Mahli and R. Lemke, "Tillage, Crop Residue and N Fertilizer Effects on Crop Yields, Nutrient Uptake, Soil Quality and Nitrous Oxide Gas Emissions in a Second 4-Year Rotation Cycle," *Soil and Tillage Research 96* (2007): 269-283

K. Mei, *et al*., "Stimulation of N_2O Emission by Conservation Tillage Management in Agricultural Lands: A Meta-Analysis," *Soil and Tillage Research 182* (2018): 86-93

M. Mkhabela, *et al*., "Gaseous and Leaching Nitrogen Losses from No-Tillage and Conventional Tillage Systems Following Surface Application of Cattle Manure," *Soil and Tillage Research 98* (2008): 187-199

A. Mosier, *et al*., "Net Global Warming Potential and Greenhouse Gas Intensity in Irrigated Cropping Systems in Northeastern Colorado," *Journal of Environmental Quality 35* (2006): 1,584-1,598

A. Mosier, *et al*., "Measurement of Net Global Warming Potential in Three Agroecosystems," *Nutrient Cycling in Agroecosystems 72* (2005): 67-76

J. Mutegi, *et al*., "Nitrous Oxide Emissions and Controls as Influenced by Tillage and Crop Residue Management Strategy," *Soil Biology and Biochemistry 42* (2010): 1,701-1,711

M. Necpalova, *et al*., "Potentials to Mitigate Greenhouse Gas Emissions from Swiss Agriculture," *Agriculture, Ecosystems and Environment 265* (2018): 84-102

R. Omonode, *et al*., "Soil Nitrous Oxide Emission in Corn Following Three Decades of Tillage and Rotation Treatments," *Soil Science Society of America Journal 75* (2011): 152-163

K. Oorts, *et al*., "Determinants of Annual Fluxes of CO_2 and N_2O in Long-term No-tillage and Conventional Tillage Systems in Northern France," *Soil and Tillage Research 95* (2007): 133-148

T. Parkin and T. Kaspar, "Nitrous Oxide Emissions from Corn-Soybean Systems in the Midwest," *Journal of Environmental Quality 35* (2006): 1,496-1,506

S. Pellerin, *et al*., "Identifying Cost-Competitive Greenhouse Gas Mitigation Potential of French Agriculture," *Environmental Science and Policy 77* (2017): 130-139

A. Perego, *et al*., "Field Evaluation Combined with Modeling Analysis to Study Fertilizer and Tillage Factors Affecting N_2O Emissions: A Case Study in the Po Valley (Northern Italy)," *Agriculture, Ecosystems and Environment 225* (2016): 72-85

S. Petersen, *et al*., "Tillage Effects on N_2O Emissions as Influenced by a Winter Cover Crop," *Soil Biology and Biochemistry 43* (2011): 1,509-1,517

D. Pelster, *et al*., "Nitrogen Fertilization but Not Soil Tillage Affects Nitrous Oxide Emissions from a Clay Soil under a Maize-Soybean Rotation," *Soil and Tillage Research 115/116* (2011): 16-26

D. Plaza-Bonilla, *et al*., "Tillage and Nitrogen Fertilization Effects on Nitrous Oxide Yield-Scaled Emissions in a Rainfed Mediterranean Area," *Agriculture, Ecosystems and Environment 189* (2014): 43-52

D. Plaza-Bonilla, *et al*., "No-Tillage Reduced Long-term Yield-Scaled Nitrous Oxide Emissions in Rainfed Mediterranean Agroecosystems: A Field and Modelling Approach," *Agriculture, Ecosystems and Environment 264* (2018): 36-47

K. Regina and L. Alukukku, "Greenhouse Gas Fluxes in Varying Soil Types Under Conventional and No-Tillage Practices," *Soil and Tillage Research 109* (2010): 144-152

G. Robertson, *et al*., "Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the radiative Forcing of the Atmosphere," *Science 289* (2000): 1,922-1,925

G. Robertson, *et al*., "The Biogeochemistry of Bioenergy Landscapes: Carbon, Nitrogen, and Water Considerations," *Ecological Applications 21* (2011): 1,055-1,067

P. Rochette, "No Till Only Increases N_2O Emissions in Poorly Aerated Soils," *Soil and Tillage Research 111* (2008): 97-100

P. Rochette, *et al*., "Estimation of N_2O Emissions from Agricultural Soils in Canada. 1. Development of a Country Specific Methodology," *Canadian Journal of Soil Science 88* (2008): 641-654

P. Rochette, *et al*., "Nitrous Oxide Emissions Respond Differently to No-Till in a Loam and a Heavy Clay Soil," *Soil Science Society of America Journal 72* (2008): 1,363-1,368

U. Sainju, *et al*., "Soil Carbon and Nitrogen Sequestration as Affected by Long-Term Tillage, Cropping Systems, and Nitrogen Fertilizer Sources," *Agriculture, Ecosystems and Environment 127* (2008): 234-240

J. Six, *et al*., "Soil Organic Matter, Biota and Aggregation in Temperate and Tropical Soils-Effects of Tillage," *Agonomie 22* (2002): 755-775

J. Six, *et al*., "The Potential to Mitigate Global Warming with No-Tillage Management is Only realized When Practiced in the Long-Term," *Global Change Biology 10* (2004): 155-160

D. Smith, *et al*., "Fertilizer and Tillage Management Impacts on Non-Carbon Dioxide Greenhouse Gas Emissions," *Soil Science Society of America Journal 75* (2011): 1,070-1,082

K. Smith, *et al*., "Impact of Tillage and Fertilizer Application Method on Gas Emissions in a Corn Cropping System," *Pedosphere 22* (2012): 604-615

P. Smith, *et al*., "Greenhouse Gas Mitigation in Agriculture," *Philosophical Transactions of the Royal Society B 363* (2008): 789-813

Y. Soon, *et al*., "Effect of Polymer-coated Urea and Tillage on the Dynamics of Available N and Nitrous Oxide Emission from Gray Luvisols," *Nutrient Cycling in Agroecosystems 90* (2011): 267-279

A. Swan, *et al*., *COMET-Planner: Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning: A Companion Report to www.comet-planner.com*, NRCS-USDA and Colorado State, 2015

Y. Tan, *et al*., "Conservation Farming Practices in Winter Wheat-Summer Maize Cropping Reduce GHG Emissions and Maintain High Yields," *Agriculture, Ecosystems and Environment 272* (2019): 266-274

A. Tellez, *et al*., “Conservation Agriculture Practices Reduce the Global Warming Potential of Rainfed Low-Input Semi-Arid Agriculture,” *European Journal of Agronomy 84* (2017): 95-104

A. Tellez-Rio, *et al*., "N_2O and CH_4 Emissions from a Fallow-Wheat Rotation in Conservation and Conventional Tillage under a Mediterranean Agroecosystem," *Science of the Total Environment 508* (2015): 85-94

S. Thomas, *et al*., "Effects of Tillage, Simulated Cattle Grazing and Sol Moisture on N_2O Emissions from a Winter Forage Crop," *Plant Soil 309* (2008): 131-145

S. Tian, *et al*. (2012), "Response of CH_4 and N_2O Emissions and Wheat Yields to Tillage Method Changes in the North China Plain," *PLoS ONE* 7(12): e51206. doi: 10.1371/journal.pone.0051206

S. Tian, *et al*. (2013) "Greenhouse Gas Flux and Crop Productivity After Ten Years of Reduced Till and No-Tillage in a Wheat-Maize Cropping System," *PLoS ONE 8*(9):e73450. doi.10.1371/journal.pone.0073450

C. Tu and F. Li, "Responses of Greenhouse Gas Fluxes to Experimental Warming in Wheat Season under Conventional Tillage and No-Tillage Fields," *Journal of Environmental Sciences 54* (2017): 314-327

D. Ussiri, *et al*., "Nitrous Oxide and Methane Emissions from Long-term Tillage under a Continuous Corn Cropping System in Ohio," *Soil and Tillage Research 104* (2009): 247-255

K. Uzoma, *et al*., "Assessing the Effects of Agricultural Management on Nitrous Oxide Emissions Using Flux Measurements and the DNDC Model," *Agriculture, Ecosystems and Environment 206* (2015): 71-83

C. van Kessel, *et al*., "Climate, Duration, and N Placement Determine N_2O Emissions in Reduced Tillage Systems: A Meta-Analysis," *Global Change Biology 19* (2013): 33-44

R. Venterea, *et al*., "Nitrogen Oxide and Methane Emissions under Varying Tillage and Fertilizer Management," *Journal of Environmental Quality 34* (2005): 1,467-1,477

R. Venterea, *et al*., "Fertilizer Source and Tillage Effects on Yield-Scaled Nitrous Oxide Emissions in a Corn Cropping System," *Journal of Environmental Quality 40* (2011): 1,521-1,531

Z. Yao, *et al*., "Nitrous Oxide and Methane Fluxes from a Rice-Wheat Crop Rotation under Wheat Residue Incorporation and No-Tillage Practices," *Atmospheric Environment 79* (2013): 641-649

S. Yonemura, *et al*., "Soil Respiration, N_2O and CH_4 Emissions from an Andisol under Conventional-Tillage and No-Tillage Cultivation for 4 Years," *Biology and Fertility of Soils 50* (2014): 63-74

C. Xu, *et al*., "Impacts of Natural Factors and Farming Practices on Greenhouse Gas Emissions in the North China Plain: A Meta-Analysis," *Ecology and Evolution 7* (2017): 6,702-6,715

A. Yogioka, *et al*., "Effect of No-Tillage with Weed Cover Mulching Versus Conventional Tillage on Global Warming Potential and Nitrate Leaching," *Agriculture, Ecosystems and Environment 200* (2015): 42-53

J. Yoo, *et al*., “Effect of No-Tillage and Conventional Tillage Practice on the Nitrous Oxide (N_2O) Emissions in an Upland Soil: Soil N_2O Emissions as Affected by Fertilizer Application,” *Applied Biological Chemistry 59* (2016): 787-797

M. Yuan, *et al*., "Soil N_2O Emissions as Affected by Long-Term Residue Removal and No-Till Practices in Continuous Corn," *Global Change Biology Bioenergy 10* (2018): 972-985

Z. Zhang, *et al*., "Effects of Tillage Practices and Straw Returning Methods on Greenhouse Gas Emissions and Net Ecosystem Economic Budget in Rice-Wheat Cropping Systems in Central China," *Atmospheric Environment 122* (2015): 616-644

X. Zhao, *et al*., “Methane and Nitrous Oxide Emissions under No-till Farming in China: a Meta-analysis,” *Global Change Biology 22* (2016): 1,372-1,384

O. Zurovec, *et al*. (2017) "Effects of Tillage Practice on Soil Structure, N_2O Emissions and Economics in Cereal Production Under Current Socio-economic Conditions in Central Bosnia and Herzegovina," *PLoS One 12*(11): e0187681.https//doi.org/10.1371/journal.pone.0187681

No tillage and reduced tillage–CH_4

F. Alluvione, *et al*., "Nitrogen Tillage and Crop Rotation Effects on Carbon Dioxide and Methane Fluxes from Irrigated Cropping Systems," *Journal of Environmental Quality 38* (2009): 2,023-2,033

D. Archer and A. Halvorson, "Greenhouse Gas Mitigation Economics for Irrigated Cropping System in Northeastern Colorado," *Soil Science Society of America Journal 74* (2010): 446-452

G. Behnke, *et al*., "Long-term Crop Rotation and Tillage Effects on Soil Greenhouse Gas Emissions and Crop Production in Illinois, USA," *Agriculture, Ecosystems and Environment 261* (2018): 62-70

S. Del Grosso, *et al*., "DAYCENT Model Analysis of Past and Contemporary Soil N_2O and Net Greenhouse Gas Flux for Major Crops in the USA," *Soil and Tillage Research 83* (2005): 9-24

S. De Gryze, *et al*., "Simulating Greenhouse Gas Budgets of Four California Cropping Systems under Conventional and Alternative Management," *Ecological Applications 20* (2010): 1,805-1,819

J. Feng, *et al*. (2018) "Impact of Agronomy Practices on the Effects of Reduced Tillage Systems on CH_4 and N_2O Emissions from Agricultural Fields: A Global Meta-Analysis," *PLoS ONE 13*(5):e0196703. https//doi.org/10.1371/journal.pone.0196703

A. Forte, *et al*., "Mitigation Impact of Minimum Tillage on CO_2 and N_2O Emissions from a Mediterranean Maize Cropped Soil under Low-Water Input," *Soil and Tillage Research 166* (2017): 167-178

I. Gelfand and G. Robertson, "Mitigation of Greenhouse Gases in Agricultural Ecosystems," in S. Hamilton, *et al*., eds., *The Ecology of Agricultural Landscapes: Long-term Research on the Path to Sustainability* (New York: Oxford University Press, 2015), pp. 310-339

Y. Huang, *et al*., "Greenhouse Gas Emissions and Crop Yield in No-Tillage Systems: A Meta-Analysis," *Agriculture, Ecosystems and Environment 268* (2018): 144-153

P. Jacinthe and W. Dick, "Soil Management and Nitrous Oxide Emissions from Cultivated Fields in Southern Ohio," *Soil and Tillage Research 41* (1997): 221-235

P. Jacinthe and R. Lal, "Labile Carbon and Methane Uptake as Affected by Tillage Intensity in a Mollisol," *Soil and Tillage Research 80* (2005): 35-45

V. Jin, *et al*., "Soil Greenhouse Gas Emissions in Response to Corn Stover Removal and Tillage Management across the US Corn Belt," *Bioenergy Research 7* (2014): 517-527

A. Kessavalou, *et al*., "Fluxes of Carbon Dioxide, Nitrous Oxide, and Methane in Grass Sod and Winter Wheat-Fallow Tillage Management," *Journal of Environmental Quality 27* (1998): 1,094-1,104

N. Koga, *et al*. (2014) "N_2O Emission and CH_4 Uptake in Arable Fields Managed Under Conventional and Reduced Tillage Cropping Systems in Northern Japan," *Global Biogeochemical Cycles 1*8, GB4025, doi:10.1029/2004GB002260

M. Krauss, *et al*., "Impact of Reduced Tillage on Greenhouse Gas Emissions and Soil Carbon Stocks in an Organic Grass-Clover Ley - Winter Wheat Cropping Sequence," *Agriculture, Ecosystems and Environment 239* (2017): 324-333

C. Li, *et al*., "Carbon Sequestration in Arable Soils is Likely to Increase Nitrous Oxide Emissions, Offsetting Reductions in Climate Radiative Forcing," *Climatic Change 72* (2005): 321-338

X. Liu, *et al*., "The Impact of Nitrogen Placement and Tillage on NO, N_2O, CH_4 and CO_2 Fluxes from a Clay Loam Soil," *Plant and Soil 280* (206): 177-188

A. Mosier, *et al*., "Net Global Warming Potential and Greenhouse Gas Intensity in Irrigated Cropping Systems in Northeastern Colorado," *Journal of Environmental Quality 35* (2006): 1,584-1,598

A. Mosier, *et al*., "Measurement of Net Global Warming Potential in Three Agroecosystems," *Nutrient Cycling in Agroecosystems 72* (2005): 67-76

M. Necpalova, *et al*., "Potentials to Mitigate Greenhouse Gas Emissions from Swiss Agriculture," *Agriculture, Ecosystems and Environment 265* (2018): 84-102

R. Omonode, *et al*., "Soil Carbon Dioxide and Methane Fluxes from Long-term Tillage Systems in Continuous Corn and Corn-Soybean Rotations," *Soil and Tillage Research 95* (2007): 182-195

K. Regina and L. Alukukku, "Greenhouse Gas Fluxes in Varying Soil Types Under Conventional and No-Tillage Practices," *Soils and Tillage Research 109* (2010): 144-152

G. Robertson, *et al*., "Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere," *Science 289* (2000): 1,922-1,925

U. Sainju, *et al*., "Soil Greenhouse Gas Emissions Affected by Irrigation, Tillage, Crop Rotation, and Nitrogen Fertilization," *Journal of Environmental Quality 41* (2012): 1,774-1,786

J. Six, *et al*., "The Potential to Mitigate Global Warming with No-Tillage Management is Only realized When Practiced in the Long-Term," *Global Change Biology 10* (2004): 155-160

D. Smith, *et al*., "Fertilizer and Tillage Management Impacts on Non-Carbon Dioxide Greenhouse Gas Emissions," *Soil Science Society of America Journal 75* (2011): 1,070-1,082

K. Smith, *et al*., "Impact of Tillage and Fertilizer Application Method on Gas Emissions in a Corn Cropping System," *Pedosphere 22* (2012): 604-615

P. Smith, *et al*., "Greenhouse Gas Mitigation in Agriculture," *Philosophical Transactions of the Royal Society B 363* (2008): 789-813

Y. Tan, *et al*., "Conservation Farming Practices in Winter Wheat-Summer Maize Cropping Reduce GHG Emissions and Maintain High Yields," *Agriculture, Ecosystems and Environment 272* (2019): 266-274

A. Tellez, *et al*., “Conservation Agriculture Practices Reduce the Global Warming Potential of Rainfed Low-Input Semi-Arid Agriculture,” *European Journal of Agronomy 84* (2017): 95-104

S. Tian, *et al*. (2012) "Response of CH_4 and N_2O Emissions and Wheat Yields to Tillage Method Changes in the North China Plain," *PLoS ONE* 7(12): e51206. doi: 10.1371/journal.pone.0051206

C. Tu and F. Li, "Responses of Greenhouse Gas Fluxes to Experimental Warming in Wheat Season under Conventional Tillage and No-Tillage Fields," *Journal of Environmental Sciences 54* (2017): 314-327

D. Ussiri, *et al*., "Nitrous Oxide and Methane Emissions from Long-term Tillage under a Continuous Corn Cropping System in Ohio," *Soil and Tillage Research 104* (2009): 247-255

R. Venterea, *et al*., "Nitrogen Oxide and Methane Emissions under Varying Tillage and Fertilizer Management," *Journal of Environmental Quality 34* (2005): 1,467-1,477

I. Volpi, *et al*., "Minimum Tillage Mitigated N_2O Emissions and Maximized Crop Yield in Faba Bean in a Mediterranean Environment," *Soil and Tillage Research 178* (2018): 11-21

C. Xu, *et al*., "Impacts of Natural Factors and Farming Practices on Greenhouse Gas Emissions in the North China Plain: A Meta-Analysis," *Ecology and Evolution 7* (2017): 6,702-6,715

Z. Yao, *et al*., "Nitrous Oxide and Methane Fluxes from a Rice-Wheat Crop Rotation under Wheat Residue Incorporation and No-Tillage Practices," *Atmospheric Environment 79* (2013): 641-649

A. Yogioka, *et al*., "Effect of No-Tillage with Weed Cover Mulching Versus Conventional Tillage on Global Warming Potential and Nitrate Leaching," *Agriculture, Ecosystems and Environment 200* (2015): 42-53

S. Yonemura, *et al*., "Soil Respiration, N_2O and CH_4 Emissions from an Andisol under Conventional-Tillage and No-Tillage Cultivation for 4 Years," *Biology and Fertility of Soils 50* (2014): 63-74

Z. Zhang, *et al*., "Effects of Tillage Practices and Straw Returning Methods on Greenhouse Gas Emissions and Net Ecosystem Economic Budget in Rice-Wheat Cropping Systems in Central China," *Atmospheric Environment 122* (2015): 616-644

X. Zhao, *et al*., “Methane and Nitrous Oxide Emissions under No-till Farming in China: a Meta-analysis,” *Global Change Biology 22* (2016): 1,372-1,384

No tillage and reduced tillage–SOC/CO_2

K. Abdalla, *et al*., "No-tillage Lessens Soil CO_2 Emissions under Arid and Sandy Soil Conditions: Results from a Meta-Analysis," *Biogeosciences 13* (2016): 3,619-3,633

J. Aertsens, *et al*., "Valuing the Carbon Sequestration Potential for European Agriculture," *Land Use Policy 31* (2013): 584-594

M. Al-Kaisi and X. Yin, "Tillage and Crop Residue Effects on Soil Carbon and Carbon Dioxide Emissions in Corn-Soybeans Rotations," *Journal of Environmental Quality 34* (2005): 437-445

M. Al-Kaisi, *et al*., "Soil Carbon and Nitrogen Changes as Affected by Tillage System and Crop Biomass in a Corn-Soybean Rotation," *Applied Soil Ecology 30* (2005): 174-191

R. Allmaras, *et al*., "Corn-Residue Transformations into Root and Soil Carbon as Related to Nitrogen, Tillage, and Stover Management," *Soil Science Society of America Journal 68* (2004): 1,366-1,375

R. Alvarez, "A Review of Fertilizer and Conservation Tillage Effects on Soil Organic Carbon Storage," *Soil Use and Management 21* (2005): 38-52

J. Alvaro-Fuentes, *et al*., "Tillage Effects on Soil Organic Fractions in Mediterranean Dryland Agroecosystems," *Soil Science Society of America Journal 72* (2008): 541-547

J. Alvaro-Fuentes, *et al*., "Tillage and Cropping Effects on Soil Organic Carbon in Mediterranean Semiarid Agroecosystems: Testing the Century Model," *Agriculture, Ecosystems and Environment 134* (2009): 211-217

J. Anderson, *et al*., *The Potential for Terrestrial Carbon Sequestration in Minnesota: A Report to the Department of Natural Resources from the Minnesota Terrestrial Carbon Sequestration Initiative*, University of Minnesota, February 2008

D. Angers, *et al*., "Dynamics of Soil Organic Matter and Corn Residues Affected by Tillage Practices," *Soil Science Society of America Journal 59* (1995): 1,311-1,315

D. Angers, *et al*., "Impact of Tillage Practices on Organic Carbon and Nitrogen Storage in Cool, Humid Soils of Eastern Canada," *Soil and Tillage Research 41* (1997): 191-201

D. Angers and N. Eriksen-Hamel, "Full Inversion Tillage and Organic Carbon Distribution in Soil Profiles: A Meta-analysis," *Soil Science Society of America Journal 72* (2008): 1,370-1,374

D. Archer and A. Halvorson, "Greenhouse Gas Mitigation Economics for Irrigated Cropping System in Northeastern Colorado," *Soil Science Society of America Journal 74* (2010): 446-452

D. Arrouays, *et al*., *Mitigation of the Greenhouse Effect: Increasing Carbon Stocks in French Agricultural Soils? Synthesis of an Assessment Report by the French Institute for Agricultural Research (INRA) on Request of the French Ministry for Ecology and Sustainable Development*, INRA, October 2002

J. Baker and T. Griffis, "Examining Strategies to Improve the Carbon Balance of Corn-Soybean Agriculture Using Eddy Covariance and Mass Balance Techniques," *Agricultural and Forest Meteorology 128* (2005): 163-177

K. Balkcom, *et al*., "Conservation Systems to Enhance Soil Carbon Sequestration in the Southeast U.S. Coastal Plain," *Soil Science Society of America Journal 77* (2013): 1,774-1,783

V. Barbera, *et al*., "Long-term Cropping Systems and Tillage Management Effects on Soil Organic Carbon Stock and Steady State level of C Sequestration Rates in a Semiarid Environment," *Land Degradation and Development 23* (2012): 83-91

J. Benjamin, *et al*., "Crop Management Effects on Crop Residue Production and Changes in Soil Organic Carbon in the Central Great Plains," *Agronomy Journal 102* (2010): 990-997

C. Bernacchi, *et al*., "The Conversion of the Corn/Soybean Ecosystem to No-Till Agriculture May Result in a Carbon Sink," *Global Change Biology 12* (2006): 1,585-1,586

A. Black and D. Tanaka, "A ConservationTillage Cropping Systems Study in the Northern Great Plains," in E. Paul, *et al*., eds. *Soil Organic Matter in Temperate Agroecosystems: Long-term Experiments in North America* (Boca Raton: CRC Press, 1997) pp. 335-342

H. Blanco-Canqui and R. Lal., "Response to the 'Comments on "No-Tillage and Soil-Profile Carbon Sequestration: An On-Farm Assessment," *Soil Science Society of America Journal 73* (2009): 690-691, (revised data in Table 2)

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

T. Brown and D. Huggins, "Soil Carbon Sequestration in the Dryland Cropping Region of the Pacific Northwest," *Journal of Soil and Water Conservation 67* (2012): 406-415

K. Brye, *et al*., "Carbon Budgets for a Prairie and Agroecosystems: Effects of Land-Use and Interannual Variability," *Ecological Applications 12* (2002): 962-979

C. Campbell, *et al*., "Carbon Sequestration in a Brown Chernozem as Affected by Tillage and Rotation," *Canadian Journal of Soil Science 75* (1995): 449-458

C. Campbell, *et al*., "Long-term Effects of Tillage and Crop Rotations on Soil Organic C and Total N in a Clay Soil in Southwestern Saskatchewan," *Canadian Journal of Soil Science 76* (1996): 395-401

C. Campbell, *et al*., "Adopting Zero Tillage Management: Impact on Soil C and N under Long-term Crop Rotations in a Thin Black Chernozem," *Canadian Journal of Soil Science 81* (2001): 139-148

C. Campbell, *et al*., "Carbon Storage in Soils of the North American Great Plains: Effect of Cropping Frequency," *Agronomy Journal 97* (2005): 349-363

M. Carter, "Long-term Tillage Effects on Cool-Season Soybean in Rotation with Barley, Soil Properties and Carbon and Nitrogen Storage for Fine Sandy Loams in the Humid Climate of Atlantic Canada," *Soil and Tillage Research 81* (2005): 109-120

J. Carvalho, *et al*., "Contribution of Above- and Belowground Bioenergy Crop Residues to Soil Carbon," *Global Change Biology-Bioenergy 9* (2017): 1,333-1,343

H. Caursarano, *et al*., "EPIC Modeling of Soil Organic Carbon Sequestration in Croplands of Iowa," *Journal of Environmental Quality 37* (2008): 1,345-1,353

M. Cavigelli, *et al*., "Simulated Soil Organic Carbon Changes in Maryland Are Affected by Tillage, Climate Change, and Crop Yield*," Journal of Environmental Quality 47* (2018): 588-595

A. Chambers, *et al*., "Soil Carbon Sequestration Potential of US Croplands and Grasslands: Implementing the 4 per Thousand Initiative," *Journal of Soil and Water Conservation 71* (2016): 68A-74A

K. Chan, *et al*., "Soil Carbon Dynamics under Different Cropping and Pasture Management in Temperate Australia: Results of Three Long-Term Experiments," *Soil Research 49* (2011): 320-328

K. Chang, *et al*., "Using DayCENT to Simulate Carbon Dynamics in Conventional and No-Till Agriculture," *Soil Science Society of America Journal 77* (2012): 941-950

J. Chi, *et al*., "Assessing Carbon and Water Dynamics of No-till and Conventional Tillage Cropping Systems in the Inland Pacific Northwest US Using the Eddy Covariance Method," *Agricultural and Forest Meteorology 218/219* (2016): 37-49

S. Christopher, *et al*., "Regional Study of No-Till Effects on Carbon Sequestration in the Midwestern United States," *Soil Science Society of America Journal 73* (2009): 207-215

C. Clapp, *et al*., "Soil Organic Carbon and ^{13}C Abundance as Related to Tillage, Crop Residue, and Nitrogen Fertilization under Continuous Corn Management in Minnesota," *Soil and Tillage Research 55* (2000): 127-142

D. Clay, *et al*., "Tillage and Corn Residue Harvesting Impact Surface and Subsurface Carbon Sequestration," *Journal of Environmental Quality 44* (2015): 803-809

K. Congreves, *et al*., "Soil Organic Carbon and Land Use: Processes and Potential in Ontario's Long-term Agro-Ecosystem Research Sites," *Canadian Journal of Soil Science 94* (2014): 317-336

J. Constantin, *et al*., "Effects of Catch Crops, No Till and Reduced Nitrogen Fertilizer on Nitrogen Leaching and Balance in Three Long-Term Experiments," *Agriculture, Ecosystems and Environment 135* (2010): 268-278

R. Dalal, *et al*., "Organic Carbon and Total Nitrogen Stocks in a Vertisol Following 40 years of No-Tillage, Crop Residue Retention and Nitrogen Fertilization," *Soil and Tillage Research 112* (2011): 133-139

W. Deen and P. Kataki, "Carbon Sequestration in a Long-term, Conventional versus Conservation Tillage Experiment," *Soil Tillage and Research 74* (2003): 143-150

S. De Gryze, *et al*., "Simulating Greenhouse Gas Budgets of Four California Cropping Systems under Conventional and Alternative Management," *Ecological Applications 20* (2010): 1,805-1,819

S. DeGryze, *et al*., "Assessing the Potential for Greenhouse Gas Mitigation in Intensively Managed Annual Cropping Systems at the Regional Scale," *Agriculture, Ecosystems and Environment 144* (2011): 150-158

S. Del Grosso, *et al*., "DAYCENT Model Analysis of Past and Contemporary Soil N_2O and Net Greenhouse Gas Flux for Major Crops in the USA," *Soil and Tillage Research 83* (2005): 9-24

C. Dell, *et al*., "No-till and Cover Crop Impacts on Soil Carbon and Associated Properties on Pennsylvania Dairy Farms," *Journal of Soil and Water Conservation 63* (2008): 136-142

C. Dell, *et al*., "Implications of Observed and Simulated Soil Carbon Sequestration for Management Options in Corn-Based Rotations," *Journal of Environmental Quality 47* (2018): 617-624

K. Denef, *et al*., "Carbon Sequestration in Microaggregates of No-Tillage Soils with Different Clay Mineralogy," *Soil Science Society of America Journal 68* (2004): 1,935-1,944

R. Desjardins, *et al*., "Management Strategies to Sequester Carbon in Agricultural Soils and to Mitigate Greenhouse Gas Emissions," *Climatic Change 70* (2005): 283-297

K. D'Haene, *et al*., "The Effect of Reduced Tillage Agriculture on Carbon Dynamics in Silt Loam Soils," *Nutrient Cycling in Agroecosystems 84* (2009): 249-265

W. Dick, *et al*., "Impacts of Agricultural Management Practices on C Sequestration in Forest-Derived Soil in the Eastern Corn Belt," *Soil and Tillage Research 47* (1998): 235-244

B. Dimassi, *et al*., "Changes in Soil Carbon and Nitrogen Following Tillage Conversion in a Long-term Experiment in Northern France," *Agriculture, Ecosystems and Environment 169* (2013): 12-20

B. Dimassi, *et al*., "Long-term Effect of Contrasted Tillage and Crop Management on Soil Carbon Dynamics during 41 years," *Agriculture, Ecosystems and Environment 188* (2014): 134-146

M. Dolan, *et al*., "Soil Organic Carbon and Nitrogen in a Minnesota Soil as Related to Tillage, Residue and Nitrogen Management," *Soil and Tillage Research 89* (2006): 221-231

A. Donigian, *et al*., "Modeling the Impacts of Agricultural Management Practices on Soil Carbon in the Central US," in R. Lal, *et al*., eds., *Soil Management and the Greenhouse Effect* (Boca Raton: CRC Press, 1995), pp 121-135

I. Dozier, *et al*., "Tillage and Cover Cropping Effects on Soil Properties and Crop Production in Illinois," *Agronomy Journal 109* (2017): 1,261-1,270

Z. Du, *et al*., "The Effect of No-Till on Organic C Storage in Chinese Soils Should not be Overemphasized: A Meta-Analysis," *Agriculture, Ecosystems and Environment 236* (2017): 1-11

A. Eagle, *et al*., *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States: A Synthesis of the Literature*, 3rd edition, Nicholas Institute, Duke University, January 2012

B. Eghball, *et al*., "Distribution of Organic Carbon and Inorganic Nitrogen in a Soil under Various Tillage and Crop Sequences," *Journal of Soil and Water Conservation 49* (1994): 201-205

M. Eve, *et al*., "Predicted Impact of Management Changes on Soil Carbon Storage for Each Cropland Region of the Coterminous United States," *Journal of Soil and Water Conservation 57* (2002): 196-204

N. Farahbakhshazad, *et al*., "Modeling Biogeochemical Impacts of Alternative Management Practices for a Row-Crop Field in Iowa," *Agriculture, Ecosystems and Environment 123* (2008): 30-48

C. Fissore, *et al*., "Limited Potential for Terrestrial Carbon Sequestration to Offset Fossil-Fuel Emissions in the Upper Midwestern USA," *Frontiers in Ecology and the Environment 8* (2010): 409-413

R. Follett, *et al*., "Soil Carbon Dynamics for Irrigated Corn under Two Tillage Systems," *Soil Science Society of America Journal 77* (2013): 951-963

S. Frank, *et al*., "The Dynamic Soil Organic Carbon Mitigation Potential of European Cropland," *Global Environmental Change 35* (2015): 269-278

A. Franzluebbers, "Soil Organic Carbon Sequestration and Agricultural Greenhouse Gas Emissions in the Southeastern USA," *Soil and Tillage Research 83* (2005): 120-147

A. Franzluebbers, "Achieving Soil Organic Carbon Sequestration with Conservation Agricultural Systems in the Southeastern United States," *Soil Science Society of America Journal 74* (2010): 347-357

A. Franzluebbers, *et al*., "*In Situ* Potential CO_2 Evolution from a Fluventic Ustochrept in Southcentral Texas as Affected by Tillage and Cropping Intensity," *Soil and Tillage Research 47* (1998): 303-308

W. Frye and R. Blevins, "Soil Organic Matter Under Long-Term No-Tillage and Conventional Corn Production in Kentucky," in E. Paul, *et al*., eds., *Soil Organic Matter in Temperate Agroecosystems: Long-term Experiments in North America* (Boca Raton: CRC Press, 1997), pp. 227-234

A. Gal, *et al*., "Soil Carbon and Nitrogen Accumulation with Long-term No-Till versus Moldboard Plowing Overestimated with Tilled-Zone Sampling Depths," *Soil and Tillage Research 96* (2007): 42-51

I. Gelfand and G. Robertson, "Mitigation of Greenhouse Gases in Agricultural Ecosystems," in S. Hamilton, *et al*., eds, *The Ecology of Agricultural Landscapes: Long-term Research on the Path to Sustainability* (New York: Oxford University Press, 2015), pp. 310-339

S. Gervois, *et al*. (2008) "Carbon and Water Balance of European Croplands Throughout the 20th Century," *Global Biogeochemical Cycles 22* GB2022, doi:10.1029/2007GB003018

H. Golany, *et al*., "Tillage and Nitrogen Fertilizer Influence on Carbon and Soluble Silica Relations in a Pacific Northwest Mollisol," *Soil Science Society of America Journal 69* (2005): 1,102-1,109

H. Gollany, *et al*., "Soil Organic Carbon Accretion vs. Sequestration Using Physiochemical Fractionation and CQESTR Simulation," *Soil Science Society of America Journal 77* (2012): 618-620

H. Golany and R. Polumsky, "Simulating Soil Organic Carbon Responses to Cropping Intensity, Tillage, and Climate Change in Pacific Northwest Dryland," *Journal of Environmental Quality 47* (2018): 625-634

A. Grandy, *et al*., "Long-term Trends in Nitrous Oxide Emissions, Soil Nitrogen, and Crop Yields of Till and No-Till Cropping Systems," *Journal of Environmental Quality 35* (2006): 1,487-1,495

A. Grandy and G. Robertson, "Land-use Intensity Effects on Soil Organic Carbon Accumulation Rates and Mechanisms," *Ecosystems 10* (2007): 58-73

E. Gregorich, *et al*., "Using a Sequential Density and Particle-Size Fractionation to Evaluate Carbon and Nitrogen Storage in the Profile of Tilled and No-Till Soils in Eastern Canada," *Canadian Journal of Soil Science 89* (2009): 255-267

J. Guzman, *et al*., "Greenhouse Gas Emissions Dynamics as Influenced by Corn Residue Removal in Continuous Corn System" *Soil Science Society of America Journal 79* (2015): 612-625

M. Halpern, *et al*., "Long-term Tillage and Residue Management Influences Soil Carbon and Nitrogen Dynamics," *Soil Science Society of America Journal 74* (2010): 1,211-1,217

A. Halvorson, *et al*., "Long-Term Tillage and Crop Residue Management Study at Akron, Colorado," in E. Paul, *et al*., eds., *Soil Organic Matter in Temperate Agroecosystems: Long-term Experiments in North America* (Boca Raton: CRC Press, 1997), pp. 361-370

A. Halvorson, *et al*., "Tillage System and Crop Rotation Effects on Dryland Crop Yields and Soil Carbon in the Central Great Plains," *Agronomy Journal 94* (2002): 1,429-1,436

A. Halvorson, *et al*., "Tillage, Nitrogen, and Cropping System Effects on Soil Carbon Sequestration," *Soil Science Society of America Journal 66* (2002): 906-912

X. Hao, *et al*., "Tillage and Crop Sequence Effects on Organic Carbon and Total Nitrogen Content in an Irrigated Alberta Soil," *Soil and Tillage Research 62* (2001): 167-169

G. Hernandez-Ramirez, *et al*., "Carbon Sources and Dynamics in Afforested and Cultivated US Corn Belt Soils," *Soil Science Society of America Journal 75* (2010): 216-225

J. Hernanz, *et al*., "Soil Carbon Sequestration and Stratification in a Cereal/Leguminous Crop Rotation with Three Tillage Systems in Semiarid Conditions," *Agriculture, Ecosystems and Environment 133* (2009): 114-122

T. Higashi, *et al*., "Tillage and Cover Crop Species Affect Soil Organic Carbon in Andosol, Kanto, Japan," *Soil and Tillage Research 138* (2014): 64-72

D. Huggins, *et al*., "Corn-Soybean Sequence and Tillage Effects on Soil Carbon Dynamics and Storage," *Soil Science Society of America Journal 71* (2007): 145-154

T. Hurisso, *et al*., "Soil Profile and Nitrogen in Prairie, Perennial Grass-Legume Mixture and Wheat-Fallow Production in the Central High Plains, USA," *Agriculture, Ecosystems and Environment 181* (2013): 179-187

ICF, *Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production Within the United States*, report prepared for USDA, February 2013

P. Jacinthe and R. Lal, "Labile Carbon and Methane Uptake as Affected by Tillage Intensity in a Mollisol," *Soil and Tillage Research 80* (2005): 35-45

M Jarecki and R. Lal, "Crop Management for Soil Carbon Sequestration," *Critical Reviews in Plant Sciences 22* (2003): 471-502

A. Kessavalou, *et al*., "Fluxes of Carbon Dioxide, Nitrous Oxide, and Methane in Grass Sod and Winter Wheat-Fallow Tillage Management," *Journal of Environmental Quality 27* (1998): 1,094-1,104

M. Krauss, *et al*., "Impact of Reduced Tillage on Greenhouse Gas Emissions and Soil Carbon Stocks in an Organic Grass-Clover Ley - Winter Wheat Cropping Sequence," *Agriculture, Ecosystems and Environment 239* (2017): 324-333

H. Kwon, *et al*., "Modeling State-level Soil Carbon Emission Factors under Various Scenarios for Direct Land Use Change Associated with United States Biofuel Feedstock Production," *Biomass and Bioenergy 55* (2013): 299-310

R. Lal, *et al*., *The Potential of US Cropland to Sequester Carbon and Mitigate the Greenhouse Effect* (Ann Arbor, Michigan: Ann Arbor Press, 1998)

M. Liebig, *et al*., "Tillage and Cropping Effects on Soil Quality Indicators in the Northern Great Plains," *Soil and Tillage Research 78* (2004): 131-141

M. Liebig, *et al*., "Greenhouse Gas Contributions and Mitigation Potential of Agricultural Practices in Northwestern USA and Western Canada," *Soil and Tillage Research 83* (2005): 25-52

R. Lopez-Garrido, *et al*., "Carbon Losses by Tillage under Semi-arid Mediterranean Rainfed Agriculture (SW Spain)," *Spanish Journal of Agricultural Research 7* (2009): 706-716

R. Lopez-Garrido, *et al*., "Conservation Tillage Influence on Carbon Dynamics under Mediterranean Conditions," *Pedosphere 24* (2014): 65-75

E. Lugato, *et al*., "Potential Carbon Sequestration of European Arable Soils Estimated by Modelling a Comprehensive Set of Management Practices," *Global Change Biology 20* (2015): 3,357-3,567

L. Luo, *et al*., "Can No-tillage Stimulate Carbon Sequestration in Agricultural Soils? A Meta-Analysis of Paired Experiments," *Agriculture, Ecosystems and Environment 139* (2010): 224-231

D. Lyon, *et al*., "Soil Organic Matter Changes Over Two Decades of Winter Wheat-Fallow Cropping in Western Nebraska," in E. Paul, *et al*., eds. *Soil Organic Matter in Temperate Agroecosystems: Long-term Experiments in North America* (Boca Raton: CRC Press, 1997), pp. 343-351

E. Maas, *et al*., "Modeling Soil Organic Carbon in Corn (*Zea mays L*.)-based Systems in Ohio under Climate Change," *Journal of Soil and Water Conservation 72* (2017): 191-204

S. Mahli, *et al*., "Tillage, Nitrogen and Crop Residue Effects on Crop Yield, Nutrient Uptake, Soil Quality and Greenhouse Gas Emissions," *Soil and Tillage Research 90* (2006): 171-183

S. Mahli and R. Lemke, "Tillage, Crop Residue and N Fertilizer Effects on Crop Yields, Nutrient Uptake, Soil Quality and Nitrous Oxide Gas Emissions in a Second 4-Year Rotation Cycle," *Soil and Tillage Research 96* (2007): 269-283

J. Manley, *et al*., "Creating Carbon Offsets in Agriculture through No-Till Cultivation: A Meta-Analysis of Costs and Carbon Benefits," *Climatic Change 68* (2005): 41-65

D. Martens, *et al*., "Atmospheric Carbon Mitigation Potential of Agricultural Management in the Southwestern United States," *Soil and Tillage Research 83* (2005): 95-119

L. Mbuthia, *et al*., "Long-term Tillage, Cover Crop, and Fertilization Effects on Microbial Community Structure, Activity: Implications for Soil Quality," *Soil Biology and Biochemistry 89* (2015): 24-34

K. McVay, *et al*., "Management Effects on Soil Physical Properties in Long-term Tillage Studies in Kansas," *Soil Science Society of America Journal 70* (2006): 434-438

A. Metay, *et al*., "Effets des Techniques Culturales sans Labour sur le Strockage de Carbone dans le Sol en Contexte Climatique Tempere," *Canadian Journal of Soil Science 89* (2009): 623-34

M. Mikha and C. Rice, "Tillage and Manure Effects on Soil and Aggregate Associated Carbon and Nitrogen," *Soil Science Society of America Journal 68* (2004): 809-816

M. Mikha, *et al*., "Cropping System Influences on Soil Chemical Properties and Soil Quality on the Great Plains," *Renewable Agriculture and Food Systems 21* (2006): 26-53

M. Mikha, *et al*., "Long-term Tillage Impacts on Soil Aggregation and Carbon Dynamics under Wheat-Fallow in the Central Great Plains," *Soil Science Society of America Journal 77* (2012): 594-605

J. Miller, *et al*., "Physical Properties of a Chernozemic Clay Loam Soil Under Long-Term Conventional Tillage and No-Till," *Canadian Journal of Soil Science 79* (1999): 325-331

B. Minasny, *et al*., "Soil Carbon 4 per Mille," *Geoderma 292* (2017): 59-86

J. Mitchell, *et al*., "Tillage and Cover Cropping Affect Crop Yields and Soil Carbon in the San Joaquin Valley, California," *Agronomy Journal 107* (2015): 588-596

A. Mosier, *et al*., "Measurement of Net Global Warming Potential in Three Agroecosystems," *Nutrient Cycling in Agroecosystems 72* (2005): 67-76

A. Mosier, *et al*., "Net Global Warming Potential and Greenhouse Gas Intensity in Irrigated Cropping Systems in Northeastern Colorado," *Journal of Environmental Quality 35* (2006): 1,584-1,598

P. Nash, *et al*., "CQESTR-Simulated Response of Soil Response of Soil Organic Carbon to Management, Yield, and Climate Change in the Northern Great Plains Region," *Journal of Environmental Quality 47* (2018): 674-683

P. Nash, *et al*., "Simulated Soil Organic Carbon Responses to Crop Rotation, Tillage, and Climate Change in North Dakota*," Journal of Environmental Quality 47* (2018): 654-662

National Academies of Sciences, Engineering and Medicine, *Negative Emissions Technologies and Reliable Sequestration: A Consensus Report of the US National Academies of Science, Engineering and Medicine* (Washington, D.C.: National Academy Press, 2019)

M. Necpalova, *et al*., "Potentials to Mitigate Greenhouse Gas Emissions from Swiss Agriculture," *Agriculture, Ecosystems and Environment 265* (2018): 84-102

R. Nocoloso, *et al*., "Carbon Saturation and Translocation in a No-Till Soil under Organic Amendments," *Agriculture, Ecosystems and Environment 264* (2018): 73-84

S. Ogle, *et al*. "Agricultural Management Impacts on Soil Organic Carbon Storage under Moist and Dry Climatic Conditions of Temperate and Tropical Regions," *Biogeochemistry 72* (2005): 87-121

S. Ogle, *et al*., *Report on GHG Mitigation Literature Review for Agricultural Systems*," prepared for USDA Climate Change Office, Natural Resource Ecology Laboratory, Colorado State University, 2010

K. Olson, *et al*., "Cover Crop Effects on Crop Yields and Soil Organic Carbon Content," *Soil Science 175* (2010): 89-97

K. Olson, *et al*. "Effects of 24 Years of Conservation Tillage Systems on Soil Organic Carbon and Soil Productivity," *Applied and Environmental Soil Science* vol 2013 article ID 617504 10 pages (2013) https://dx.doi.org/10.155/2013/617504

K. Olson, *et al*., "Long-term Effects of Cover Crops on Crop Yields, Soil Organic Carbon Stocks and Sequestration," *Open Journal of Soil Science 4* (2014): 282-292

R. Omonode, *et al*., "Short-term Versus Continuous Chisel and No-Till Effects on Soil Carbon and Nitrogen," *Soil Science Society of America Journal 70* (2006): 419-425

K. Oorts, *et al*., "Determinants of Annual Fluxes of CO_2 and N_2O in Long-term No Tillage and Conventional Tillage Systems in Northern France," *Soil and Tillage Research 95* (2007): 133-148

S. Pellerin, *et al*., "Identifying Cost-Competitive Greenhouse Gas Mitigation Potential of French Agriculture," *Environmental Science and Policy 77* (2017): 130-139

D. Place-Bonilla, *et al*., "Tillage Effects on Soil Aggregation and Soil Organic Carbon Profile Distribution under Mediterranean Conditions," *Soil Use and Management 26* (2010): 465-474

W. Post, *et al*., "Management Oportunities for Enhacing Terrestrial Carbon Dioxide Sinks," *Frontiers in Ecology and the Environment 10* (2012): 554-561

W. Post, *et al*., "Management Opportunities for Enhancing Terrestrial Carbon Dioxide Sinks," *Frontiers in Ecology 10* (2012): 554-561

K. Potter, *et al*., "Distribution and Amount of Soil Organic C in Long-term Management Systems in Texas," *Soil and Tillage Research 47* (1998): 309-321

D. Powlson, *et al*., "Limited Potential of No-Till Agriculture for Climate Change Mitigation," *Nature Climate Change 4* (2014): 678-683

P. Puget and R. Lal, "Soil Organic Carbon and Nitrogen in a Mollisol in Central Ohio as Affected by Tillage and Land Use," *Soil and Tillage Research 80* (2005): 201-213

G. Robertson, *et al*., "Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere," *Science 289* (2000): 1,922-1,925

G. Robertson, *et al*., "The Biogeochemistry of Bioenergy Landscapes: Carbon, Nitrogen, and Water Considerations," *Ecological Applications 21* (2011): 1,055-1,067

U. Sainju, *et al*., "Long-term Effects of Tillage, Cover Crops, and Nitrogen Fertilization on Organic Carbon and Nitrogen Concentrations in Sandy Soils in Georgia, USA," *Soil and Tillage Research 63* (2002): 167-179

U. Sainju, *et al*., "Tillage, Cropping Systems, and Nitrogen Fertilizer Source Effects on Soil Carbon Sequestration and Fractions," *Journal of Environmental Quality 37* (2008): 880-888

U. Sainju, *et al*., "Tillage and Crop Rotation Effects on Dryland Soil and Residue Carbon and Nitrogen," *Soil Science Society of America Journal 70* (2006): 668-678

U. Sainju, *et al*., "Carbon Supply and Storage in Tilled and Non-tilled Soils as Influenced by Cover Crops and Nitrogen Fertilization," *Journal of Environmental Quality 35* (2006): 1,507-1,517

U. Sainju, *et al*., "Carbon Accumulation in Cotton, Sorghum, and Underlying Soil as Influenced by Tillage, Cover Crops, and Nitrogen Fertilization," *Plant and Soil 273* (2005): 219-234

U. Sainju, *et al*., "Soil Carbon and Crop Yields Affected by Irrigation, Tillage, Cropping System, and Nitrogen Fertilization," *Soil Science Society of America Journal 78* (2014): 936-948

U. Sainju, *et al*., "Net Global Warming Potential and Greenhouse Gas Intensity Influenced by Irrigation, Tillage, Crop Rotation, and Nitrogen Fertilization," *Journal of Environmental Quality 43* (2014): 777-788

U. Sainju, *et al*., "Dryland Soil Carbon and Nitrogen after Thirty Years of Tillage and Cropping Sequence," *Agronomy Journal 107* (2015): 1,822-1,830

U. Sainju, *et al*., "Soil Total Carbon and Crop Yield Affected by Crop Rotation and Cultural Practice," *Agronomy Journal 109* (2017): 1-9

J. Sanderman, *et al*., *Soil Carbon Sequestration Potential: A Review for Australian Agriculture*. A Report Prepared for Department of Climate Change and Energy Efficiency, CSIRO, 2009

A. Sanz-Cobena, *et al*., "Strategies for Greenhouse Gas Emissions Mitigation in Mediterranean Agriculture: A Review," *Agriculture, Ecosystems and Environment 238* (2017): 5-24

M. Schmer, *et al*., "Tillage and Residue Management Effects on Soil Carbon and Nitrogen under Irrigated Continuous Corn," *Soil Science Society of America Journal 78* (2014): 1,987-1,996

S. Senthilkumar, *et al*., "Topography Influences Management System Effects on Total Carbon and Nitrogen," *Soil Science Society of America Journal 73* (2009): 2,059-,

S. Senthilkumar, *et al*., "Contemporary Evidence of Soil Carbon Loss in the US Corn Belt," *Soil Science Society of America Journal 73* (2009): 2,078-2,086

X. Shi, *et al*., "Zone Tillage Impacts on Organic Carbon of a Clay Loam in Southwestern Ontario," *Soil Science Society of America Journal 75* (2011): 1,083-1,088

X. Shi, *et al*., "Impact of Ridge Tillage on Soil Organic Carbon and Selected Physical Properties of a Clay Loam in Southwestern Ontario," *Soil and Tillage Research 120* (2012): 1-7

B. Shrestha, *et al*., "Effects of Crop Rotation, Crop Type and Tillage on Soil Organic Carbon in Semiarid Climate," *Canadian Journal of Soil Science 93* (2013): 137-146

J. Six, *et al*., "Aggregate and Soil Organic Matter Dynamics under Conventional and No-Tillage Systems," *Soil Science Society of America Journal 63* (1999): 1,350-1,358

J. Six, *et al*., "Soil Organic Matter, Biota and Aggregation in Temperate and Tropical Soils-Effects of Tillage," *Agonomie 22* (2002): 755-775

J. Six, *et al*., "The Potential to Mitigate Global Warming with No-Tillage Management is Only Realized When Practices in the Long-Term," *Global Change Biology 10* (2004): 155-160

P. Smith, *et al*., "Meeting Europe's Climate Change Commitments: Quantitative Estimates of the Potential for Carbon Mitigation by Agriculture," *Global Change Biology 6* (2000): 525-539

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

P. Smith, *et al*., "Carbon Sequestration Potential in European Croplands Has Been Overestimated," *Global Change Biology 11* (2005): 2153-2163

P. Smith, *et al*., "Greenhouse Gas Mitigation in Agriculture," *Philosophical Transactions of the Royal Society B 363* (2008): 789-813

W. Smith, *et al*., "Estimated Changes in Soil Carbon Associated with Agricultural Practices in Canada," *Canadian Journal of Soil Science 81* (2001): 221-227

M. Sperow, *et al*., "Potential Soil C Sequestration on U.S. Agricultural Soils," *Climatic Change 57* (2003): 319-339

M. Sperow, "An Enhanced Method Using the IPCC Approach to Estimate Soil Organic Carbon Storage Potential on US Agricultural Soils," *Agriculture, Ecosystems and Environment 193* (2014): 96-107

M. Sperow, "Estimating Carbon Sequestration in US Agricultural Top Soils," *Soil and Tillage Research 155* (2016): 390-400

C. Stockle, *et al*., "Carbon Storage and Nitrous Oxide Emissions of Cropping Systems of Eastern Washington: A Simulation Study," *Journal of Soil and Water Conservation 67* (2012): 365-377

B. Sun, *et al*., "Distribution of Soil Carbon and Microbial Biomass in Arable Soils under Different Tillage Regines," *Plant and Soil 338* (2011): 17-25

A. Swan, *et al*., *COMET-Planner: Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning: A Companion Report to www.comet-planner.com*, NRCS-USDA and Colorado State, 2015

S. Syswerda, *et al*., "Agricultural Management and Soil Carbon Storage in Surface vs. Deep Layers," *Soil Science Society of America Journal 75* (2010): 92-101

A. Tellez, *et al*., "Conservation Agriculture Practices Reduce the Global Warming Potential of Rainfed Low-Input Semi-Arid Agriculture," *European Journal of Agronomy 84* (2017): 95-104

V. Tolbert, *et al*., "Changes in Soil Quality and Below-Ground Carbon Storage with Conversion of Traditional Agricultural Croplands to Bioenergy Crop Production," *Environmental Pollution 116* (2002): S97-S106

D. Ussiri and R. Lal, "Long-term Tillage Effects on Soil Carbon Storage and Carbon Dioxide Emissions in Continuous Corn Cropping System from an Alfisol in Ohio," *Soil and Tillage Research 104* (2009): 39-47

L. Van Eerd, *et al*., "Long-term, Tillage and Crop Rotation Effects on Soil Quality, Organic Carbon, and Total Nitrogen," *Canadian Journal of Soil Science 94* (2014): 303-315

A. VandenBygaart, *et al*. "Influence of Agricultural Management on Soil Organic Carbon: A Compendium and Assessment of Canadian Studies," *Canadian Journal of Soil Science 83* (2003): 363-380

A, VandenBygaart, *et al*., "Soil Carbon Change Factors for the Canadian Agriculture National Greenhouse Gas Inventory," *Canadian Journal of Soil Science 88* (2008): 671-680

A. VandenBygaart, *et al*., "Soil Organic Carbon Stocks on Long-term Agroecosystem Experiments in Canada," *Canadian Journal of Soil Science 90* (2010): 543-550

A. VandenBygaart, *et al*., "Impact of Sampling Depth on Differences in Soil Carbon Stocks in Long-term Agroecosystem Experiments," *Soil Science Society of America Journal 75* (2011): 226-234

G. Varvel and W. Wilhelm, "Long-term Soil Organic Carbon as Affected by Tillage and Cropping Systems," *Soil Science Society of America Journal 74* (2010): 915-921

G. Varvel and W. Wilhelm, "No-Tillage Increases Soil Profile Carbon and Nitrogen under Long-term Rainfed Cropping Systems," *Soils and Tillage Research 114* (2011): 28-36

J. Veenstra, *et al*., "Tillage and Cover Cropping Effects on Aggregate-Protected Carbon in Cotton and Tomato," *Soil Science Society of America Journal 71* (2007): 362-371

M. Veloso, *et al*., "High Carbon Storage in a Previously Degraded Subtropical Soil under No-Tillage with Legime Cover Crops," *Agriculture, Ecosystems and Environment 268* (2018): 15-23

R. Venterea, *et al*., "Carbon and Nitrogen Storage are Greater under Biennial Tillage in a Minnesota Corn-Soybean Rotation," *Soil Science Society of America Journal 70* (2006): 1,752-1,762

M. Villamil and E. Nafiger, "Corn Residue and Nitrogen Rate Effects on Soil Carbon and Nutrient Stocks in Illinois," *Geoderma 253/254* (2015): 61-66

I. Virto, *et al*., "Carbon Input Differences as the Main Factor Explaining the Variability in Soil Organic C Storage in No-Tilled Compared to Inversion Tilled Agrosystems," *Biogeochemistry 108* (2012): 17-26

L. Vleeshouwers and A. Verhagen, "Carbon Emission and Sequestration by Agricultural Land Use: A Model Study for Europe," *Global Change Biology 8* (2002): 519-530

M. Walia, *et al*., "Deep Soil Carbon after 44 Years of Tillage and Fertilizer Management in Southern Illinois Compared to Forest and Restored Prairie Soils," *Journal of Soil and Water Conservation 72* (2017): 405-415

W. Wang and R. Dalal, "Carbon Inventory for a Cereal Cropping System under Contrasting Tillage, Nitrogen Fertilization and Stubble Management Practices," *Soil and Tillage Research 91* (2006): 68-74

S. Wanniarachchi, *et al*., "Tillage Effects on the Dynamics of Total and Corn Residue-Derived Soil Organic Matter in Two Southern Ontario Soils," *Canadian Journal of Soil Science 79* (1999): 473-480

T. West and G. Marland, "Net Carbon Flux from Agricultural Ecosystems: Methodology for Full Carbon Cycle Analyses," *Environmental Pollution 116* (2002): 439-444

T. West and W. Post, "Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation: A Global Data Analysis," *Soil Science Society of America Journal 66* (2002): 1,930-1,946

B. Wienhold, *et al*., "CQESTR Simulated Change in Soil Organic Carbon under Residue Management Practices in Continuous Corn Systems," *Bioenergy Research 9* (2016): 23-30

X. Yang, *et al*., "Impacts of Long-term and Recently Imposed Tillage Practices on the Vertical Distribution of Soil Organic Carbon," *Soil and Tillage Research 100* (2008): 120-124

X. Yang and B. Kay, "Impacts of Tillage Practices on Total, Loose- and Occluded-Particulate, and Humidified Organic Carbon Fractions in Soils Within a Field in Southern Ontario," *Canadian Journal of Soil Science 81* (2001): 149-156

X. Yang and B. Kay, "Rotation and Tillage Effects on Soil Organic Carbon Sequestration in a Typic Hapludalf in Southern Ontario," *Soil and Tillage Research 59* (2001): 107-114

X. Yang and M. Wander, "Tillage Effects on Soil Organic Carbon Distribution and Storage in a Silt Loam Soil in Illinois," *Soil and Tillage Research 52* (1999): 1-9

A. Yogioka, *et al*., "Effect of No-Tillage with Weed Cover Mulching Versus Conventional Tillage on Global Warming Potential and Nitrate Leaching," *Agriculture, Ecosystems and Environment 200* (2015): 42-53

S. Zuber, *et al*., "Crop Rotation and Tillage Effects on Soil Physical and Chemical Properties in Illinois," *Agronomy Journal 107* (2015): 971-978

Hay (alfalfa, nonleguminous perennial grasses) replacing annual crops: N_2O

M. Baranski and S. Del Grosso, *US Agriculture and Forestry Greenhouse Gas Inventory 1990-2013*, Technical Bulletin 1943, Office of the Chief Economist, US Department of Agriculture, September 2016

J. Barsotti, *et al*., "Net Greenhouse Gas Emissions Affected by Sheep Grazing in Drland Cropping Systems," *Soil Science Society of America Journal 77* (2012): 1,012-1,025

M. Carter, *et al*., "Consequences of Field N_2O Emissions for the Environmental Sustainability of Plant-Based Biofuels Produced within an Organic Farming System," *Global Change Biology 4* (2012): 435-452

D. Chianese, *et al*., "Simulation of Nitrous Oxide from Dairy Farms to Assess Greenhouse Gas Reduction Strategies," *Transactions of the ASABA 52* (2009): 1,325-1,335

M. Dusenbury, *et al*., "Nitrous Oxide Emissions from a Northern Great Plains Soil as Influenced by Nitrogen Management abd Cropping Systems," *Journal of Environmental Quality 38* (2008): 542-550

I. Galbally, *et al*., "Nitrous Oxide Emissions from a Legume Pasture and the Influences of Liming and Urine Addition," *Agriculture, Ecosystems and Envirinment 136* (2010): 262-272

I. Gelfand and G. Robertson, "Mitigation of Greenhouse Gases in Agricultural Ecosystems," in S. Hamilton, *et al*., eds, *The Ecology of Agricultural Landscapes: Long-term Research on the Path to Sustainability* (New York: Oxford University Press, 2015), pp. 310-339

I. Gelfand, *et al*., "Long-term Nitrous Oxide Fluxes in Annual and Perennial Agricultural and Unmanaged Ecosystems in the Upper Midwest," *Global Change Biology 22* (2016): 3,594-3,607

E. Gregorich, *et al*., "Greenhouse Gas Contributions of Agricultural Soils and Potential Mitigation Practices in Eastern Canada," *Soil and Tillage Research 83* (2005): 53-72

E. Jensen, *et al*., "Legumes for Mitigation of Climate Change and the Provision of Feedstock for Biofuels and Biorefineries. A Review," *Agronmy for Sustainble Development 32* (2012): 329-364

S. Maas, *et al*., "Net CO_2 and N_2O Exchange during Perennial Forage Establishment in an Annual Crop Rotation in the Red River Valley, Manitoba," *Canadian Journal of Soil Science 93* (2013): 639-652

A. MacKenzie, *et al*., "Nitrous Oxide Emission as Affected by Tillage, Corn-Soybean-Alfalfa Rotations, and Nitrogen Fertilization," *Canadian Journal of Soil Science 77* (1977): 145-152

G. Robertson, *et al*., "Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere," *Science 289* (2000): 1,922-1,925

P. Rochette, *et al*., "Emissions of N_2O from Alfalfa and Soybean Crops in Eastern Canada," *Soil Science Society of America Journal 68* (2004): 493-506

P. Rochette and H. Janzen, "Towards a Revised Coefficient for Estimating N_2O Emissions from Legumes," *Nutrient Cycling in Agroecosystems 73* (2005): 171-179

S. Shafer and E. Thompson, *A New Comparison of Greenhouse Gas Emissions from California Agricultural and Urban Land Uses*, American Farmland Trust, 2015

C. Wagner-Riddle, *et al*., "Estimates of Nitrous Oxide Emissions from Agricultural Fields Over 28 Months," *Canadian Journal of Soil Science 77* (1997): 135-144

Hay (alfalfa, nonleguminous perennial grasses) replacing annual crops: SOC/CO_2

G. Alberti, *et al*., "Changes in CO_2 Emissions after Crop Conversion from Continuous Maize to Alfalfa," *Agriculture, Ecosystems and Environment 136* (2010): 139-147

M. Al-Kaisi, *et al*., "Soil Carbon and Nitrogen Changes as influenced by Tillage and Cropping Systems in Some Iowa Soils," *Agriculture, Ecosystems and Environment 105* (2005): 635-647

M. Baranski and S. Del Grosso, *US Agriculture and Forestry Greenhouse Gas Inventory 1990-2013*, Technical Bulletin 1943, Office of the Chief Economist, US Department of Agriculture, September 2016

J. Barsotti, *et al*., "Net Greenhouse Gas Emissions Affected by Sheep Grazing in Drland Cropping Systems," *Soil Science Society of America Journal 77* (2012): 1,012-1,025

G. Borjesson, *et al*., "Organic Carbon Stocks in Topsoil in Long-term Ley and Cereal Monoculture Rotations," *Biology and Fertility of Soils 54* (2018): 549-558

C. Campbell, *et al*., "Quantifying Short-term Effects of Crop Rotations on Soil Organic Carbon in Southwestern Saskatchewan," *Canadian Journal of Sol Science 80* (2000): 192-202

S. Chang, *et al*. (2012) "Alfalfa Carbon and Nitrogen Sequestration Patterns and Effects of Temperature and Precipitation in Three Agro-Pastoral Ecotones of Northern China," *PLoS ONE 7* (11):e50544. doi:10.1371/journal.pone.0050544

K. Denef, *et al*., *Greenhouse Gas Emissions from U.S. Agriculture and Forestry: A Review of Emission Sources, Controlling factors, and Mitigation Potential*. Interim Report to USDA under contract #G-23F-8182H, ICF International, 2011

A. Eagle, *et al*., *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States: A Synthesis of the Literature*, 3rd edition, Nicholas Institute, Duke University, January 2012

M. Eve, *et al*., "Predicted Impact of Management Changes on Soil Carbon Storage for Each Cropland Region of the Coterminous United States," *Journal of Soil and Water Conservation 57* (2002): 196-204

F. Ferchaud, *et al*., "Changes in Soil Carbon Stocks under Perennial and Annual Bioenergy Crops," *Global Change Biology 8* (2016): 290-306

C. Fissore, *et al*., "Limited Potential for Terrestrial Carbon Sequestration to Offset Fossil-Fuel Emissions in the Upper Midwestern USA," *Frontiers in Ecology and the Environment 8* (2010): 409-413

A. Freibauer, *et al*., "Carbon Sequestration in the Agricultural Soils of Europe," *Geoderma 122* (2004): 1-23

I. Gelfand and G. Robertson, "Mitigation of Greenhouse Gases in Agricultural Ecosystems," in S. Hamilton, *et al*., eds., *The Ecology of Agricultural Landscapes: Long-term Research on the Path to Sustainability* (New York: Oxford University Press, 2015), pp. 310-339

T. Gilmanov, *et al*., "Productivity and Carbon Dioxide Exchange of Leguminous Crops: Estimates from Flux Tower Measurements," *Agronomy Journal 106* (2014): 545-559

A. Grandy and G. Robertson, "Land-use Intensity Effects on Soil Organic Carbon Accumulation Rates and Mechanisms," *Ecosystems 10* (2007): 58-73

E. Gregorich, *et al*., "Changes in Soil Carbon under Long-term Maize in Monoculture and Legume-based Rotation," *Canadian Journal of Soil Science 81* (2001): 21-31

R. Izaurralde, *et al*., "Carbon Balance of the Breton Classical Plots over Half a Century," *Soil Science Society of America Journal 65* (2001): 431-441

E. Lugato, *et al*., "Potential Carbon Sequestration of European Arable Soils Estimated by Modelling a Comprehensive Set of Management Practices," *Global Change Biology 20* (2015): 3,357-3,567

S. Mahli, *et al*., "Cultivation and Grassland Type Effects on Light Fraction and Total Organic C and N in a Dark Brown Chernozemic Soil," *Canadian Journal of Soil Science 83* (2003): 145-153

S. Maas, *et al*., "Net CO_2 and N_2O Exchange during Perennial Forage Establishment in an Annual Crop Rotation in the Red River Valley, Manitoba," *Canadian Journal of Soil Science 93* (2013): 639-652

A. Mosier, *et al*., "Measurement of Net Global Warming Potential in Three Agroecosystems," *Nutrient Cycling in Agroecosystems 72* (2005): 67-76

S. Pellerin, *et al*., "Identifying Cost-Competitive Greenhouse Gas Mitigation Potential of French Agriculture," *Environmental Science and Policy 77* (2017): 130-139

A. Robertson, *et al*., "Climate Change Impacts on Yields and Soil Carbon in Row Crop Dryland Agriculture," *Journal of Environmental Quality 47* (2018): 684-694

G. Robertson, *et al*., "Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere," *Science 289* (2000): 1,922-1,925

U. Sainju and A. Lenssen, "Dryland Carbon Dynamics under Alfalfa and Durum-Forage Cropping Sequences," *Soil and Tillage Research 113* (2011): 30-37

S. Shafer and E. Thompson, *A New Comparison of Greenhouse Gas Emissions from California Agricultural and Urban Land Uses*, American Farmland Trust, 2015

L. Sherrod, *et al*., "Carbon and Nitrogen Dynamics as Affected by Rotation Intensity in the Great Plains," *Agronomy Abstracts*, American Society of Agronomy, Madison, WI, 1995, pp. 1-135

L. Sherrod, *et al*., "Soil Carbon Pools in Dryland Agroecosystems as Affected by Several Years of Drought," *Journal of Environmental Quality 47* (2018): 766-773

P. Smith, *et al*., "Carbon Sequestration Potential in European Croplands Has Been Overestimated," *Global Change Biology 11* (2005): 2,153-2,163

A. Swan, *et al*., *COMET-Planner: Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning: A Companion Report to ww.comet-planner.com*, NRCS-USDA and Colorado State, 2015

A. VandenBygaart, *et al*., "Influence of Agricultural Management on Soil Organic Carbon: A Compendium and Assessment of Canadian Studies," *Canadian Journal of Soil Science 83* (2003): 363-380

A. VandenBygaart, *et al*., "Soil Carbon Change Factors for the Canadian Agriculture National Greenhouse Gas Inventory," *Canadian Journal Soil Science 88* (2008): 671-680

X. Yang and B. Kay, "Rotation and Tillage Effects on Soil Organic Carbon Sequestration in a Typic Hapludalf in Southern Ontario," *Soil and Tillage Research 59* (2001): 107-114

Extend rotation by adding alfalfa or nonleguminous hay: N_2O

M. Baranski and S. Del Grosso, *US Agriculture and Forestry Greenhouse Gas Inventory 1990-2013*, Technical Bulletin 1943, Office of the Chief Economist, US Department of Agriculture, September 2016

M. Benoit, *et al*., "Nitrous Oxide Emissions and Nitrate Leaching in an Organic and a Conventional Cropping System (Seine Basin, France)," *Agriculture, Ecosystems and Environment 213* (2015): 131-141

C. Drury, *et al*., "Influence of 49-51 Years of Fertilization and Crop Rotation on Growing Season Nitrous Oxide Emissions, Nitrogen Uptake and Corn Yields," *Canadian Journal of Soil Science 94* (2014): 421-433

A. Eagle, *et al*., *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States: A Synthesis of the Literature*, 3rd edition, Nicholas Institute, Duke University, January 2012

B. Ellert and H. Janzen, "Nitrous Oxide, Carbon Dioxide and Methane Emissions from Irrigated Cropping Systems as Influenced by Legumes, Manure and Fertilizer," *Canadian Journal of Soil Science 88* (2008): 207-217

H. Flessa, *et al*., "Integrated Evaluation of Greenhouse Gas Emissions (CO_2, CH_4, N_2O) from Two Farming Systems in Southern Germany," *Agriculture, Ecosystems and Environment 91* (2002): 175-189

J. Johnson, *et al*., "Do Mitigation Strategies Reduce Global Warming Potential in the Northern U.S. Corn Belt," *Journal of Environmental Quality 40* (2011): 1,551-1,559

J. Johnson, *et al*., "Greenhouse Gas Emissions from Contrasting Management Scenarios in the Northern Corn Belt," *Soil Science Society of America Journal 74* (2010): 396-406

A. MacKenzie, *et al*. "Nitrous Oxide Emission as Affected by Tillage, Corn-Soybean-Alfalfa Rotations, and Nitrogen Fertilization," *Canadian Journal of Soil Science 77* (1977): 145-152

A. MacKenzie, *et al*., "Nitrous Oxide Emissions in Three Years as Affected by Tillage, Corn-Soybean-Alfalfa Rotation, and N Fertilization," *Journal of Environmental Quality 27* (1998): 698-703

W. Osterholz, *et al*., "Seasonal Nitrous Oxide and Methane Fluxes from Grain- and Forage-Based Production Systems in Wisconsin USA," *Journal of Environmental Quality 43* (2014): 1,833-1,843

P. Smith, *et al*., "Greenhouse Gas Mitigation in Agriculture," *Philosophical Transactions of the Royal Society B 363* (2008): 789-813

A. Swan, *et al*., *COMET-Planner: Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning: A Companion Report to www.comet-planner.com*, NRCS-USDA and Colorado State, 2015

K. Uzoma, *et al*., "Assessing the Effects of Agricultural Management on Nitrous Oxide Emissions Using Flux Measurements and the DNDC Model," *Agriculture, Eocsystems and Environment 206* (2015): 71-83

M. Westphal, *et al*., "Nitrous Oxide Emissions with Organic Crop Production Depends on Fall Soil Moisture," *Agriculture, Ecosystems and Environment 254* (2018): 41-49

Extend rotation by adding alfalfa or nonleguminous hay: SOC/CO_2

M. Baranski and S. Del Grosso, *US Agriculture and Forestry Greenhouse Gas Inventory 1990-2013*, Technical Bulletin 1943, Office of the Chief Economist, US Department of Agriculture, September 2016

L. Bell, *et al*., "Soil Profile Carbon and Nutrient Stocks under Long-term Conventional and Organic Crop and Alfalfa Crop-rotations and Re-established Grassland," *Agriculture, Ecosystems and Environment 158* (2012): 156-163

T. Brown and D. Huggins, "Soil Carbon Sequestration in the Dryland Cropping Region of the Pacific Northwest," *Journal of Soil and Water Conservation 67* (2012): 406-415

C. Campbell, *et al*., "Effect of Crop Rotation and Cultural Practices on Soil Organic Matter, Microbial Biomass and Respiration in a Thin Black Chernozem," *Canadian Journal of Soil Science 71* (1991): 363-376

C. Dell, *et al*., "Implications of Observed and Simulated Soil Carbon Sequestration for Management Options in Corn-Based Rotations," *Journal of Environmental Quality 47* (2018): 617-624

K. Denef, *et al*., *Greenhouse Gas Emissions from U.S. Agriculture and Forestry: A Review of Emission Sources, Controlling factors, and Mitigation Potential*. Interim Report to USDA under contract #G-23F-8182H, ICF International, 2011

R. Desjardins, *et al*., "Management Strategies to Sequester Carbon in Agricultural Soils and to Mitigate Greenhouse Gas Emissions," *Climatic Change 70* (2005): 283-297

A. Eagle, *et al*., *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States: A Synthesis of the Literature*, 3rd edition, Nicholas Institute, Duke University, January 2012

E. Gregorich, *et al*., "Changes in Soil Carbon under Long-term Maize in Monoculture and Legume-based Rotation," *Canadian Journal of Soil Science 81* (2001): 21-31

M. Jarecki, *et al*., "Long-Term Trends in Corn Yields and Soil Carbon under Diversified Crop Rotations," *Journal of Environmental Quality 47* (2018): 635-643

J. Johnson, *et al*., "Do Mitigation Strategies Reduce Global Warming Potential in the Northern U.S. Corn Belt," *Journal of Environmental Quality 40* (2011): 1,551-1,559

A. Johnston, *et al*., "Changes in Soil Organic Matter over 70 Years in Continuous Arable and Ley-Arable Rotations on a Sandy Loam Soil in England," *European Journal of Soil Science 68* (2017): 305-316

S. Khan, *et al*., "The Myth of Nitrogen Fertilization for Soil Carbon Sequestration," *Journal of Environmental Quality 36* (2007): 1,821-1,832

R. Lal, *et al*., "Long-Term Tillage and Rotation Properties of a Central Ohio Soil," *Soil Science Society of America Journal 58* (1994): 517-522

E. Lugato, *et al*., "Potential Carbon Sequestration of European Arable Soils Estimated by Modelling a Comprehensive Set of Management Practices," *Global Change Biology 20* (2015): 3,357-3,567

M. Mikha, *et al*., "Cropping System Influences on Soil Chemical Properties and Soil Quality on the Great Plains," *Renewable Agriculture and Food Systems 21* (2006): 26-53

E. Paul, *et al*., "Management Effects on the Dynamics and Storage Rates of Organic Matter in Long-term Crop Rotations," *Canadian Journal of Soil Science 84* (2004): 49-61

J. Pikul, *et al*., "Change in Surface Soil Carbon under Rotated Corn in Eastern South Dakota," *Soil Science Society of America Journal 72* (2008): 1,738-1,744

C. Robinson, *et al*., "Cropping Systems and Nitrogen Effects on Mollisol Organic Carbon," *Soil Science Society of America Journal 60* (1996): 264-269

A. Russell, *et al*., "Impact of Nitrogen Fertilizer and Cropping System on Carbon Sequestration in Midwestern Mollisols," *Soil Science Society of America Journal 69* (2005): 413-422

G. Sanford, *et al*., "Soil Carbon Lost from Mollisols of the North Central USA with 20 Years of Agricultural Best Management Practices," *Agriculture, Ecosystems and Environment 162* (2012): 68-76

P. Smith, *et al*., "Carbon Sequestration Potential in European Croplands Has Been Overestimated," *Global Change Biology 11* (2005): 2,153-2,163

A. Swan, *et al*., *COMET-Planner: Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning: A Companion Report to www.comet-planner.com*, NRCS-USDA and Colorado State, 2015

A. VandenBygaart, *et al.,* "Influence of Agricultural Management on Soil Organic Carbon: A Compendium and Assessment of Canadian Studies," *Canadian Journal of Soil Science 83* (2003): 363-380

A. VandenBygaart, *et al*., "Impact of Sampling Depth on Differences in Soil Carbon Stocks in Long-term Agroecosystem Experiments," *Soil Science Society of America Journal 75* (2011): 226-234

T. West and W. Post, "Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation: A Global Data Analysis," *Soil Science Society of America Journal 66* (2002): 1,930-1,946

M. Zeri, *et al*., "Carbon Exchange by Establishing Biofuels Crops in Central Illinois," *Agriculture, Ecosystems and Environment 144* (2011): 319-329

Corn-soybean rotation replacing continuous corn-N_2O

M. Adviento, *et al*., "Soil Greenhouse Gas Fluxes and Global Warming Potential in Four High-Yielding Maize Systems," *Global Change Biology 13* (2007): 1,972-1,988

D. Archer and A. Halvorson, "Greenhouse Gas Mitigation Economics for Irrigated Cropping System in Northeastern Colorado," *Soil Science Society of America Journal 74* (2010): 446-452

G. Behnke, *et al*., "Long-term Crop Rotation and Tillage Effects on Soil Greenhouse Gas Emissions and Crop Production in Illinois, USA," *Agriculture, Ecosystems and Environment 261* (2018): 62-70

C. Decock, "Mitigating Nitrous Oxide Emissions from Corn Cropping Systems in the Midwestern US: Potential and Data Gaps," *Environmental Science and Technology 48* (2014): 4,247-4,256

W. Dick, *et al*., "Impacts of Agricultural Management Practices on C Sequestration in Forest-Derived Soil in the Eastern Corn Belt," *Soil and Tillage Research 47* (1998): 235-244

A. Dobermann, *et al*., "Global Warming Potential of High Yielding Continuous Corn and Corn-Soybean Systems," *Better Crops 91* (2007): 16-19

C. Drury, *et al*., "Nitrous Oxide and Carbon Dioxide Emissions from Monoculture and Rotational Cropping of Corn, Soybeans and Winter Wheat," *Canadian Journal of Soil Science 88* (2008): 163-174

G. Hernandez-Ramirez, *et al*., "Greenhouse Gas Fluxes in an Eastern Corn Belt Soil: Weather, Nitrogen Source, and Rotation," *Journal of Environmental Quality 38* (2009): 841-854

P. Jacinthe and W. Dick, "Soil Management and Nitrous Oxide Emissions from Cultivated Fields in Southern Ohio," *Soil and Tillage Research 41* (1997): 221-235

A. MacKenzie, *et al*., "Nitrous Oxide Emission as Affected by Tillage, Corn-Soybean-Alfalfa Rotations, and Nitrogen Fertilization," *Canadian Journal of Soil Science 77* (1977): 145-152

A. Mosier, *et al*., "Measurement of Net Global Warming Potential in Three Agroecosystems," *Nutrient Cycling in Agroecosystems 72* (2005): 67-76

A. Mosier, *et al*., "Net Global Warming Potential and Greenhouse Gas Intensity in Irrigated Cropping Systems in Northeastern Colorado," *Journal of Environmental Quality 35* (2006): 1,584-1,598

R. Omonode, *et al*., "Soil Nitrous Oxide Emission in Corn Following Three Decades of Tillage and Rotation Treatments," *Soil Science Society of America Journal 75* (2010): 152-163

W. Osterholz, *et al*., "Seasonal Nitrous Oxide and Methane Fluxes from Grain- and Forage-Based Production Systems in Wisconsin USA," *Journal of Environmental Quality 43* (2014): 1,833-1,843

G. Robertson, *et al*., "The Biogeochemistry of Bioenergy Landscapes: Carbon, Nitrogen, and Water Considerations," *Ecological Applications 21* (2011): 1,055-1,067

R. Venterea, *et al*., "Urea Decrease Nitrous Oxide Emissions Compared with Anhydrous Ammonia in a Minnesota Corn Cropping System," *Soil Science Society of America Journal 74* (2010): 407-418

R. Venterea and J. Coulter, "Split Application of Urea Does Not Decrease and May Increase Nitrous Oxide Emissions in Rainfed Corn," *Agronomy Journal 107* (2015): 337-348

D. Walters, *et al*.,"Closing the Corn Yield Gap: Management Practices that Improve Soil Quality and Net Productivity but Reduce Global Warming Potential," *2007 Indiana CCA Conference Proceedings, Indianapolis, December 2007*

Corn-soybean rotation placing continuous corn-SOC/CO_2

M. Adviento, *et al*., "Soil Greenhouse Gas Fluxes and Global Warming Potential in Four High-Yielding Maize Systems," *Global Change Biology 13* (2007): 1,972-1,988

D. Archer and A. Halvorson, "Greenhouse Gas Mitigation Economics for Irrigated Cropping System in Northeastern Colorado," *Soil Science Society of America Journal 74* (2010): 446-452

J. Coulter, *et al*., "Soil Organic Matter Response to Cropping System and Nitrogen Fertilization," *Agronomy Journal 101* (2009): 592-599

A. Dobermann, *et al*., "Global Warming Potential of High Yielding Continuous Corn and Corn-Soybean Systems," *Better Crops 91* (2007): 16-19

L. Eerd, *et al*., "Long-term, Tillage and Crop Rotation Effects on Soil Quality, Organic Carbon, and Total Nitrogen," *Canadian Journal of Soil Science 94* (2014): 303-315

A. Gal., *et al*., "Soil Carbon and Nitrogen Accumulation with Long-term No-Till versus Moldboard Plowing Overestimated with Tilled Zone Sampling Depths," *Soil and Tillage Research 96* (2007): 42-51

D. Huggins, *et al*., "Corn-Soybean Sequence and Tillage Effects on Soil Carbon Dynamics and Storage," *Soil Science Society of America Journal 71* (2007): 145-154

S. Jagadamma, *et al*., "Nitrogen Fertilization and Cropping Systems effects on Soil Organic Carbon and Total Nitrogen Pools Under Chisel-Plow in Illinois," *Soil and Tillage Research 95* (2007): 348-356

J. Johnson, *et al*., "Greenhouse Gas Contributions and Mitigation Potential of Agriculture in the Central USA," *Soil and Tillage Research 83* (2005): 73-94

C. Jones, *et al*., "Perennialization and Cover Cropping Mitigate Soil Carbon Loss from Residue Harvesting," *Journal of Environmental Quality 47* (2018): 710-717

S. Khan, *et al*., "The Myth of Nitrogen Fertilization for Soil Carbon Sequestration," *Journal of Environmental Quality 36* (2007): 1,821-1,832

M. Liebig, *et al*., "Crop Sequence and Nitrogen Fertilization Effects on Soil Properties in the Western Corn Belt," *Soil Science Society of America Journal 66* (2002): 596-601

A. Mosier, *et al*., "Measurement of Net Global Warming Potential in Three Agroecosystems," *Nutrient Cycling in Agroecosystems 72* (2005): 67-76

A. Mosier, *et al*., "Net Global Warming Potential and Greenhouse Gas Intensity in Irrigated Cropping Systems in Northeastern Colorado," *Journal of Environmental Quality 35* (2006): 1,584-1,598

J. Pikul, *et al*., "Change in Surface Soil Carbon under Rotated Corn in Eastern South Dakota," *Soil Science Society of America Journal 72* (2008): 1738-1744

H. Poffenbarger, *et al*. (2017) "Maximum Soil Organic Carbon Storage in Midwest US Cropping Systems When Crops Are Optimally Nitrogen-Fertilized," *PLoS One 12*(3): e0172293. doi:10.1371/journal.pone0172293

G. Robertson, *et al*., "The Biogeochemistry of Bioenergy Landscapes: Carbon, Nitrogen, and Water Considerations," *Ecological Applications 21* (2011): 1,055-1,067

A. Russell, *et al*., "Impact of Nitrogen Fertilizer and Cropping System on Carbon Sequestration in Midwestern Mollisols," *Soil Science Society of America Journal 69* (2005): 413-422

S. Verma, *et al*., "Annual Carbon Dioxide Exchange in Irrigated and Rainfed Maize-Based Agroecosystems," *Agricultural and Forest Meteorology 131* (2005): 77-96

G. Varvel, "Rotation and Nitrogen Fertilization Effects on Changes in Soil Carbon and Nitrogen," *Agronomy Journal 86* (1994): 319-325

G. Varvel, "Soil Organic Carbon Changes in Diversified Rotations of the Western Corn Belt," *Soil Science Society of America Journal 70* (2006): 426-433

G. Varvel and W. Wilhelm, "Soil Carbon Levels in Irrigated Western Corn Belt Rotations," *Agronomy Journal 100* (2008): 1,180-1,184

G. Varvel and W. Wilhelm, "Long-term Soil Organic Carbon as Affected by Tillage and Cropping Systems," *Soil Science Society of America Journal 74* (2010): 915-921

D. Walters, *et al*., "Closing the Corn Yield Gap: Management Practices that Improve Soil Quality and Net Productivity but Reduce Global Warming Potential," *2007 Indiana CCA Conference Proceedings, Indianapolis, December 2007*

T. West and W. Post, "Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation: a Global Data Analysis," *Soil Science Society of America Journal 66* (2002): 1,930-1,946

S. Zuber, *et al*., "Crop Rotation and Tillage Effects on Soil Physical and Chemical Properties in Illinois," *Agronomy Journal 107* (2015): 971-978

Database references for practices for which only preliminary results are available

Constructed wetlands–CH_4

M. Abdalla, *et al*., "Emissions of Methane from Northern Peatlands: A Review of Management Impacts and Implications for Future Management Options," *Ecology and Evolution 6* (2016): 7,080-7,102

A. Altor and W. Mitsch, "Methane Flux from Created Riparian Marshes: Relationship to Intermittent Versus Continuous Inundation and Emergent Macrophytes," *Ecological Engineering 28* (2006): 224-234

A. Altor and W. Mitsch, "Methane and Carbon Dioxide Dynamics in Wetland Mesocosms: Effects of Hydrology and Soils," *Ecological Applications 18* (2008): 1,307-1,320

F. Anderson, *et al*., "Variation of Energy and Carbon Fluxes from a Restored Temperate Freshwater Wetland and Implications for Carbon Market Verification Protocols," *Journal of Geophysical Research-Biosciences 121* (2016): 777-795

J. de Klein and A. Werf, "Balancing Carbon Sequestration and GHG Emissions in a Constructed Wetland," *Ecological Engineering 66* (2014): 36-42

T. Groh, *et al*., "Nitrogen Removal and Greenhouse Gas Emissions from Constructed Wetlands Receiving Tile Drainage Water," *Journal of Environmental Quality 44* (2015): 1,001-1,010

A. Liikanen, *et al*., "Temporal and Seasonal Changes in Greenhouse Gas Emissions from a Constructed Wetland Purifying Peat Mining Runoff Waters," *Ecological Engineering 26* (2006): 241-251

R. Miller, "Carbon Gas Fluxes in Re-established Wetlands on Organic Soils Differ Relative to Plant Community and Hydrology," *Wetlands 31* (2011): 1,055-1,066

W. Mitsch, *et al*., "Creating Wetlands: Primary Succession, Water Quality Changes, and Self Design over 15 years," *BioScience 62* (2012): 237-250

W. Mitsch, *et al*., "Wetlands, Carbon, and Climate Change," *Landscape Ecology 28* (2013): 583-597

T. Morin, *et al*., "Environmental Drivers of Methane Fluxes from an Urban Temperate Wetland Park," *Journal of Geophysical Research-Biosciences 119* (2014): 2,188-2,208

A. Nahlik and W. Mitsch, "Methane Emissions from Created Riverine Wetlands," *Wetlands 30* (2010): 783-793

S. Nag, *et al*., "Emission of Greenhouse Gases and Soil Carbon Sequestration in a Riparian Marsh Wetland in Central Ohio," *Environmental Monitoring and Assessment 189* (2017): 580

C. Sha, *et al*., "Methane Emissions from Freshwater Wetlands," *Ecological Engineering 37* (2011): 16-24

A. Sovik, *et al*., "Emission of the Greenhouse Gases Nitrous Oxide and Methane from Constructed Wetlands in Europe," *Journal of Environmental Quality 35* (2006): 2,360-2,373

J. Stadmark and L. Leonardson, "Emissions of Greenhouse Gases from Ponds Constructed for Nitrogen Removal," *Ecological Engineering 25* (2005): 542-551

K. Stefanik and W. Mitsch, "Metabolism and Methane Flux of Dominant Macrophyte Communities in Created Riverine Wetlands Using Open Water Flow-Through Chambers," *Ecological Engineering 72* (2013): 67-73

G. Thiere, *et al*., "Nitrogen Retention versus Methane Emission: Environmental Benefits and Risks of Large-Scale Wetland Creation," *Ecological Engineering 37* (2011): 6-15

E. Waletzko and W. Mitsch, "Methane Emissions from Wetlands: An *In-situ* Side-by Side Comparison of Two Static Accumulation Chamber Designs," *Ecological Engineering 72* (2014): 95-102

U. Wild, *et al*., "Cultivation of *Typha spp*. In Constructed Wetlands for Peatland Restoration," *Ecological Engineering 17* (2001): 49-54

Constructed wetlands–N_2O

J. de Klein and A. Werf, "Balancing Carbon Sequestration and GHG Emissions in a Constructed Wetland," *Ecological Engineering 66* (2014): 36-42

C. Freeman, *et al*., "Nitrous Oxide Emissions and the Use of Wetlands for Water Quality Amelioration," *Environmental Science and Technology 31* (1997): 2,438-2,440

T. Groh, *et al*., "Nitrogen Removal and Greenhouse Gas Emissions from Constructed Wetlands Receiving Tile Drainage Water," *Journal of Environmental Quality 44* (2015): 1,001-1,010

A. Liikanen, *et al*., "Temporal and Seasonal Changes in Greenhouse Gas Emissions from a Constructed Wetland Purifying Peat Mining Runoff Waters," *Ecological Engineering 26* (2006): 241-251

S. Nag, *et al*., "Emission of Greenhouse Gases and Soil Carbon Sequestration in a Riparian Marsh Wetland in Central Ohio," *Environmental Monitoring and Assessment 189* (2017): 580

A. Sovik, *et al*., "Emission of the Greenhouse Gases Nitrous Oxide and Methane from Constructed Wetlands in Europe," *Journal of Environmental Quality 35* (2006): 2,360-2,373

U. Wild, *et al*., "Cultivation of *Typha spp.* In Constructed Wetlands for Peatland Restoration," *Ecological Engineering 17* (2001): 49-54

Constructed wetlands–SOC/CO_2

C. Ahn and S. Jones, "Assessing Organic Matter and Organic Carbon Contents in Soils of Created Mitigation Wetlands in Virginia," *Environmental Engineering Research 18* (2013): 151-156

F. Anderson, *et al*., "Variation of Energy and Carbon Fluxes from a Restored Temperate Freshwater Wetland and Implications for Carbon Market Verification Protocols," *Journal of Geophysical Research-Biosciences 121* (2016): 777-795

C. Anderson and W. Mitsch, "Sediment, Carbon and Nutrient Accumulation at Two 10-Year Old Created Riverine Marshes," *Wetlands 26* (2006): 779-792

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

D. Campbell, *et al*., "A Comparison of Created and Natural Wetlands in Pennsylvania, USA," *Wetlands Ecology and Management 10* (2002): 41-49

J. de Klein and A. Werf, "Balancing Carbon Sequestration and GHG Emissions in a Constructed Wetland," *Ecological Engineering 66* (2014): 36-42

M. Fennessy, *et al*., "Patterns of Plant Decomposition and Nutrient Cycling in Natural and Created Wetlands," *Wetlands 28* (2008): 300-310

S. Fennessy and C. Craft, "Agricultural Conservation Practices Increase Wetland Ecosystem Services in the Glaciated Interior Plains," *Ecological Applications 21* (2011): S49-S64

B. Budigopuram, *et al*., "Carbon Sequestration in a Surface Flow Constructed Wetland after 12 Years of Swine Wastewater treatment," *Water Science and Technology 73* (2016): 2,501-2,508

K. Hossler and V. Bouchard, "Soil Development and Establishment of Carbon-Based Properties in Created Freshwater Marshes," *Ecological Applications 20* (2010): 539-553

K. Hossler, *et al*., "No-Net Loss Not Met for Nutrient Function in Freshwater Marshes: Recommendations for Wetland Mitigation Policies," *Ecosphere 2* (2011): 1-35

C. Maucieri, *et al*., "Biomass Production and Soil Organic Carbon Accumulation in a Free Water Surface Constructed Wetland Treating Agricultural Wastewater in North Eastern Italy," *Ecological Engineering 70* (2014): 422-428

J. Maynard, *et al*., "Soil Carbon Cycling and Sequestration in a Seasonally Saturated Wetland Receiving Agricultural Runoff," *Biogeosciences 8* (2011): 3,391-3,406

W. Mitsch, *et al*., "Wetlands, Carbon and Climate," *Landscape Ecology 28* (2013): 583-597

T. Moore and W. Hunt, "Ecosystem Service Provision by Stormwater Wetlands and Ponds - A Means for Evaluation?" *Water Research 46* (2012): 6,811-6,823

K. Stefanik and W. Mitsch, "Metabolism and Methane Flux of Dominant Macrophyte Communities in Created Riverine Wetlands Using Open Water Flow-Through Chambers," *Ecological Engineering 72* (2013): 67-73

E. Stumper, *et al*., "Sediment Accretion and Carbon Storage in Constructed Wetlands Receiving Water Treated with Metal-based Coagulants," *Ecological Engineering 111* (2018): 176-185

L. Yu, *et al*. (2017) "A synthesis of Soil Carbon and Nitrogen Recovery after Wetland Restoration and Creation in the United States," *Scientific Reports* 7:7966. doi: 10.1038/s41598-017-08511-y

Restored wetlands–CH_4

J. Anderson, *et al*., "Variation of Energy and Carbon Fluxes from a Restored Temperate Freshwater Wetland and Implications for Carbon Market Verification Protocols," *Journal of Geophysical Research-Biosciences 121* (2016): 777-795

J. Audet, *et al*., "Greenhouse Gas Emissions from a Danish Riparian Wetland Before and After Restoration," *Ecological Engineering 57* (2013): 170-182

D. Baldocchi, *et al*., "Exploring Methane and Carbon Dioxide Exchange from Agricultural and Wetland Use Classes in the Sacramento-San Joaquin Peatland Delta in California," Royal Society Seminar, Chicheley Hall, United Kingdom, December 2013

S. Beetz, *et al*., "Effects of Land Use Intensity on the Full Greenhouse Gas Balance in an Atlantic Peat Bog," *Biogeosciences 10* (2013): 1,067-1,082

C. Beyer and H. Hoper, "Greenhouse Gas Exchange of Rewetted Bog Peat Extractions Sites and a Sphagnum Cultivation Site in Northwest Germany," *Biogeosciences 12* (2015): 2,101-2,017

L. Bortolotti, *et al*., "Net Ecosystem Production and Carbon Greenhouse Gas Fluxes in Three Prairie Wetlands," *Ecosystems 19* (2015): 411-425

E. Bortoluzzi, *et al*., "Carbon Balance of a European Mountain Bog at Contrasting Stages of Regeneration," *New Phytologist 172* (2006): 708-718

S. Chamberlain, *et al*., “Soil Properties and Sediment Accretion Modulate Methane Fluxes from Restored Wetlands,” *Global Change Biology 24* (2018): 4,107-4,121

J. Cleary, *et al*., "Greenhouse Gas Emissions from Canadian Peat Extraction, 1990-2000: A Life-Cycle Analysis," *Ambio 34* (2005): 456-461

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

A. Eagle, *et al*., *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States: A Synthesis of the Literature*, 3rd edition, Nicholas Institute, Duke University, January 2012

J. Fargione, *et al*. (2018) "Natural Climate Solutions for the United States," *Science Advances.4.*eaat1869. DOI: 10.1126/sciadv.aat1869

R. Finocchiaro, *et al*., "Greenhouse Gas Fluxes of Grazed and Hayed Wetland Catchments in the U.S. Prairie Pothole Region," *Ecological Monographs 22* (2014): 305-324

R. Gleason, *et al*., "Greenhouse Gas Flux from Cropland and Restored Wetlands in the Prairie Pothole Region," *Soil Biology and Biochemistry 41* (2009): 2,501-2,507

D. Hendriks, *et al*., "The Full greenhouse Gas Balance of an Abandoned Peat Meadow," *Biogeosciences 4* (2007): 411-424

M. Herbst, *et al*., "Interpreting the Variations in Atmospheric Methane Fluxes Observed Above a Restored Wetland," *Agricultural and Forest Meteorology 151* (2011): 841-853

M. Herbst, *et al*., "Catchment-Wide Atmospheric Greenhouse Gas Exchange as Influenced by Land Use Diversity," *Vadose Zone Journal 10* (2011): 67-77

M. Herbst, *et al*., "Climate and Site Management as Driving Factors for the Atmospheric Greenhouse Gas Exchange of a Restored Wetland," *Biogeosciences 10* (2013): 39-52

Intergovernmental Panel on Climate Change, *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (Switzerland: IPCC, 2014)

J. Jarveoja, *et al*., "Impact of water Table Level on Annual Carbon and Greenhouse Gas Balances of a Restored Peat Extraction Area," *Biogeosciences 13* (2016): 2,637-2,651

H. Juottonen, *et al*., "Methane-Cycling Microbial Communities and Methane Emissions in Natural and Restored Peatlands," *Applied and Environmental Microbiology 78* (2012): 6,386-6,389

T. Kandel, *et al*., "Complete Annual CO_2, CH_4, and N_2O Balance of a Temperate Riparian Wetland 12 years After Rewetting," *Ecological Engineering 127* (2019): 527-535

S. Karki, *et al*., "Carbon Balance of Rewetted and Drained Peat Soils Used for Biomass Production: A Mesocosm Study," *Global Change Biology-Bioenergy 8* (2016): 969-980

S. Knox, *et al*., "Agricultural Peatland Restoration: Effects of Land-Use Change on Greenhouse Gas (CO_2 and CH_4) Fluxes in the Sacramento-San Joaquin Delta," *Global Change Biology 21* (2015): 750-765

C. Lazcano, *et al*., "Short-term Effects of Fen Peatland Restoration through the Moss Lay Transfer Technique on the Soil CO_2 and CH_4 Efflux," *Ecological Engineering 125* (2018): 149-158

S. Lee, *et al*., "Annual greenhouse Gas Budget for a Bog Ecosystem Undergoing Restoration by Rewetting," *Biogeosciences 14* (2017): 2.799-2.814

M. Maljanen, *et al*., "Greenhouse Gas Balances of Managed Peatlands in the Nordic Countries - Present Knowledge and Gaps," *Biogeosciences 7* (2010): 2,711-2,738

M Peacock, *et al*., "The Full Carbon Balance of a Rewetted Cropland Fen and a Conservation-Managed Fen," *Agriculture, Ecosystems and Environment 269* (2019): 1-12

D. Pennock, *et al*., "Landscape Controls on N_2O and CH_4 Emissions from Freshwater Mineral Soil Wetlands of the Canadian Prairie Pothole Region," *Geoderma 155* (2010): 308-319

A. Petrescu, *et al*., "The Uncertain Footprint of Wetlands under Human Pressure," *Proceedings of the National Academy of Sciences 112* (2015): 4,594-4,599

A. Ployda, *et al*., "Greenhouse Gas Emissions from Fen Soils Used for Forage Production in Northern Germany," *Biogeosciences 13* (2016): 5,221-5,244

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

B. Richards and C. Craft, "Greenhouse Gas Fluxes from Restored Agricultural Wetlands and Natural Wetlands, Northwestern Indiana," in J. Vymazal, ed., *The Role of Natural and Constructed Wetlands in Nutrient Cycling and Retention on the Landscape,* (New York*:* Springer, 2005) pp. 17-31

E. Samaritani, *et al*., "Seasonal Net Ecosystem Carbon Exchange of a Regenerating Cut-away Bog: How Long Does it Take to Restore the C-Sequestration Function?" *Restoration Ecology 19* (2011): 440-449

A. Schrier-Uijl, *et al*., "Agricultural Peatlands: Towards a Greenhouse Gas Sink - a Synthesis of a Dutch Landscape Study," *Biogeosciences 11* (2014): 4,559-4,576

M. Strack, *et al*., "Growing Season Carbon Dioxide and Methane Exchange at a Restored Peatland on the Western Boreal Plain," *Ecological Engineering 64* (2014): 231-239

M. Strack and Y. Zuback, "Annual Carbon Balance of a Peatland 10 yr Following Restoration," *Biogeosciences 10* (2013): 2885-2896

B. Tangen, *et al*., "Effects of Land Use on Greenhouse Gas Fluxes and Soil Properties of Wetland Catchments in the Prairie Pothole Region of North America," *Science of the Total Environment 533* (2015): 391-409

E. Tuittila, *et al*., "Methane Dynamics of a Restored Cut-Away Peatland," *Global Change Biology 6* (2000): 569-581

Z. Urbanova, *et al*., "Methane Emissions and Methanogenic Archaea on Pristine, Drained and Restored Mountain Peatlands, Central Europe," *Ecosystems 16* (2013): 664-677

Z. Urbanova, *et al*., "Sensitivity of Carbon Fluxes to Weather Variability on Pristine, Drained and Rewetted Temperate Bogs," *Mires and Peat 11* (2013): 1-14

Venselow-Algan, *et al*., "High methane Emissions Dominated Annual Greenhouse Gas Balances 30 Years after Bog Rewetting," *Biogeosciences 12* (2015): 4,361-4,371

P. Vidon, *et al*., "Hydrobiogeochemical Controls on Riparian Nutrient and Greenhouse Gas Dynamics: 10 Years Post Restoration," *Journal of the American Water Resources Association 50* (2014): 639-651

J. Waddington and S. Day (2007) "Methane Emissions from a Peatland Following Restoration," *Journal of Geophysical Research 112*, G03018, doi:10.1029/2007JG000400

D. Wilson, *et al*., "Rewetting of Cutaway Peatlands: Are We Re-Creating Hot Spots of Methane Emissions?" *Restoration Ecology 17* (2008): 796-806

D. Wilson, *et al*., "Greenhouse Gas Emission Factors Associated with Rewetting of Organic Soils," *Mires and Peat 17* (2016): 1-28

S. Yamulki, *et al*., "Soil CO_2, CH_4 and N_2O Fluxes from an Afforested Lowland Raised Peat Bog in Scotland: Implications for Drainage and Restoration," *Biogosciences 10* (2013): 1,051-1,065

M. Yli-Petays, *et al*., "Carbon Gas Exchange of a Re-Vegetated Cut-Away Peatland Five Decades after Abandonment," *Boreal Environment Research 12* (2007): 177-190

Restored wetlands–N_2O

J. Audet, *et al*., "Greenhouse Gas Emissions from a Danish Riparian Wetland Before and After Restoration," *Ecological Engineering 57* (2013): 170-182

P. Badiou, *et al*., "Greenhouse Gas Emissions and Carbon Sequestration Potential in Restored Wetlands of the Canadian Prairie Pothole Region," *Wetlands Ecology and Management 19* (2011): 237-256

S. Beetz, *et al*., "Effects of Land Use Intensity on the Full Greenhouse Gas Balance in an Atlantic Peat Bog," *Biogeosciences 10* (2013): 1,067-1,082

C. Beyer and H. Hoper, "Greenhouse Gas Exchange of Rewetted Bog Peat Extractions Sites and a Sphagnum Cultivation Site in Northwest Germany," *Biogeosciences 12* (2015): 2,101-2,117

A. Eagle, *et al*., *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States: A Synthesis of the Literature*, 3rd edition, Nicholas Institute, Duke University, January 2012

R. Gleason, *et al*., "Greenhouse Gas Flux from Cropland and Restored Wetlands in the Prairie Pothole Region," *Soil Biology and Biochemistry 41* (2009): 2,501-2,507

Intergovernmental Panel on Climate Change, *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (Switzerland: IPCC, 2014)

J. Jarveoja, *et al*., "Impact of water Table Level on Annual Carbon and Greenhouse Gas Balances of a Restored Peat Extraction Area," *Biogeosciences 13* (2016): 2,637-2,651

T. Kandel, *et al*., "Complete Annual CO_2, CH_4, and N_2O Balance of a Temperate Riparian Wetland 12 years After Rewetting," *Ecological Engineering 127* (2019): 527-535

L. Kluber, *et al*., "Multistate Assessment of Wetland Restoration on CO_2 and N_2O Emissions and Soil Bacterial Communities," *Applied Soil Ecology 76* (2014): 87-94

M. Maljanen, *et al*., "Greenhouse Gas Balances of Managed Peatlands in the Nordic Countries - Present Knowledge and Gaps," *Biogeosciences 7* (2010): 2,711-2,738

D. Pennock, *et al*., "Landscape Controls on N_2O and CH_4 Emissions from Freshwater Mineral Soil Wetlands of the Canadian Prairie Pothole Region," *Geoderma 155* (2010): 308-319

A. Ployda, *et al*., "Greenhouse Gas Emissions from Fen Soils Used for Forage Production in Northern Germany," *Biogeosciences 13* (2016): 5,221-5,244

B. Richards and C. Craft, "Greenhouse Gas Fluxes from Restored Agricultural Wetlands and Natural Wetlands, Northwestern Indiana," in J. Vymazal, ed., *The Role of Natural and Constructed Wetlands in Nutrient Cycling and Retention on the Landscape* (New York: Springer, 2005), pp. 17-31

P. Smith, *et al*., "Greenhouse Gas Mitigation in Agriculture," *Philosophical Transactions of the Royal Society B 363* (2008): 789-813

B. Tangen, *et al*., "Effects of Land Use on Greenhouse Gas Fluxes and Soil Properties of Wetland Catchments in the Prairie Pothole Region of North America," *Science of the Total Environment 533* (2015): 391-409

Z. Urbanova, *et al*., "Sensitivity of Carbon Fluxes to Weather Variability on Pristine, Drained and Rewetted Temperate Bogs," *Mires and Peat 11* (2013): 1-14

Venselow-Algan, *et al*., "High methane Emissions Dominated Annual Greenhouse Gas Balances 30 Years after Bog Rewetting," *Biogeosciences 12* (2015): 4,361-4,371

P. Vidon, *et al*., "Hydrobiogeochemical Controls on Riparian Nutrient and Greenhouse Gas Dynamics: 10 Years Post Restoration," *Journal of the American Water Resources Association 50* (2014): 639-651

D. Wilson, *et al*., "Rewetting of Cutaway Peatlands: Are We Re-Creating Hot Spots of Methane Emissions?" *Restoration Ecology 17* (2008): 796-806

D. Wilson, *et al*., "Greenhouse Gas Emission Factors Associated with Rewetting of Organic Soils," *Mires and Peat 17* (2016): 1-28

S. Yamulki, *et al*., "Soil CO_2, CH_4 and N_2O Fluxes from an Afforested Lowland Raised Peat Bog in Scotland: Implications for Drainage and Restoration," *Biogeosciences 10* (2013): 1051-1065

Restored wetlands–SOC/CO_2

J. Anderson, *et al*., *The Potential for Terrestrial Carbon Sequestration in Minnesota: A Report to the Department of Natural Resources from the Minnesota Terrestrial Carbon Sequestration Initiative*, University of Minnesota, February 2008

J. Anderson, *et al*., "Variation of Energy and Carbon Fluxes from a Restored Temperate Freshwater Wetland and Implications for Carbon Market Verification Protocols," *Journal of Geophysical Research-Biosciences 121* (2016): 777-795

J. Audet, *et al*., "Greenhouse Gas Emissions from a Danish Riparian Wetland Before and After Restoration," *Ecological Engineering 57* (2013): 170-182

P. Badiou, *et al*., "Greenhouse Gas Emissions and Carbon Sequestration Potential in Restored Wetlands of the Canadian Prairie Pothole Region," *Wetlands Ecology and Management 19* (2011): 237-256

D. Baldocchi, *et al*., "Exploring Methane and Carbon Dioxide Exchange from Agricultural and Wetland Use Classes in the Sacramento-San Joaquin Peatland Delta in California," Royal Society Seminar, Chicheley Hall, United Kingdom, December 2013

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

S. Beetz, *et al*., "Effects of Land Use Intensity on the Full Greenhouse Gas Balance in an Atlantic Peat Bog," *Biogeosciences 10* (2013): 1067-1082

N. Bessasie and M. Buckley, "Carbon Sequestration Potential at Central Wisconsin Wetland Reserve Program Sites," *Soil Science Society of America Journal 76* (2012): 1,904-1,910

C. Beyer and H. Hoper, "Greenhouse Gas Exchange of Rewetted Bog Peat Extractions Sites and a Sphagnum Cultivation Site in Northwest Germany," *Biogeosciences 12* (2015): 2,101-2,017

L. Bortolotti, *et al*., "Net Ecosystem Production and Carbon Greenhouse Gas Fluxes in Three Prairie Wetlands," *Ecosystems 19* (2015): 411-425

E. Bortoluuzi, *et al*., "Carbon Balance of a European Mountain Bog at Contrasting Stages of Regeneration," *New Phytologist 172* (2006): 708-718

J. Cleary, *et al*., "Greenhouse Gas Emissions from Canadian Peat Extraction, 1990-2000: A Life-Cycle Analysis," *Ambio 34* (2005): 456-461

A. Eagle, *et al*., *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States: A Synthesis of the Literature*, 3rd edition, Nicholas Institute, Duke University, January 2012

N. Euliss, *et al*., "North American Prairie Wetlands are Important Nonforested Land-based Carbon Storage Sites," *Science of the Total Environment 361* (2006): 179-188

J. Fargione, *et al*. (2018) "Natural Climate Solutions for the United States," *Science Advances.4.*eaat1869. DOI: 10.1126/sciadv.aat1869

S. Fennessy and C. Craft, "Agricultural Conservation Practices Increase Wetland Ecosystem Services in the Glaciated Interior Plains," *Ecological Applications 21* (2011): S49-S64

C. Fissore, *et al*. "Limited Potential for Terrestrial Carbon Sequestration to Offset Fossil-Fuel Emissions in the Upper Midwestern USA," *Frontiers in Ecology and the Environment 8* (2010): 409-413

R. Gleason, *et al*., *Potential of Restored Prairie Wetlands in the Glaciated North American Prairie to Sequester Atmospheric Carbon*, Publication no. 8-2005, USGS North Prairie Wildlife Center, 2005

R. Gleason, *et al*., "Greenhouse Gas Flux from Cropland and Restored Wetlands in the Prairie Pothole Region," *Soil Biology and Biochemistry 41* (2009): 2,501-2,507

R. Gleason, *et al*., *Ecosystem Services Derived from Wetland Conservation Practices in the United States Prairie Pothole Region with an Emphasis on the US Department of Agriculture Conservation Reserve and Wetlands Reserve Programs*, USGS Professional Paper 1745, US Geological Survey, 2008

D. Hendriks, *et al*., "The Full greenhouse Gas Balance of an Abandoned Peat Meadow," *Biogeosciences 4* (2007): 411-424

M. Herbst, *et al*., "Climate and Site Management as Driving Factors for the Atmospheric Greenhouse Gas Exchange of a Restored Wetland," *Biogeosciences 10* (2013): 39-52

M. Herbst, *et al*., "Catchment-Wide Atmospheric Greenhouse Gas Exchange as Influenced by Land Use Diversity," *Vadose Zone Journal 10* (2011): 67-77

M. Herbst, *et al*., "Interpreting the Variations in Atmospheric Methane Fluxes Observed Above a Restored Wetland," *Agricultural and Forest Meteorology 151* (2011): 841-853

ICF International, *Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States*, report prepared for USDA, Climate Change Program Office, February 2013

Intergovernmental Panel on Climate Change, *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (Switzerland: IPCC, 2014)

J. Jarveoja, *et al*., "Impact of Water Table Level on Annual Carbon and Greenhouse Gas Balances of a Restored Peat Extraction Area," *Biogeosciences 13* (2016): 2,637-2,651

R. Jensen, *et al*., "Direct and Indirect Controls of the Interannual Variability in Atmospheric CO_2 Exchange of Three Contrasting Ecosystems in Denmark," *Agricultural and Forest Meteorology 233* (2017): 12-31

X. Jin, *et al*., "Dynamic of Organic Matter in Heavy Fraction after Abandonment of Cultivated Wetlands," *Biology and Fertility of Soils 44* (2008): 997-1,001

T. Kandel, *et al*., "Complete Annual CO_2, CH_4, and N_2O Balance of a Temperate Riparian Wetland 12 years After Rewetting," *Ecological Engineering 127* (2019): 527-535

S. Karki, *et al*., "Carbon Balance of Rewetted and Drained Peat Soils Used for Biomass Production: A Mesocosm Study," *Global Change Biology-Bioenergy 8* (2016): 969-980

S. Knox, *et al*., "Agricultural Peatland Restoration: Effects of Land-Use Change on Greenhouse Gas (CO_2 and CH_4) Fluxes in the Sacramento-San Joaquin Delta," *Global Change Biology 21* (2015): 750-765

V. Komulainen, *et al*., "Restoration of Drained Peatlands in Southern Finland: Initial Effects on Vegetation Change and CO_2 Balance," *Journal of Applied Ecology 36* (1999): 634-648

R. Lal, *et al*., *The Potential of US Cropland to Sequester Carbon and Mitigate the Greenhouse Effect* (Ann Arbor: Ann Arbor Press, 1998)

R. Lal, *et al*., "Achieving Soil Carbon Sequestration in the United States: A challenge to the Policymakers," *Soil Science 168* (2003): 827-845

C. Lazcano, *et al*., "Short-term Effects of Fen Peatland Restoration through the Moss Lay Transfer Technique on the Soil CO_2 and CH_4 Efflux," *Ecological Engineering 125* (2018): 149-158

S. Lee, *et al*., "Annual Greenhouse Gas Budget for a Bog Ecosystem Undergoing Restoration by Rewetting," *Biogeosciences 14* (2017): 2,799-2,814

M. Maljanen, *et al*., "Greenhouse Gas Balances of Managed Peatlands in the Nordic Countries - Present Knowledge and Gaps," *Biogeosciences 7* (2010): 2,711-2,738

J. Marton, *et al*., "USDA Conservation Practices Increase Carbon Storage and Water Quality Improvement Functions: An Example from Ohio," *Restoration Ecology 22* (2014): 117-124

J. Marton, *et al*., "Functional Differences between Natural and Restored Wetlands in the Glaciated Interior Plains," *Journal of Environmental Quality 43* (2013): 409-417

C. Meyer, *et al*., "Ecosystem Recovery across a Chronosequence of Restored Wetlands in the Platte River Valley," *Ecosystems 11* (2008): 193-208

D. Moreno-Mateos, *et al*. (2012) "Structural and Functional Loss in Restored Wetland Ecosystems," *Plos Biology 10* (1):e1001247.doi:10.1371/journalplos.1001247

M Peacock, *et al*., "The Full Carbon Balance of a Rewetted Cropland Fen and a Conservation-Managed Fen," *Agriculture, Ecosystems and Environment 269* (2019): 1-12

A. Petrescu, *et al*., "The Uncertain Footprint of Wetlands under Human Pressure," *Proceedings of the National Academy of Sciences 112* (2015): 4,594-4,599

R. Petrone, *et al*., "Ecosystem-scale Flux of CO_2 from a Restored Vacuum Harvested Peatland," *Wetlands Ecology and Management 11* (2003): 419-432

A. Ployda, *et al*., "Greenhouse Gas Emissions from Fen Soils Used for Forage Production in Northern Germany," *Biogeosciences 13* (2016): 5,221-5,244

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

E. Samaritani, *et al*., "Seasonal Net Ecosystem Carbon Exchange of a Regenerating Cut-away Bog: How Long Does it Take to Restore the C-Sequestration Function?" *Restoration Ecology 19* (2011): 440-449

A. Schrier-Uijl, *et al*., "Agricultural peatlands: Towards a Greenhouse Gas Sink - A synthesis of a Dutch Landscape Study," *Biogeosciences 11* (2014): 4,559-4,576

A. Sharifi, *et al*., "Carbon Dynamics and Export from Flooded Wetlands: A Modeling Approach," *Ecological Modelling 263* (2013): 196-210

M. Strack and Y. Zuback, "Annual Carbon Balance of a Peatland 10 Years Following Restoration," *Biogeosciences 10* (2013): 2,885-2,896

M. Strack, *et al*., "Growing Season Carbon Dioxide and Methane Exchange at a Restored Peatland on the Western Boreal Plain," *Ecological Engineering 64* (2014): 231-239

E. Tuittila, *et al*., "Restored Cut-Away Peatland as a Sink for Atmospheric CO_2," *Oecologia 120* (1999): 563-574

Z. Urbanova, *et al*., "Sensitivity of Carbon Fluxes to Weather Variability on Pristine, Drained and Rewetted Temperate Bogs," *Mires and Peat 11* (2013): 1-14

M. Vanselow-Algan, *et al*., "High Methane Emissions Dominated Annual Greenhouse Gas Balances 30 Years after Bog Rewetting," *Biogeosciences 12* (2015): 4,361-4,371

J. Waddington and J. Price, "Effect of Peatland Drainage, Harvesting, and Restoration on Atmospheric Water and Carbon Exchange," *Physical Geography 21* (2000): 433-451

J. Waddington, *et al*. (2010) "Towards Restoring the Net Carbon Sink Function of Degraded Peatlands: Short-term Response in CO_2 Exchange to Ecosystem Restoration," *Journal of Geophysical Research* 115, G01008, doi:10.1029/2009JG001090

D. Wilson, *et al*., "Greenhouse Gas Emission Factors Associated with Rewetting of Organic Soils," *Mires and Peat 17* (2016): 1-27

M. Yli-Petays, *et al*., "Carbon Gas Exchange of a Re-Vegetated Cut-Away Peatland Five Decades after Abandonment," *Boreal Environmental Research 12* (2007): 177-190

L. Yu, *et al*. (2017) "A Synthesis of Soil Carbon and Nitrogen Recovery after Wetland Restoration and Creation in the United States," *Scientific Reports* 7:7966. doi: 10.1038/s41598-017-08511-y

Controlled release fertilizer–N_2O

D. Abalos, *et al*., "Improving Fertilizer Management in the US and Canada for N_2O Mitigation: Understanding Potential Positive and Negative Side-Effects," *Agriculture, Ecosystems and Environment 221* (2016): 214-221

H. Akiyama, *et al*., "Effect of Dicyandiamide and Polymer Coated Urea Applications on N_2O, NO and CH_4 Fluxes from Andosol and Fluvisol Fields," *Soil Science and Plant Nutrition 61* (2015): 541-551

H. Akiyama, *et al*., "Evaluation of Effectiveness of Enhanced-Efficiency Fertilizers as Mitigation Options for N_2O and NO Emissions from Agricultural Soils: A Meta-analysis," *Global Change Biology 16* (2010): 1,837-1,846

H. Asgedom, *et al*., "Nitrous Oxide Emissions from a Clay Soil Receiving Granular Urea Formulations and Dairy Manure," *Agronomy Journal 106* (2014): 732-744

B. Ball, *et al*., "Mitigation of Greenhouse Gas Emissions from Soil under Silage Production by Use of Organic Manures or Slow Release Fertilizer," *Soil Use and Management 20* (2004): 287-295

L. Bastos, *N Fertilizer Source and Placement Impacts Nitrous Oxide Losses, Grain Yield and N Use Efficiency in No-Till Corn*, MS Thesis, Kansas State, 2015

R. Braun, *et al*., "Nitrous Oxide Emissions and Carbon Sequestration in Turfgrass: Effects of Irrigation and Nitrogen Fertilization," *Turfgrass Research, K-State Research Notes*, July 2016

D. Burton, *et al*., "Influence of Fertilizer Nitrogen Source and Management Practice on N_2O Emissions from Two Black Chernozemic Soils," *Canadian Journal Soil Science 88* (2008): 219-227

W. Cheng, *et al*., "N_2O and NO Emissions from a Field of Chinese Cabbage as Influenced by Land Application of Urea or Controlled Release Urea Fertilizers," *Nutrient Cycling in Agroecosystems 63* (2002): 231-238

C. Decock, "Mitigating Nitrous Oxide Emissions from Corn Cropping Systems in the Midwestern US: Potential and Data Gaps," *Environmental Science and Technology 48* (2014): 4,247-4,256

C. Dell, *et al*., "Nitrous Oxide Emissions with Enhanced Efficiency Nitrogen Fertilizers in a Rainfed System," *Agronomy Journal 106* (2014): 723-731

K. Dobbie and K. Smith, "Impact of Different Forms of N Fertilizer on N_2O Emissions from Intensive Grassland," *Nutrient Cycling in Agroecosystems 67* (2003): 37-46

C. Drury, *et al*., "Nitrogen Source, Application Time, and Tillage Effects on Soil Nitrous Oxide Emissions and Corn Grain Yields," *Soil Science Society of America Journal 76* (2012): 1,268-1,279

A. Eagle, *et al*., "Fertilizer Management and Environmental Factors Drive N_2O and NO_3 Losses in Corn: A Meta-Analysis," *Soil Science Society of America Journal 81* (2016): 1,191-1,202

N. Farahbakhshazad, *et al*., "Modeling Biogeochemical Impacts of Alternative Management Practices for a Row-Crop Field in Iowa," *Agriculture, Ecosystems and Environment 123* (2008): 30-48

J. Feng, *et al*., "Integrated Assessment of the Impact of Enhanced-Efficiency Nitrogen Fertilizer on N_2O Emission and Crop Yield," *Agriculture, Ecosystems and Environment 231* (2016): 218-228

F. Fernandez, *et al*., "Nitrous Oxide Emissions from Anhydrous Ammonia, Urea, and Polymer-Coated Urea in Illinois Cornfields," *Journal of Environmental Quality 44* (2015): 415-422

X. Gao, *et al*., "Enhanced Efficiency Urea Sources and Placement Effects on Nitrous Oxide Emissions," *Agronomy Journal 107* (2015): 1-12

W. Gao and X. Bian (2017) "Evaluation of the Agronomic Impacts on Yield-Scaled N_2O Emissions from Wheat and Maize Fields in China," *Sustainability* 9(7) 1201, doi: 10.3990/su9071201

A. Halvorson, *et al*., "Nitrogen Source Effects on Nitrous Oxide Emissions from Irrigated Strip-till Corn," *Journal of Environmental Quality 40* (2011): 1,775-1,786

A. Halvorson, *et al*., "Nitrogen Source Effects on Nitrous Oxide Emissions from Irrigated No-Till Corn," *Journal of Environmental Quality 39* (2010): 1,554-1,562

A. Halvorson and S. Del Grosso, "Nitrogen Source and Placement Effects on Soil Nitrous Oxide Emissions from No-Till Corn," *Journal of Environmental Quality 41* (2012): 1,349-1,359

A. Halvorson and S. Del Grosso, "Nitrogen Placement and Source Effects on Nitrous Oxide Emissions and Yields of Irrigated Corn," *Journal of Environmental Quality 42* (2013): 312-322

Z. Han, *et al*., "N_2O Emissions from Grain Cropping Systems: A Meta-Analysis of the Impacts of Fertilizer-based and Ecologically-based Nutrient Management Strategies," *Nutrient Cycling in Agroecosystems 107* (2017): 335-355

B. Hopkins, "Polymer Coated urea: Mitigating Nitrogen Loss to the Environment," in *Proceedings, International Nitrogen Initiative Conference: Solutions to Improve Nitrogen Use Efficiency Fertilizer Control*, *Melbourne, Australia, December 2016*

X. Hu, *et al*., "Greenhouse Gas Emissions from a Wheat-Maize Double Cropping System with Different Nitrogen Fertilization Regimes," *Environmental Pollution 176* (2013): 198-207

D. Hunt, *et al*., "Effect of Polymer-Coated Urea on Nitrous Oxide Emission in Zero-till and Conventionally Tilled Silage Corn," *Canadian Journal Soil Science 96* (2016): 12-22

C. Hyatt, *et al*., "Polymer-Coated Urea Maintains Potato Yields and Reduces Nitrous Oxide Emissions in a Minnesota Loamy Sand," *Soil Science Society of America Journal 74* (2010): 419-428

J. Jiang, *et al*., "Nitrous Oxide Emissions from Chinese Cropland Fertilized With a Range of Slow-Release Nitrogen Compounds," *Agriculture, Ecosystems and Environment 135* (2010): 216-225

O. Jumadi, *et al*., "Influences of Chemical Fertilizers and a Nitrification Inhibitor on Greenhouse Gas Fluxes in a Corn (*Zea mays L*.) Field in Indonesia," *Microbes and Environment 23* (2008): 29-34

J. LeMonte, *et al*. (2016) "Polymer Coated Urea in Turfgrass Maintains Vigor and Mitigates Nitrogen's Environmental Impacts," *PLoS ONE* 11(1): e0146761. doi:10.1371/journal.pone.0146761

C. Li, *et al*., "Nitrous Oxide Emissions in Response to ESN and Urea, Herbicide Management and Canola Cultivar in a No-Till Cropping System," *Soil and Tillage Research 118* (2012): 87-106

N. Li, et al., "N_2O Emissions and Yield in Maize Field Fertilized with Polymer-Coated Urea under Subsoiling or Rotary Tillage," *Nutrient Cycling in Agroecosystems 102* (2015): 397-410

S. Liu, *et al*., "Ammonia and Greenhouse Gas Emissions from a Subtropical Wheat Field under Different Nitrogen Fertilization Strategies," *Journal of Environmental Science 57* (2017): 196-210

B. Maharjan and R. Venterea, "Nitrate Intensity Explains N Management Effects on N_2O Emissions in Maize," *Soil Biology and Biochemistry 66* (2013): 229-238

B. Maharjan, *et al*., "Fertilizer and Irrigation Management Effects on Nitrous Oxide Emissions and Nitrate Leaching," *Agronomy Journal 106* (2014): 703-714

D. Majumdar, *et al*., "Nitrous Oxide Emission from a Sandy Loam Inceptisol under Irrigated Wheat in India as Influenced by Different Nitrification Inhibitors," *Agriculture, Ecosystems and Environment 91* (2002): 283-293

G. Malla, *et al*., "Mitigating Nitrous Oxide and Methane Emissions from Soil in Rice-Wheat System of the Indo-Gangetic Plain with Nitrification and Urease Inhibitors," *Chemosphere 58* (2005): 141-147

M. McLeod, *et al*., "Developing Greenhouse Gas Marginal Abatement Cost Curves for Agricultural Emissions from Crops and Soils in the UK," *Agricultural Systems 103* (2010): 198-209

A. Mosier, *et al*., "Mitigating Net Global Warming Potential (CO_2, CH_4 and N_2O) in Upland Crop Production," in *Proc. Third International Methane and Nitrous Oxide Mitigation Conference, Beijing, November 17-21, 2003*

P. Nash, *et al*., "Nitrous Oxide Emissions from Claypan Soils Due to Nitrogen Fertilizer Source and Tillage/Fertilizer Placement Practices," *Soil Science Society of America Journal 76* (2012): 983-993

P. Nash, *et al*., "Ammonia and Nitrous Oxide Loss with Subsurface Drainage and Polymer-Coated Urea Fertilizer in a Poorly Drained Soil," *Journal of Soil and Water Conservation 70* (2015): 267-275

T. Parkin and J. Hatfield "Enhanced Efficiency Fertilizers Effects on Nitrous Oxide Emissions in Iowa," *Agronomy Journal 105* (2013): 1-9

I. Shcherbak, *et al*., "Global Meta-Analysis of the Nonlinear Response of Soil Nitrous Oxide (N_2O) Emissions to Fertilizer Nitrogen," *Proceedings of the National Academy of Sciences 111* (2014): 9,199-9,204

A. Shakoor, *et al*. (2018) "Effects of Fertilizer Application Schemes and Soil Environmental Factors on Nitrous Oxide Emission Fluxes in a Rice-Wheat Cropping System, East China," PLoS ONE 13(8): e0202016. https://doi.org/10.1371/journal.pone.0202016

K. Sistani, *et al*.. "Emissions of Nitrous Oxide, Methane and Carbon Dioxide from Different Fertilizers," *Journal of Environmental Quality 40* (2011): 1,797-1,800

J. Soares, *et al*., "Enhanced Efficiency Fertilizers in Nitrous Oxide Emissions from Urea Applied to Sugar Cane," *Journal of Environmental Quality 44* (2015): 423-430

Y. Soon, *et al*., "Effect of Polymer-Coated Urea and Tillage on the Dynamics of Available N and Nitrous Oxide Emission from Gray Luvisols," *Nutrient Cycling in Agroecosystems 90* (2011): 267-279

Z. Tian, *et al*., "Application Effects of Coated Urea and Urease and Nitrification Inhibitors on Ammonia and Greenhouse Gas Emissions from a Subtropical Cotton Field of the Mississippi Delta Region," *Science of the Total Environment 533* (2010): 329-338

R. Venterea, *et al*., "Fertilizer Source and Tillage Effects on Yield-Scaled Nitrous Oxide Emissions in a Corn Cropping System," *Journal of Environmental Quality 40* (2011): 1,521-1,531

D. Watts, *et al*., "Impacts of Enhanced Efficiency Nitrogen Fertilizers on Greenhouse Gas Emissions in a Coastal Plain Soil under Cotton," *Journal of Environmental Quality 44* (2015): 1,699-1,710

B. Zebarth, *et al*., "Controlled Release Fertilizer Product Effects on Potato Crop Response and Nitrous Oxide Emissions under Rain-Fed Production on a Medium-Textured Soil," *Canadian Journal Soil Science 92* (2012): 759-769

Controlled release fertilizer–CH_4

H. Akiyama, *et al*., "Effect of dicyandiamide and Polymer Coated Urea Applications on N_2O, NO and CH_4 Fluxes from Andosol and Fluvisol Fields," *Soil Science and Plant Nutrition 61* (2015): 541-551

X. Hu, *et al*., "Greenhouse Gas Emissions from a Wheat-Maize Double Cropping System with Different Nitrogen Fertilization Regimes," *Environmental Pollution 176* (2013): 198-207

O. Jumadi, *et al*., "Influences of Chemical Fertilizers and a Nitrification Inhibitor on Greenhouse Gas Fluxes in a Corn (*Zea mays L*.) Field in Indonesia," *Microbes and Environment 23* (2008): 29-34

S. Liu, *et al*., "Ammonia and Greenhouse Gas Emissions from a Subtropical Wheat Field under Different Nitrogen Fertilization Strategies," *Journal of Environmental Science 57* (2017): 196-210

K. Sistani, *et al*., "Emissions of Nitrous Oxide, Methane and Carbon Dioxide from Different Fertilizers," *Journal of Environmental Quality 40* (2011): 1,797-1,800

Z. Tian, *et al*., "Application Effects of Coated Urea and Urease and Nitrification Inhibitors on Ammonia and Greenhouse Gas Emissions from a Subtropical Cotton Field of the Mississippi Delta Region," *Science of the Total Environment 533* (2010): 329-338

D. Watts, *et al*., "Impacts of Enhanced Efficiency Nitrogen Fertilizers on Greenhouse Gas Emissions in a Coastal Plain Soil under Cotton," *Journal of Environmental Quality 44* (2015): 1,699-1,710

Nitrification and urease inhibitors–N_2O

D. Abalos, *et al*., "Effectiveness of Urease Inhibition on the Abatement of Ammonia, Nitrous Oxide and Nitric Oxide Emissions in a Non-Irrigated Mediterranean Barley Field," *Chemosphere 89* (2012): 310-318

D. Abalos, *et al*., "Scenario Analysis of Fertilizer Management Practices for N_2O Mitigation from Corn Systems in Canada," *Science of the Total Environment 573* (2016): 356-365

D. Abalos, *et al*., "Improving Fertilizer Management in the US and Canada for N_2O Mitigation: Understanding Potential Positive and Negative Side-Effects," *Agriculture, Ecosystems and Environment 221* (2016): 214-221

C. Aita, *et al*., "Reducing Nitrous Oxide Emissions from a Maize-Wheat Sequence by Decreasing Soil Nitrate Concentration: Effects of Split Application of Pig Slurry and Dicyandiamide," *European Journal of Soil Science 66* (2015): 359-368

H. Akiyama, *et al*., "Evaluation of Effectiveness of Enhanced-Efficiency Fertilizers as Mitigation Options for N_2O and NO Emissions from Agricultural Soils: A Meta-analysis," *Global Change Biology 16* (2010): 1,837-1,846

H. Akiyama, *et al*. "Effect of Dicyandiamide and Polymer Coated Urea Applications on N_2O, NO and CH_4 Fluxes from Andosol and Fluvisol fields," *Soil Science and Plant Nutrition 61* (2015): 541-551

F. Albanito, *et al*. (2017) "Direct Nitrous Oxide Emissions from Tropical and Subtropical Agricultural Systems - A Review and Modeling of Emission Factors," *Scientific Reports 7*:44235. doi.10.1038/srep44235

H. Asgedom, *et al*., "Nitrous Oxide Emissions from a Clay Soil Receiving Granular Urea Formulations and Dairy Manure," *Agronomy Journal 106* (2014): 732-744

L. Bastos, *N Fertilizer Source and Placement Impacts Nitrous Oxide Losses, Grain Yield and N Use Efficiency in No Till Corn*, MS Thesis, Kansas State, 2015

M. Bell, *et al*., "Nitrous Oxide Emissions from Fertilized UK Arable Soils: Fluxes, Emission Factors and Mitigation," *Agriculture, Ecosystems and Environment 212* (2015): 134-147

M. Bell., *et al*., "Quantifying N_2O 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

A. Bhatia, *et al*., "Mitigating Nitrous Oxide Emission from Soil under Conventional and No-tillage in Wheat Using Nitrification Inhibitors," *Agriculture, Ecosystems and Environment 136* (2010): 247-253

D. Burton, *et al*., "Influence of Fertilizer Nitrogen Source and Management Practice on N_2O Emissions from Two Black Chernozemic Soils," *Canadian Journal Soil Science 88* (2008): 219-227

J. Burzaco, *et al*., "Nitrous Oxide Emissions in Midwest US Maize Production Vary Widely with Band-Injected Fertilizer Rates, Timing and Nitrapyrin Presence," *Environmental Research Letters 8,* article 035031 (2013)

L. Cardenas, *et al*.,"Effects of the Application of Cattle Urine with and without the Nitrification Inhibitor DCD, and Dung on Greenhouse Gas Emissions from a US Grassland Soil," *Agriculture, Ecosystems and Environment 235* (2016): 229-241

M. Cayuela, *et al*., "Direct Nitrous Oxide Emissions in Mediterranean Climate Cropping Systems: Emission Factors on a Meta-Analysis of Available Measurement Data," *Agriculture, Ecosystems and Environment 238* (2017): 25-35

T. Clough, *et al*., "The Mitigation Potential of Hippuric Acid on N_2O Emissions from Urine Patches: An In Situ Determination of its Effect," *Soil Biology and Biochemistry 41* (2009): 2,222-2,229

C. de Klein, *et al*., "Repeated Annual Use of the Nitrification Inhibitor Dicyandiamide (DCD) Does Not Alter Its Effectiveness in Reducing N_2O Emissions from Cow Urine," *Animal Feed Science and Technology 166/7* (2011): 480-491

C. de Klein, *et al*., "Evaluating the Effects of Dicyandiamide (DCD) on Nitrogen Cycling and Dry Matter Production in a 3-Year Trial on a Dairy Pasture in South Otago, New Zealand," *New Zealand Journal of Agricultural Research 57* (2014): 316-331

C. Decock, "Mitigating Nitrous Oxide Emissions from Corn Cropping Systems in the Midwestern US: Potential and Data Gaps," *Environmental Science and Technology 48* (2014): 4,247-4,256

C. Dell, *et al*., "Nitrous Oxide Emissions with Enhanced Efficiency Nitrogen Fertilizers in a Rainfed System," *Agronomy Journal 106* (2014): 723-731

K. Denef, *et al*., *Greenhouse Gas Emissions from U.S. Agriculture and Forestry: A Review of Emission Sources, Controlling factors, and Mitigation Potential*. Interim Report to USDA under contract #G-23F-8182H, ICF International, 2011

Q. Deng, *et al*. (2015) "Corn Yield and Soil Nitrous Oxide Emissions under Different Fertilizer and Soil Management: a Three-Year Field Experiment in Middle Tennessee," *PLoS One 10*(4): e0125406. Doi:10.1371/journal.pone.0125406

Q. Deng, *et al*., "Assessing the Impacts of Tillage and Fertilization Management on Nitrous Oxide Emissions in a Cornfield Using the DNDC Model," *Journal of Geophysical Research Biogeosciences 121* (2016): 337-349

H. Di and K. Cameron, "The Use of a Nitrification Inhibitor, Dicyandiamide (DCD), to Decrease Nitrate Leaching and Nitrous Oxide Emissions in a Simulated Grazed and Irrigated Grassland," *Soil Use and Management 18* (2002): 395-403

H. Di and K. Cameron, "Mitigation of Nitrous Oxide Emissions in Spray-Irrigated Grazed Grassland by Treating the Soil with Dicyandiamide, a Nitrification Inhibitor," *Soil Use and Management 19* (2003): 284-290

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

H. Di, *et al*., "Comparison of the Effectiveness of a Nitrification Inhibitor Dicyandiamide in Reducing Nitrous Oxide Emission in Four Different Soils under Different Climatic and Management Conditions," *Soil Use and Management 23* (2007): 1-9

W. Ding, *et al*., "Impact of Urease and Nitrification Inhibitors on Nitrous Oxide Emissions from Fluvo-Aquic Soil in the North China Plain," *Biology and Fertility of Soils 47* (2011): 91-99

K. Dobbie and K. Smith, "Impact of Different Forms of N Fertilizer on N_2O Emissions from Intensive Grassland," *Nutrient Cycling in Agroecosystems 67* (2003): 37-46

D. Dong, *et al.*, “Effects of Urease and Nitrification Inhibitors on Nitrous Oxide Emissions and Nitrifying/Denitrifying Microbial Communities in a Rainfed Maize Soil: A 6-Year Observation,” *Soil and Tillage Research 180* (2018): 83-90

C. Drury, *et al*., "Combining Urease and Nitrification Inhibitors with Incorporation Reduced Ammonia and Nitrous Oxide Emissions and Increased Corn Yields," *Journal of Environmental Quality 46* (2017): 939-949

R. Dungan, *et al*., "Greenhouse Gas Emissions from an Irrigated Dairy Forage Rotation as Influenced by Fertilizer and Manure Applications," *Soil Science Society of America Journal 81* (2017): 537-545

A. Eagle, *et al*., *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States: A Synthesis of the Literature*, 3rd edition, Nicholas Institute, Duke University, January 2012

A. Eagle, *et al*., "Fertilizer Management and Environmental Factors Drive N_2O and NO_3 Losses in Corn: A Meta-Analysis," *Soil Science Society of America Journal 81* (2016): 1,191-1,202

N. Farahbakhshazad, *et al.*, "Modeling Biogeochemical Impacts of Alternative Management Practices for a Row-Crop Field in Iowa," *Agriculture, Ecosystems and Environment 123* (2008): 30-48

J. Feng, *et al*., "Integrated Assessment of the Impact of Enhanced-Efficiency Nitrogen Fertilizer on N_2O Emission and Crop Yield," *Agriculture, Ecosystems and Environment 231* (2016): 218-228

X. Gao, *et al*., "Enhanced Efficiency Urea Sources and Placement Effects on Nitrous Oxide Emissions," *Agronomy Journal 107* (2015): 1-12

W. Gao and X. Bian, "Evaluation of the Agronomic Impacts on Yield-Scaled N_2O Emissions from Wheat and Maize Fields in China," *Sustainability 9*, 1201, doi: 10.3990/su9071201 (2017)

C. Gilsanz, *et al*., "Development of Emission Factors and Efficiency of Two Nitrification Inhibitors, DCD and DMPP," *Agriculture, Ecosystems and Environment 216* (2016): 1-8

G. Guardia, *et al*., “Effect of Inhibitors and Fertigation Strategies on GHG Emissions, NO Flux and Yield in Irrigated Maize,” *Field Crop Research 204* (2017): 133-145

A. Halvorson, *et al*., "Nitrogen Source Effects on Nitrous Oxide Emissions from Irrigated No-Till Corn," *Journal of Environmental Quality 39* (2010): 1,554-1,562

A. Halvorson, *et al*. "Nitrogen Source Effects on Nitrous Oxide Emissions from Irrigated Strip-till Corn," *Journal of Environmental Quality 40* (2011): 1,775-1,786

A. Halvorson, *et al*., "Manure and Inorganic Nitrogen Affect Trace Gras Emissions under Semi-Arid Irrigated Corn," *Journal of Environmental Quality 45* (2016): 906-914

A. Halvorson and S. Del Grosso, "Nitrogen Source and Placement Effects on Soil Nitrous Oxide Emissions from No-Till Corn," *Journal of Environmental Quality 41* (2012): 1,349-1,359

A. Halvorson and S. Del Grosso, "Nitrogen Placement and Source Effects on Nitrous Oxide Emissions and Yields of Irrigated Corn," *Journal of Environmental Quality 42* (2013): 312-322

A. Halvorson, *et al*., "Tillage and Inorganic Nitrogen Source Effects on Nitrous Oxide Emissions from Irrigated Cropping Systems," *Soil Science Society of America Journal 74* (2010): 436-445

Z. Han, *et al*., "N_2O Emissions from Grain Cropping Systems: A Meta-analysis of the Impacts of Fertilizer-based and Ecologically-based Nutrient Management Strategies," *Nutrient Cycling in Agroecosystems 107* (2017): 335-355

M. Harty, *et al*., "Reducing Nitrous Oxide Emissions by Changing N Fertilizer Use from Calcium Ammonium Nitrate (CAN) to Urea Based Formulations," *Science of the Total Environment 563/564* (2016): 576-586

X. Hu, *et al*., "Greenhouse Gas Emissions from a Wheat-Maize Double Cropping System with Different Nitrogen Fertilization Regimes," *Environmental Pollution 176* (2013): 198-207

S. Hube, *et al*., "Effect of Nitrification and Urease Inhibitors on Nitrous Oxide and Methane Emissions from an Oat Crop in a Volcanic Soil," *Agriculture, Ecosystems and Environment 238* (2017): 46-54

ICF International, *Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States*, report prepared for the USDA, Climate Change Program Office, February 2013

J. Jiang, *et al*., "Nitrous Oxide Emissions from Chinese Cropland Fertilized With a Range of Slow-Release Nitrogen Compounds," *Agriculture, Ecosystems and Environment 135* (2010): 216-225

O. Jumadi, *et al*., "Influences of Chemical Fertilizers and a Nitrification Inhibitor on Greenhouse Gas Fluxes in a Corn (Zea mays L.) Field in Indonesia," *Microbes and Environment 23* (2008): 29-34

X. Kong, *et al*., "Evaluation of the Nitrification Inhibitor 3,4-Dimethylpyrazole Phosphate (DMPP) for Mitigating Soil N_2O Emissions after Grassland Cultivation," *Agriculture, Ecosystems and Environment 259* (2018): 174-183

S. Lam, *et al*., "Using Nitrification Inhibitors to Mitigate Agricultural N_2O Emissions: A Double-Edged Sword?" *Global Change Biology 23* (2017): 485-489

J. Li, *et al*., "Use of Nitrogen Process Inhibitors for Reducing Gaseous Nitrogen Losses from Land-applied Farm Effluents," *Biology and Fertility of Soils 50* (2014): 133-145

J. Li, *et al*., "Nitrous Oxide Emissions from Dairy Farm Effluent Applied to a New Zealand Pasture Soil," *Soil Use and Management 31* (2015): 279-289

C. Liu, *et al*., "Effects of Nitrification Inhibitors (DCD and DMPP) on Nitrous Oxide Emission, Crop Yields and Nitrogen Uptake in a Wheat-Maize Cropping System," *Biogeosciences 10* (2013): 2,427-2,437

S. Liu, *et al*., "Ammonia and Greenhouse Gas Emissions from a Subtropical Wheat Field under Different Nitrogen Fertilization Strategies," *Journal of Environmental Science 57* (2017): 196-210

J. Luo, *et al*., "Effect of Dicyandiamide (DCD) Delivery Method, Application Rate, and Season on Pasture Urine Patch Nitrous Oxide Emissions," *Biology and Fertility of Soils 51* (2015): 453-464

B. Maharjan and R. Venterea, "Nitrate Intensity Explains N Management Effects on N_2O Emissions in Maize," *Soil Biology and Biochemistry 66* (2013): 229-238

B. Maharjan, *et al.*, "Fertilizer and Irrigation Management Effects on Nitrous Oxide Emissions and Nitrate Leaching," *Agronomy Journal 106* (2014): 703-714

D. Majumdar, *et al*., "Nitrous Oxide Emission from a Sandy Loam Inceptisol under Irrigated Wheat in India as Influenced by Different Nitrification Inhibitors," *Agriculture, Ecosystems and Environment 91* (2002): 283-293

G. Malla, *et al*., "Mitigating Nitrous Oxide and Methane Emissions from Soil in Rice-Wheat System of the Indo-Gangetic Plain with Nitrification and Urease Inhibitors," *Chemosphere 58* (2005): 141-147

M. McLeod, *et al*., "Developing Greenhouse Gas Marginal Abatement Cost Curves for Agricultural Emissions from Crops and Soils in the UK," *Agricultural Systems 103* (2010): 198-209

A. Meijide, *et al*., "Nitrogen Oxide Emissions from an Irrigated Maize Crop Amended with Treated Pig Slurries and Composts in a Mediterranean Climate," *Agriculture, Ecosystems and Environment 121* (2007): 383-394

S. Menendez, *et al*., "Effect of N-(n-butyl) Thiophosphoric Triamide and 3,4-Dimethylpyrazole Phosphate on Gaseous Emissions from Grasslands under Different Soil Water Contents," *Journal of Environmental Quality 38* (2009): 27-35

M. Migliorati, *et al*., "Influence of Different Nitrogen Rates and DMPP Nitrification Inhibitor on Annual N_2O Emissions from a Subtropical Wheat-Maize Cropping System," *Agriculture, Ecosystems and Environment 186* (2014): 33-43

T. Misselbrook, *et al*., "An Assessment of Nitrification Inhibitors to Reduce Nitrous Oxide Emissions from UK Agriculture," *Environmental Research Letters 9* (2014): 1-11

A. Mosier, *et al.*, "Mitigating Net Global Warming Potential (CO_2, CH_4 and N_2O) in Upland Crop Production," in *Proc. Third International Methane and Nitrous Oxide Mitigation Conference, Beijing, November 17-21, 2003*

Y. Niu, *et al*., "Effects of Biochar and Nitrapyrin on Nitrous Oxide and Nitric Oxide Emissions from a Sandy Loam Soil Cropped to Maize," *Biology and Fertility of Soils 54* (2018): 645-658

R. Omonode and T. Vyn, "Nitrification Kinetics and Nitrous Oxide Emissions from Nitrapyrin Coapplied with Urea-Ammonium Nitrate," *Agronomy Journal 105* (2013): 1,475-1,486

T. Parkin and J. Hatfield "Enhanced Efficiency Fertilizers Effects on Nitrous Oxide Emissions in Iowa," *Agronomy Journal 105* (2013): 1-9

T. Parkin, *et al*., "Rye Cover Crop Effects on Direct and Indirect Nitrous Oxide Emissions," *Soil Science Society of America Journal 80* (2016): 1,551-1,559

H. Pfab, *et al*., "Influence of a Nitrification Inhibitor and of Placed N-Fertilization on N_2O Fluxes from a Vegetable Cropped Loamy Soil," *Agriculture, Ecosystems and Environment 150* (2012): 91-101

J. Recio, *et al*., "The Effect of Nitrification Inhibitors on NH_3 and N_2O Emissions in Highly N Fertilized Irrigated Mediterranean Cropping Systems," *Science of the Total Environment 636* (2018): 427-436

D. Riches, *et al*., "Mitigation of Nitrous Oxide Emissions with Nitrification Inhibitors in Temperate Vegetable Cropping in Southern Australia," *Soil Research 54* (2016): 535-543

A. Robinson, *et al*., "The Effect of Soil pH and Dicyandiamide (DCD) on N_2O Emissions and Ammonia Oxidizer Abundance in a Stimulated Grazed Pasture Soil," *Journal of Soil and Sediments 14* (2014): 1,434-1,444

L. Roche, *et al*., "Impact of Fertiliser Nitrogen Formulation and N Stabilisers on Nitrous Oxide Emissions in Spring Barley," *Agriculture, Ecosystems and Environment 233* (2016): 229-237

R. Ruser and R. Schulz, "The Effect of Nitrification Inhibitors on the Nitrous Oxide (N_2O) Release from Agricultural Soils - A Review," *Journal of Plant Nutrition and Soil Science 178* (2015): 171-188

A. Sanz-Cobena, *et al*., "Gaseous Emissions of N_2O, and NO and NO_3^- Leaching from Urea Applied with Urease and Nitrification Inhibitors to a Maize (*Zea mays L.*) Crop," *Agriculture, Ecosystems and Environment 149* (2012): 64-73

A. Sanz-Cobena, *et al*., "Strategies for Greenhouse Gas Emissions Mitigation in Mediterranean Agriculture: A Review," *Agriculture, Ecosystems and Environment 238* (2017): 5-24

C. Scheer, *et al*. (2017) "Nitrification Inhibitors Can Increase Post-harvest Nitrous Oxide Emissions in an Intensive Vegetable Production System," *Scientific Reports 7*:43677. doi:10.1038/srep43677

G. Schwenke, *et al*. (2016) "Greenhouse Gas (N_2O and CH_4) Fluxes Under Nitrogen-Fertilized Dryland Wheat and Barley on Subtropical Vertisols: Risk, Rainfall, and Alternatives," *Soil Research 54*. 10.1071/SR 15338

D. Selbie, *et al*., "The Effect of Urinary Nitrogen Loading Rate and a Nitrification Inhibitor on Nitrous Oxide Emissions from a Temperate Grassland Soil," *The Journal of Agricultural Science 152* (2014): 159-171

A. Shakoor, *et al*. (2018) "Effects of Fertilizer Application Schemes and Soil Environmental Factors on Nitrous Oxide Emission Fluxes in a Rice-Wheat Cropping Systems, East China," *PLoS ONE 13*(8): e0202016. https://doi.org/10.1371/journal.pone.0202016

K. Sistani, *et al*., "Emissions of Nitrous Oxide, Methane and Carbon Dioxide from Different Fertilizers," *Journal of Environmental Quality 40* (2011): 1,797-1,800

L. Smith, *et al*., "Effect of Dicyandiamide Applied in a Granular Form on Nitrous Oxide Emissions from a Grazed Dairy Pasture in Southland, New Zealand," *New Zealand Journal of Agricultural Research 51* (2008): 387-396

K. Smith, *et al*., "The Effect of N Fertilizer Forms on Nitrous Oxide Emissions from UK Arable Land and Grassland," *Nutrient Cycling in Agroecosystems 93* (2012): 127-149

J. Soares, *et al*., "Enhanced Efficiency Fertilizers in Nitrous Oxide Emissions from Urea Applied to Sugar Cane," *Journal of Environmental Quality 44* (2015): 423-430

R. Thapa, *et al*., "Effect of Enhanced Efficiency Fertilizers on Nitrous Oxide Emissions and Crop Yields: A Meta-Analysis," *Soil Science Society of America Journal 80* (2016): 1,121-1,134

Z. Tian, *et al.,* "Application Effects of Coated Urea and Urease and Nitrification Inhibitors on Ammonia and Greenhouse Gas Emissions from a Subtropical Cotton Field of the Mississippi Delta Region," *Science of the Total Environment 533* (2010): 329-338

A. Vallejo, *et al*., "Comparison of N Losses (NO_3^-, N_2O, NO) from Surface Applied, Injected or Amended (DCD) Pig Slurry of an Irrigated Soil in a Mediterranean Climate," *Plant and Soil 272* (2005): 313-325

A. Vallejo, *et al*., "Nitrogen Oxides Emission from Soils Bearing a Potato Crop as Influenced by Fertilization with Treated Pig Slurries and Composts," *Soil Biology and Biochemistry 38* (2006): 2,782-2,793

T. van der Weerden, *et al*., "Nitrous Oxide Emissions from Urea Fertilizer and Effluent with and without Inhibitors Applied to Pasture," *Agriculture, Ecosystems and Environment 219* (2016): 58-70

R. Venterea, *et al.*, "Fertilizer Source and Tillage Effects on Yield-Scaled Nitrous Oxide Emissions in a Corn Cropping System," *Journal of Environmental Quality 40* (2011): 1,521-1,531

B. Vinzent, *et al*., "N_2O Emissions and Nitrogen Dynamics of Winter Rapeseed Fertilized with Different N Forms and a Nitrification Inhibitor," *Agriculture, Ecosystems and Environment 259* (2018): 86-97

D. Watts, *et al*., "Impacts of Enhanced Efficiency Nitrogen Fertilizers on Greenhouse Gas Emissions in a Coastal Plain Soil under Cotton," *Journal of Environmental Quality 44* (2015): 1,699-1,710

Y. Wang, *et al*., "Mitigating Greenhouse Gas and Ammonia Emissions from Swine Manure Management: A Systems Analysis," *Environmental Science and Technology 51* (2017): 4,503-4,511

J. Wolt, "A Meta-Evaluation of Nitrapyrin Agronomic and Environmental Effectiveness with Emphasis on Corn Production in the Midwestern USA," *Nutrient Cycling in Agroecosystems 69* (2004): 23-41

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

Q. Yi, *et al*. (2017) "Effects of Nitrogen Application Rate, Nitrogen Synergist and Biochar on Nitrous Oxide Emissions from Vegetable Field in South China," *PLoS One 12*(4):e0175325. https://doi.org/10.1371/journal.pone0175325

M. Zamam, *et al*., "Reducing NH_3, N_2O and NO_3^- Losses from a Pasture Soils with Urease or Nitrification Inhibitors and Elemental S-Amended Nitrogenous Fertilizers," *Biology and Fertility of Soils 44* (2008): 693-705

M. Zaman, *et al*., "Effect of Urease and Nitrification Inhibitors on N Transformation, Gaseous Emissions of Ammonia and Nitrous Oxide, Pasture Yield and N Uptake in Grazed Pasture System," *Soil Biology and Biochemistry 41* (2009): 1,270-1,280

M. Zaman, *et al*., "The Effect of Urease and Nitrification Inhibitors on Ammonia and Nitrous Oxide Emissions from Simulated Urine Patches in Pastoral Systems: A Two-Year Study," *Science of the Total Environment 465* (2013): 97-106

M. Zaman and J. Blennerhassett, "Effects of the Different Rates Urease and Nitrification Inhibitors on Gaseous Emissions of Ammonia and Nitrous Oxide, Nitrate Leaching and Pasture Production from Urine Patches in an Intensively Grazed Pasture System," *Agriculture, Ecosystems, and Environment 136* (2010): 236-246

M. Zaman and M. Nguyen, "How Application Timings of Urease and Nitrification Inhibitors Affect N Losses from Urine Patches in Pastoral System," *Agriculture, Ecosystems, and Environment 156* (2012): 37-48

Nitrification and urease inhibitors–CH_4

H. Akiyama, *et al*., "Effect of Dicyandiamide and Polymer Coated Urea applications on N_2O, NO and CH_4 Fluxes from Andosol and Fluvisol fields," *Soil Science and Plant Nutrition 61* (2015): 541-551

L. Cardenas, *et al*.,"Effects of the Application of Cattle Urine with and without the Nitrification Inhibitor DCD, and Dung on Greenhouse Gas Emissions from a US Grassland Soil," *Agriculture, Ecosystems and Environment 235* (2016): 229-241

Y. Dai, *et al.,* "Effects of Nitrogen Application Rate and a Nitrification Inhibitor Dicyandiamide on Methanotroph Abundance and Methane Uptake in a Grazed Pasture Soil," *Environmental Science and Pollution Research 20* (2013): 8.680-8.689

R. Dungan, *et al*., "Greenhouse Gas Emissions from an Irrigated Dairy Forage Rotation as Influenced by Fertilizer and Manure Applications," *Soil Science Society of America Journal 81* (2017): 537-545

A. Halvorson, *et al*., "Manure and Inorganic Nitrogen Affect Trace Gas Emissions under Semi-Arid Irrigated Corn," *Journal of Environmental Quality 45* (2016): 906-914

X. Hu, *et al*., "Greenhouse Gas Emissions from a Wheat-Maize Double Cropping System with Different Nitrogen Fertilization Regimes," *Environmental Pollution 176* (2013): 198-207

X. Huerfano, *et al*., "Splitting the Application of 3,4-Dimethylpyrazole Phosphate (DMPP): Influence on Greenhouse Gases Emissions and Wheat Yield and Quality under Humid Mediterranean Conditions," *European Journal of Agronomy 64* (2015): 47-57

O. Jumadi, *et al*., "Influences of Chemical Fertilizers and a Nitrification Inhibitor on Greenhouse Gas Fluxes in a Corn (*Zea mays L*.) Field in Indonesia," *Microbes and Environment 23* (2008): 29-34

S. Liu, *et al*., "Ammonia and Greenhouse Gas Emissions from a Subtropical Wheat Field under Different Nitrogen Fertilization Strategies," *Journal of Environmental Science 57* (2017): 196-210

E. Minet, *et al*., "Amendment of Cattle Slurry with Nitrification Inhibitor Dicyandiamide during Storage: An Effective and Practical N_2O Mitigation Measure for Landspreading," *Agriculture; Ecosystems and Environment 215* (2016): 68-75

K. Sistani, *et al*., "Emissions of Nitrous Oxide, Methane and Carbon Dioxide from Different Fertilizers," *Journal of Environmental Quality 40* (2011): 1,797-1,800

Z. Tian, *et al*., "Application Effects of Coated Urea and Urease and Nitrification Inhibitors on Ammonia and Greenhouse Gas Emissions from a Subtropical Cotton Field of the Mississippi Delta Region," *Science of the Total Environment 533* (2010): 329-338

D. Watts, *et al*., "Impacts of Enhanced Efficiency Nitrogen Fertilizers on Greenhouse Gas Emissions in a Coastal Plain Soil under Cotton," *Journal of Environmental Quality 44* (2015): 1,699-1,710

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–N_2O

D. Abalos, *et al*., "Improving Fertilizer Management in the US and Canada for N_2O Mitigation: Understanding Potential Positive and Negative Side-Effects," *Agriculture, Ecosystems and Environment 221* (2016): 214-221

D. Abalos, *et al*., "Scenario Analysis of Fertilizer Management Practices for N_2O Mitigation from Corn Systems in Canada," *Science of the Total Environment 573* (2016): 356-365

C. Aita, *et al*., "Reducing Nitrous Oxide Emissions from a Maize-Wheat Sequence by Decreasing Soil Nitrate Concentration: Effects of Split Application of Pig Slurry and Dicyandiamide," *European Journal of Soil Science 66* (2015): 359-368

H. Akiyama, *et al*., "Nitrification, Ammonia-Oxidizing Communities and N_2O and CH_4 Fluxes in an Imperfectly Drained Agricultural Field Fertilized with Coated Urea With and Without Dicyandiamide," *Biology and Fertility of Soils 49* (2013): 213-223

D. Allen, *et al*., "Effect of Nitrogen Fertilizer Management and Waterlogging on Nitrous Oxide Emission from Subtropical Sugarcane Soils," *Agriculture, Ecosystems and Environment 136* (2010): 209-217

M. Bell, *et al*., "Nitrous Oxide Emissions from Fertilized UK Arable Soils: Fluxes, Emission Factors and Mitigation," *Agriculture, Ecosystems and Environment 212* (2015): 134-147

M. Bell., *et al*., "Quantifying N_2O 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

R. Bhandral, *et al*., "Emissions of Nitrous Oxide after Application of Dairy Slurry on Bare Soil and Perennial Grass in a Maritime Climate," *Canadian Journal of Soil Science 88* (2008): 517-527

D. Burton, *et al*., "Effect of Split Application of Fertilizer Nitrogen on N_2O Emissions from Potatoes," *Canadian Journal of Soil Science 88* (2008): 229-239

C. Decock, "Mitigating Nitrous Oxide Emissions from Corn Cropping Systems in the Midwestern US: Potential and Data Gaps," *Environmental Science and Technology 48* (2014): 4,247-4,256

Q. Deng, *et al*. (2015) "Corn Yield and Soil Nitrous Oxide Emissions under Different Fertilizer and Soil Management: a Three-Year Field Experiment in Middle Tennessee," *PLoS One 10*(4): e0125406. Doi:10.1371/journal.pone.0125406

Q. Deng, *et al*., "Assessing the Impacts of Tillage and Fertilization Management on Nitrous Oxide Emissions in a Cornfield Using the DNDC Model," *Journal of Geophysical Research Biogeosciences 121* (2016): 337-349

C. Drury, *et al*., "Nitrogen Source, Application Time, and Tillage Effects on Soil Nitrous Oxide Emissions and Corn Grain Yields," *Soil Science Society of America Journal 76* (2012): 1,268-1,279

J. Feng, *et al*., "Integrated Assessment of the Impact of Enhanced-Efficiency Nitrogen Fertilizer on N_2O Emission and Crop Yield," *Agriculture, Ecosystems and Environment 231* (2016): 218-228

N. Farahbakhshazad, *et al*., "Modeling Biogeochemical Impacts of Alternative Management Practices for a Row-Crop Field in Iowa," *Agriculture, Ecosystems and Environment 123* (2008): 30-48

X. Huerfano, *et al*., "Splitting the Application of 3,4-Dimethylpyrazole Phosphate (DMPP): Influence on Greenhouse Gases Emissions and Wheat Yield and Quality under Humid Mediterranean Conditions," *European Journal of Agronomy 64* (2015): 47-57

H. Jamali, *et al*., "Effect of Reduced Irritation and Split Urea Application on N_2O Production and Emissions in a Sorghum Crop: A Lysimeter Study," *Proceedings of the 18th Australian Society of Agronomy Conference, 24-28 September 2017, Ballarat, Australia, 2017*

H. Li, *et al*., "Estimates of N_2O Emissions and Mitigation Potential from a Spring Maize Field Based on DNDC Model," *Journal of Integrative Agriculture 11* (2012): 2,067-2,078

S. Liu, *et al*., "Ammonia and Greenhouse Gas Emissions from a Subtropical Wheat Field under Different Nitrogen Fertilization Strategies," *Journal of Environmental Science 57* (2017): 196-210

B. Ma, *et al.*, "Nitrous Oxide Fluxes from Corn Fields: On-Farm Assessment of the Amount and Timing of Nitrogen Fertilizer," *Global Change Biology 16* (2010): 156-170

H. Mielenz, *et al*., "Nitrous Oxide Emissions from Grain Production Systems across a Wide Range of Environmental Conditions in Eastern Australia," *Soil Research 54* (2016): 659-674

A. Roy, *et al*., "Nitrogen Application Rate, Timing and History Effects on Nitrous Oxide Emissions from Corn (*Zea Mays L*.)," *Canadian Journal of Soil Science 94* (2014): 563-573

I. Shcherbak, *et al*., "Global Meta-Analysis of the Nonlinear Response of Soil Nitrous Oxide (N_2O) Emissions to Fertilizer Nitrogen," *Proceedings of the National Academy of Sciences 111* (2014): 9,199-9,204

G. Schwenke, *et al*. (2016) "Greenhouse Gas (N_2O and CH_4) Fluxes Under Nitrogen-Fertilized Dryland Wheat and Barley on Subtropical Vertisols: Risk, Rainfall, and Alternatives," *Soil Research 54*. 10.1071/SR 15538

D. Smith, *et al*., "Fertilizer and Tillage Management Impacts on Non-Carbon Dioxide Greenhouse Gas Emissions," *Soil Science Society of America 75* (2011): 1,070-1,082

R. Thapa, *et al*., "Effect of Enhanced Efficiency Fertilizers on Nitrous Oxide Emissions and Crop Yields: A Meta-analysis," *Soil Society of America Journal 80* (2016): 1,121-1,134

R. Venterea and J. Coulter, "Split Application of Urea Does Not Decrease and May Increase Nitrous Oxide Emissions in Rainfed Corn," *Agronomy Journal 107* (2015): 337-348

S. Wang, *et al*., "Effect of Split Application of Nitrogen on Nitrous Oxide Emissions from Plastic Mulching Maize in the Semiarid Loess Plateau," *Agriculture, Ecosystems and Environment 220* (2016): 21-27

Y. Yu, *et al*., "Ability of Split Urea Applications to Reduce Nitrous Oxide Emissions: A Laboratory Incubation Experiment," *Applied Soil Ecology 100* (2016): 75-80

B. Zebarth, *et al*., "Effect of Fertilizer Nitrogen Management on N_2O emissions in Commercial Corn Fields," *Canadian Journal Soil Science 88* (2008): 189-195

B. Zebarth, *et al*., "Controlled Release Fertilizer Product Effects on Potato Crop Response and Nitrous Oxide Emissions under Rain-Fed Production on a Medium-Textured Soil," *Canadian Journal Soil Science 92* (2012): 759-769

Fertilizer application timing: Delayed application–N_2O

D. Abalos, *et al*., "Scenario Analysis of Fertilizer Management Practices for N_2O Mitigation from Corn Systems in Canada," *Science of the Total Environment 573* (2016): 356-365

J. Burzaco, *et al*., "Nitrous Oxide Emissions in Midwest US Maize Production Vary Widely with Band-Injected Fertilizer Rates, Timing and Nitrapyrin Presence," *Environmental Research Letters 8,* article 035031 (2013)

A. Eagle, *et al*., "Fertilizer Management and Environmental Factors Drive N_2O and NO_3 Losses in Corn: A Meta-Analysis," *Soil Science Society of America Journal 81* (2016): 1,191-1,202

R. Phillips, *et al.,* "Fertilizer Application Timing Influences Greenhouse Gas Fluxes over a Growing Season," *Journal of Environmental Quality 38* (2009): 1,569-1,579

Fertilizer application timing: Split or delayed application–CH_4

H. Akiyama, *et al*., "Nitrification, Ammonia-Oxidizing Communities and N_2O and CH_4 Fluxes in an Imperfectly Drained Agricultural Field Fertilized with Coated Urea With and Without Dicyandiamide," *Biology and Fertility of Soils 49* (2013): 213-223

X. Huerfano, *et al*., "Splitting the Application of 3,4-Dimethylpyrazole Phosphate (DMPP): Influence on Greenhouse Gases Emissions and Wheat Yield and Quality under Humid Mediterranean Conditions," *European Journal of Agronomy 64* (2015): 47-57

S. Liu, *et al*., "Ammonia and Greenhouse Gas Emissions from a Subtropical Wheat Field under Different Nitrogen Fertilization Strategies," *Journal of Environmental Science 57* (2017): 196-210

G. Schwenke, *et al*. (2016) "Greenhouse Gas (N_2O and CH_4) Fluxes Under Nitrogen-Fertilized Dryland Wheat and Barley on Subtropical Vertisols: Risk, Rainfall, and Alternatives," *Soil Research 54*. 10.1071/SR15338

D. Smith, *et al*., "Fertilizer and Tillage Management Impacts on Non-Carbon Dioxide Greenhouse Gas Emissions," *Soil Science Society of America Journal 75* (2011): 1,070-1,082

B. Sun, *et al*., "The Effects of Nitrogen Fertilizer Applications on Methane and Nitrous Oxide Emission/Uptake in Chinese Cropland," *Journal of Integrative Agriculture 15* (2016): 440-450

Fertilizer placement: Subsurface placement–N_2O

D. Abalos, *et al*., "Micrometeorological Measurements over 3 Years Reveal Differences in N_2O Emissions between Annual and Perennial Crops," *Global Change Biology 22* (2016): 1,244-1,255

D. Abalos, *et al*., "Scenario Analysis of Fertilizer Management Practices for N_2O Mitigation from Corn Systems in Canada," *Science of the Total Environment 573* (2016): 356-365

L. Bastos, *N Fertilizer Source and Placement Impacts Nitrous Oxide Losses, Grain Yield and N Use Efficiency in No Till Corn*, MS Thesis, Kansas State, 2015

G. Breitenbeck, *Emissions of Nitrous Oxide from Soils Fertilized with Anhydrous Ammonia*, PhD Dissertation, Iowa State University, 1984

G. Breitenbeck and J. Bremner, "Effects of Rate and Depth of Fertilizer Application on Emission of Nitrous Oxide from Soil Fertilized with Anhydrous Ammonia," *Biology and Fertility of Soils 2* (1986): 201-204

C. Brink, *et al*., "Ammonia Abatement and Its Impact on Emissions of Nitrous Oxide and Methane in Europe - Part I: Method," *Atmospheric Environment 35* (2001): 6,299-6,312

D. Burton, *et al*., "Influence of Fertilizer Nitrogen Source and Management Practice on N_2O Emissions from Two Black Chernozemic Soils," *Canadian Journal Soil Science 88* (2008): 219-227

G. Cambareri, *et al*., "Anaerobically Digested Dairy Manure as an Alternative Nitrogen Source to Mitigate Nitrous Oxide Emissions in Fall-Fertilized Corn," *Canadian Journal of Soil Science 97* (2017): 439-450

G. Cambareri, *et al*., "Year Round Nitrous Oxide Emissions as Affected by Timing and Method of Dairy Manure Application to Corn," *Soil Science Society of America Journal 81* (2017): 166-178

M. Carter, *et al*., "Consequences of Field N_2O Emissions for the Environmental Sustainability of Plant-Based Biofuels Produced within an Organic Farming System," *Global Change Biology 4* (2012): 435-452

C. Drury, *et al*., "Emissions of Nitrous Oxide and Carbon Dioxide: Influence of Tillage Type and Nitrogen Placement Depth," *Soil Science Society of America Journal 70* (2006): 570-581

C. Drury, *et al*., *Improved Application Methods and N Sources for Corn in Southwestern Ontario*, Final Report Project #CAN-4RCO_2 (Bridge Funding), Agriculture and Agri-Food Canada, April 2015

C. Drury, *et al*., "Combining Urease and Nitrification Inhibitors with Incorporation Reduced Ammonia and Nitrous Oxide Emissions and Increased Corn Yields," *Journal of Environmental Quality 46* (2017): 939-949

E. Duncan, *et al*., "Nitrous Oxide and Ammonia Emissions from Injected and Broadcast-Applied Dairy Slurry," *Journal of Environmental Quality 46* (2017): 36-44

R. Engel, *et al*., "Influence of Urea Fertilizer Placement on Nitrous Oxide Production from a Silt Loam Soil," *Journal of Environmental Quality 39* (2010): 115-125

N. Farahbakhshazad, *et al*., "Modeling Biogeochemical Impacts of Alternative Management Practices for a Row-Crop Field in Iowa," *Agriculture, Ecosystems and Environment 123* (2008): 30-48

J. Feng, *et al*., "Integrated Assessment of the Impact of Enhanced-Efficiency Nitrogen Fertilizer on N_2O Emission and Crop Yield," *Agriculture, Ecosystems and Environment 231* (2016): 218-228

R. Fujinuma, *et al*., "Broadcast Urea Reduces N_2O but Increases NO Emissions Compared With Conventional and Shallow-Applied Anhydrous Ammonia in a Coarse Textured Soil," *Journal of Environmental Quality 40* (2011): 1,806-1,815

X. Gao, *et al*., "Enhanced Efficiency Urea Sources and Placement Effects on Nitrous Oxide Emissions," *Agronomy Journal 107* (2015): 1-12

A. Halvorson, *et al*., "Nitrogen Source Effects on Nitrous Oxide Emissions from Irrigated Strip-till Corn," *Journal of Environmental Quality 40* (2011): 1,775-1,786

A. Halvorson and S. Del Grosso, "Nitrogen Source and Placement Effects on Soil Nitrous Oxide Emissions from No-Till Corn," *Journal of Environmental Quality 41* (2012): 1,349-1,359

Z. Han, *et al*., "N_2O Emissions from Grain Cropping Systems: A Meta-Analysis of the Impacts of Fertilizer-based and Ecologically-based Nutrient Management Strategies," *Nutrient Cycling in Agroecosystems 107* (2017): 335-355

Y. Hosen, *et al*., "Effects of Deep Application of Urea on NO and N_2O Emissions from an Andisol," *Nutrient Cycling in Agroecosystems 63* (2002): 197-206

A. Hou and H.Tsuruta, "Nitrous Oxide and Nitric Oxide Fluxes from an Upland Field in Japan: Effect of Urea Type, Placement, and Crop Residues," *Nutrient Cycling in Agroecosystems 65* (2003): 191-200

Y. Hou, *et al*., "Mitigation of Ammonia, Nitrous Oxide and Methane Emissions from Manure Management Chains: A Meta-Analysis and Integrated Assessment," *Global Change Biology 21* (2015): 1,293-1,312

J. Huijsmans and R. Schils, "Ammonia and Nitrous Oxide Emissions Following Field-Application of Manure: State of the Art Measurements in the Netherlands," in *Proceedings of the International Fertilizer Society Conference, Cambridge, UK, December 10, 2009*

G. Hultgreen and P. Leduc, *The Effect of Nitrogen Fertilizer Placement, Formulation, Timing and Rate of Greenhouse Gas Emissions and Agronomic Performance. Final Report*, Project no. 5300G, Agriculture and Agri-Food Canada and Prairie Agricultural Machinery Institute, Saskatchewan, 2003

K. Klemedtsson and K. Smith, "The Significance of Nitrous Oxide Emission Due to Cropping of Grain for Biofuel Production: A Swedish Perspective," *Biogeosciences 8* (2011): 3,581-3,591

B. Langevin, *et al*., "Simulation of Field NH_3 and N_2O Emissions from Slurry Spreading," *Agronomy for Sustainable Development 35* (2015): 347-358

R. Lemke, *et al*., *The Effect of Nitrogen Fertilizer Placement, Formulation, Timing and Rate on Greenhouse Gas Emissions and Agronomic Performance: Final Report*, Agriculture and Agri-Food Canada, December 2003

X. Liu, *et al*., "The Impact of Nitrogen Placement and Tillage on NO, N_2O, CH_4 and CO_2 Fluxes from a Clay Loam Soil," *Plant and Soil 280* (2006): 177-188

B. Maharjan and R. Venterea, "Anhydrous Ammonia Injection Depth Does Not Affect Nitrous Oxide Emissions in a Silt Loam Over Two Growing Seasons," *Journal of Environmental Quality* 43 (2014): 1,527-1,535

P. Nash, *et al*., "Nitrous Oxide Emissions from Claypan Soils Due to Nitrogen Fertilizer Source and Tillage/Fertilizer Placement Practices," *Soil Science Society of America Journal 76* (2012): 983-993

S. Ogle, *et al*., *Report on GHG Mitigation Literature Review for Agricultural Systems*, Submitted to USDA Climate Change Office, Natural Resources Ecology Laboratory, Colorado State University, 2010; data reported in Swan, *et al*. (2015)

P. Perala, "Influence of Slurry and Mineral fertilizer Application Techniques on N_2O and CH_4 Fluxes from a Barley Field in Southern Finland," *Agriculture, Ecosystems and Environment 117* (2006): 71-78

H. Pfab, *et al*., "Influence of a Nitrification Inhibitor and of Placed N-Fertilization on N_2O Fluxes from a Vegetable Cropped Loamy Soil," *Agriculture, Ecosystems and Environment 150* (2012): 91-101

L. Rodhe, *et al*., "Nitrous Oxide, Methane and Ammonia Emissions Following Slurry Spreading on Grassland," *Soil Use and Management 22* (2006): 229-237

A. Sadeghpour, *et al*., "Nitrous Oxide Emissions from Surface versus Injected Manure in Perennial Hay Crops," *Soil Science Society of America Journal 82* (2018): 156-166

E. Sajeev, *et al*., "Greenhouse Gas and Ammonia Emissions from Different Stages of Liquid Manure Management Chains: Abatement Options and Emission Interactions," *Journal of Environmental Quality 47* (2018): 30-41

M. Severin, *et al*., "Soil, Slurry and Application Effects on Greenhouse Gas Emissions," *Plant Soil Environment 8* (2015): 344-351

K. Sistani, *et al*., "Greenhouse Gas Emissions from Swine Effluent Applied to Soils by Different Methods," *Soil Science Society of America Journal 74* (2010): 429-435

K. Smith, *et al*., "Impact of Tillage and Fertilizer Application Method on Gas Emissions in a Corn Cropping System," *Pedosphere 22* (2012): 604-615

I. Thomsen, *et al*., "Effects of Slurry Pre-Treatment and Application Technique on Short-term N_2O Emissions as Determined by a New Non-linear Approach," *Agriculture, Ecosystems and Environment 136* (2010): 227-235

A. Vallejo, *et al*., "Comparison of N Losses (NO_3^-, N_2O, NO) from Surface Applied, Injected or Amended (DCD) Pig Slurry of an Irrigated Soil in a Mediterranean Climate," *Plant and Soil 272* (2005): 313-325

C. van Kessel, *et al*., "Climate, Duration and N Placement Determine N_2O Emissions in Reduced Tillage Systems: A Meta-Analysis," *Global Change Biology 19* (2013): 33-44

G. Velthof, *et al*., "Nitrous Oxide Emission from Animal Manures Applied to Soil under Controlled Conditions," *Biology and Fertility of Soils 37* (2003): 221-230

G. Velthof and J. Mosquera, "The Impact of Slurry Application Technique on Nitrous Oxide Emissions from Agricultural Soils," *Agriculture, Ecosystems and Environment 140* (2011): 298-308

R. Venterea, *et al*., "Nitrogen Oxide and Methane Emissions under Varying Tillage and Fertilizer Management," *Journal of Environmental Quality 34* (2005): 1,467-1,477

R. Venterea, *et al*., "Urea Decreases Nitrous Oxide Emissions Compared with Anhydrous Ammonia in a Minnesota Corn Cropping System," *Soil Science Society of America Journal 74* (2010): 407-418

Y. Wang, *et al*., "Mitigating Greenhouse Gas and Ammonia Emissions from Swine Manure Management: A Systems Analysis," *Environmental Science and Technology 51* (2017): 4,503-4,511

S. Wulf, *et al*., "Application Technique and Slurry Cofermentation Effects on Ammonia, Nitrous Oxide and Methane Emissions after Spreading: II. Greenhouse Gas Emissions," *Journal of Environmental Quality 31* (2002): 1,795-1,801

X. Zhu-Barker, *et al*., "Knife-Injected Anhydrous Ammonia Increases Yield-Scaled N_2O Emissions Compared to Broadcast or Band-Applied Ammonium Sulfate," *Agriculture, Ecosystems and Environment 212* (2015): 148-157

Fertilizer placement: Subsurface placement–CH_4

M. Carter, *et al*., "Consequences of Field N_2O Emissions for the Environmental Sustainability of Plant-Based Biofuels Produced within an Organic Farming System," *Global Change Biology 4* (2012): 435-452

X. Liu, *et al*., "The Impact of Nitrogen Placement and Tillage on NO, N_2O, CH_4 and CO_2 Fluxes from a Clay Loam Soil," *Plant and Soil 280* (2006): 177-188

P. Perala, "Influence of Slurry and Mineral fertilizer Application Techniques on N_2O and CH_4 Fluxes from a Barley Field in Southern Finland," *Agriculture, Ecosystems and Environment 117* (2006): 71-78

L. Rodhe, *et al*., "Nitrous Oxide, Methane and Ammonia Emissions Following Slurry Spreading on Grassland," *Soil Use and Management 22* (2006): 229-237

K. Sistani, *et al*., "Greenhouse Gas Emissions from Swine Effluent Applied to Soils by Different Methods," *Soil Science Society of America Journal 74* (2010): 429-435

K. Smith, *et al*., "Impact of Tillage and Fertilizer Application Method on Gas Emissions in a Corn Cropping System," *Pedosphere 22* (2012): 604-615

Spring fertilizer application in lieu of fall application–N_2O

D. Abalos, *et al*., "Micrometeorological Measurements over a 3 Years Reveal Differences in N_2O Emissions between Annual and Perennial Crops," *Global Change Biology 22* (2016): 1,244-1,255

D. Abalos, *et al*., "Scenario Analysis of Fertilizer Management Practices for N_2O Mitigation from Corn Systems in Canada," *Science of the Total Environment 573* (2016): 356-365

D. Abalos, *et al*., "Improving Fertilizer Management in the US and Canada for N_2O Mitigation: Understanding Potential Positive and Negative Side-Effects," *Agriculture, Ecosystems and Environment 221* (2016): 214-221

M. Bell, et al., "How Do Emission Rates and Emission Factors for Nitrous Oxide and Ammonia Vary with Manure Type and Time of Application in a Scottish Farmland," *Geoderma 264* (2016): 81-93

D. Burton, *et al.,* "Influence of Fertilizer Nitrogen Source and Management Practice on N_2O Emissions from Two Black Chernozemic Soils," *Canadian Journal of Soil Science 88* (2008): 219-227

G. Cambareri, *et al*., "Year Round Nitrous Oxide Emissions as Affected by Timing and Method of Dairy Manure Application to Corn," *Soil Science Society of America Journal 81* (2017): 166-178

B. Grant, *et al*., "Estimated N_2O and CO_2 Emissions as Influenced by Agricultural Practices in Canada," *Climatic Change 65* (2004): 315-332

Z. Han, et al., "N_2O Emissions from Grain Cropping Systems: A Meta-Analysis of the Impacts of Fertilizer-based and Ecologically-based Nutrient Management Strategies," *Nutrient Cycling in Agroecosystems 107* (2017): 335-355

X. Hao, *et al*., "Nitrous Oxide Emissions from an Irrigated Soil as Affected by Fertilizer and Straw Management," *Nutrient Cycling in Agroecosystems 60* (2001): 1-8

G. Hernandez-Ramirez, *et al*., "Greenhouse Gas Fluxes in an Eastern Corn Belt Soil: Weather, Nitrogen Source, and Rotation," *Journal of Environmental Quality 38* (2009): 841-854

G. Hultgreen and P. Leduc, *The Effect of Nitrogen Fertilizer Placement, Formulation, Timing and Rate of Greenhouse Gas Emissions and Agronomic Performance. Final Report*, Project no. 5300G, Agriculture and Agri-Food Canada and Prairie Agricultural Machinery Institute, Saskatchewan, 2003

R. Lemke, *et al*., *The Effect of Nitrogen Fertilizer Placement, Formulation, Timing and Rate on Greenhouse Gas Emissions and Agronomic Performance: Final Report*, Agriculture and Agri-Food Canada, December 2003

S. Ogle, "Data on N_2O Emissions from N Management Options by Crop and Region," Colorado State University, Fort Collins, CO

P. Rochette, *et al*., "Carbon Dioxide and Nitrous Oxide Emissions Following Fall and Spring Applications of Pig Slurry to an Agricultural Soil," *Soil Society of America Journal 68* (2004): 1,410-1,420

T. Sawamoto, *et al*., "No Significant Difference in N_2O Emissions, Fertilizer-Induced Emission Factor, and CH_4 Absorption Between Anaerobically Digested Cattle Slurry and Chemical Fertilizer Applied to Timothy (*Phleum pratense L*.) Sward in Central Hokkaido, Japan," *Soil Science and Plant Nutrition 56* (2010): 492-502

E. Schwager, *et al*., "Field Nitrogen Losses Induced by Application Timing of Digestate from Dairy Biogas Production," *Journal of Environmental Quality 45* (2016): 1,829-1,837

Y. Soon, *et al*., "Effect of Polymer-coated Urea and Tillage on the Dynamics of Available N and Nitrous Oxide Emission from Gray Luvisols," *Nutrient Cycling in Agroecosystems 90* (2011): 267-279

M. Tenuta, *et al*., "Nitrous Oxide and Methane Emission from a Coarse-Textured Grassland Soil Receiving Hog Slurry," *Agriculture, Ecosystems and Environment 138* (2010): 35-43

M. Tenuta, *et al*., "Lower Nitrous Oxide Emissions from Anhydrous Ammonia Application Prior to Soil Freezing in Late Fall That Spring Preplant Application," *Journal of Environmental Quality 45* (2016): 1,133-1,143

K. Uzoma, *et al*., "Assessing the Effects of Agricultural Management on Nitrous Oxide Emissions Using Flux Measurements and the DNDC Model," *Agriculture, Ecosystems and Environment 206* (2015): 71-83

Biochar – N_2O

T. Angst, *et al*., "Impact of Pine Char Biochar on Trace Greenhouse Gas Emissions and Soil Nutrient Dynamics in an Annual Ryegrass System in California," *Agriculture, Ecosystems and Environment 191* (2014): 17-26

N. Borchard, *et al*., "Biochar, Soil and Land-Use Interactions that Reduce Nitrate Leaching and N_2O Emissions: A Meta-Analysis," *Science of the Total Environment 651* (2019): 2,354-2,364

S. Case, *et al*., "Can Biochar Reduce Soil Greenhouse Gas Emissions from a Miscanthus Bioenergy Crop? *Global Change Biology 6* (2014): 76-89

S. Castaldi, *et al*., "Impact of Biochar Application to a Mediterranean Wheat Crop on Soil Microbial Activity and Greenhouse Gas Fluxes," *Chemosphere 85* (2011): 1,464-1,471

M. Cayuela, *et al*., "Biochar's Role in Mitigating Soil Nitrous Oxide Emissions: A Review and Meta-Analysis," *Agriculture, Ecosystems and Environment 191* (2014): 5-16

M. Cayuela, *et al*., "The Molar H:C Org Ratio of Biochar is a Key factor in Mitigating N_2O Emissions from Soil," *Agriculture, Ecosystems and Environment 202* (2015): 135-138

J. Chen, *et al*. (2015) "Effects of Biochar Addition on CO_2 and N_2O Emissions Following Fertilizer Application to a Cultivated Grassland Soil," *PLoS ONE 10*(5): e0126841. https://doi.org/10.1371/journal.pone.0126841

K. Denef, *et al*., *Greenhouse Gas Emissions from U.S. Agriculture and Forestry: A Review of Emission Sources, Controlling factors, and Mitigation Potential*. Interim Report to USDA under contract #G-23F-8182H, ICF International, 2011

Q. Deng, *et al*. (2015) "Corn Yield and Soil Nitrous Oxide Emissions under Different Fertilizer and Soil Management: a Three-Year Field Experiment in Middle Tennessee," *PLoS One 10*(4): e0125406. Doi:10.1371/journal.pone.0125406

B. Fang, *et al*., "Impacts of Straw Additions on Agricultural Soil Quality and Greenhouse Gas Fluxes in Karst Area, Southwest China," *Soil Science and Plant Nutrition 62* (2016): 526-533

J. Edwards, *et al*., "Dynamic Biochar Effects on Soil Nitrous Oxide Emissions and Underlying Microbial Processes During the Maize growing Season," *Soil Biology and Biochemistry 122* (2018): 81-90

J. Gaunt and J. Lehmann, "Energy Balance and Emissions Associated with Biochar Sequestration and Pyrolysis Bioenergy Production," *Environmental Science and Technology 42* (2008): 4,152-4,158

N. Hagemann, *et al*., "Does Soil Aging Affect the N_2O Mitigation Potential of Biochar? A Combined Microcosm and Field Study," *Global Change Biology-Bioenergy 9* (2017): 953-964

Y. He, *et al*., "Effects of Biochar Application on Soil Greenhouse Gas fluxes: A Meta-Analysis," Global *Change Biology-Bioenergy 9* (2017): 743-755

R. Huppi, *et al*., "Effect of Biochar on Soil Nitrous Oxide Emissions from a Temperate Maize Cropping System," *Soil 1* (2015): 707-717

J. Jia, *et al*., “Effects of Biochar Application on Vegetable Production and Emissions of N_2O and CH_4,” *Soil Science and Plant Nutrition 58* (2012): 503-509

J. Junxiang, *et al*., "Effects of Biochar Application on Vegetable Production and Emissions of N_2O and CH_4," *Soil Science and Plant Nutrition 58* (2012): 503-509

Q. Liu, *et al*., "How Does Biochar Influence Soil N Cycle? A Meta-Analysis," *Plant Soil 426* (2018): 211-225

S. Martin, *et al*., "Biochar Mediated Reductions in Greenhouse Gas Emissions from Soil Amended with Anaerobic Digestates," *Biomass and Bioenergy 29* (2015): 39-49

S. Saarnio, *et al*., "Biochar Addition Indirectly Affects N_2O Emissions via Soil Moisture and Plant N Uptake," *Soil Biology and Biochemistry 58* (2013): 99-106

S. Schimmelpfennig, *et al*., "Biochar, Hydrochar and Uncarbonized Feedstock Application to Permanent Grassland-Effects on Greenhouse Gas Emissions and Plant Growth," *Agriculture, Ecosystems and Environment 191* (2014): 39-52

X. Song, *et al*. (2016) "Effects of Biochar Application on Fluxes of Three Biogenic Greenhouse Gases: A Meta-analysis," *Ecosystem Health and Sustainability 2(2)*: e01202. doi:10.1002/ehs2.1202

C. Stewart, *et al*., "Co-Generated Fast Pyrolysis Biochar Mitigated Greenhouse Gas Emissions and Increases Carbon Sequestration in Temperate Soils," *Global Change Biology-Bioenergy 5* (2013): 153-164

L. Sun, *et al*., "Combined Effects of Nitrogen Deposition and Biochar Application on Emissions of N_2O, CO_2 and NH_3 from Agricultural and Forest Soils," *Soil Science and Plant Nutrition 60* (2014): 254-265

A. Taghizadeh-Toosi, *et al*., "Biochar Incorporation into Pasture Soil Suppresses *In Situ* Nitrous Oxide Emissions from Ruminant Urine Patches," *Journal of Environmental Quality 40* (2011): 468-476

L. van Zwieten, *et al*., "Biochar Effects on Nitrous Oxide and Methane Emissions from Soil," in J. Lehmann and S. Joseph, eds., *Biochar for Environmental Management* (New York: Routledge), pp 487-518

E. Verhoeven, *et al*., "Towards a Better Assessment of Biochar-Nitrous Oxide Mitigation Potential at the Field Scale," *Journal of Environmental Quality 46* (2017): 237-246

Q. Yi, *et al*. (2017) "Effects of Nitrogen Application Rate, Nitrogen Synergist and Biochar on Nitrous Oxide Emissions from Vegetable Field in South China," *PLOS One* 12(4): e0175325. https://doi.org/10./1371/journal.pone.0175325

J. Wang, *et al*., "Effects of Biochar Amendment in Two Soils on Greenhouse Gas Emissions and Crop Production," *Plant Soil 360* (2012): 287-298

Z. Wang, *et al*., "Characterization and Influence of Biochars on Nitrous Oxide Emission from Agricultural Soil," *Environmental Pollution 174* (2013): 289-296

D. Woolf, *et al*. (2010) "Sustainable Biochar to Mitigate Global Climate Change," *Nature Communications* 1:56. doi.10.1038/ncomms1053

D. Zhang, *et al*., "Biochar Helps Enhance Maize Productivity and Reduce Greenhouse Gas Emissions under Balanced Fertilization in a Rainfed Low Fertility Inceptisol," *Chemosphere 142* (2016): 106-113

J. Zheng, *et al*., "Biochar Compound Increases Nitrogen Productivity and Economic Benefits but Decreases Carbon Emission of Maize Production," *Agriculture, Ecosystems and Environment 241* (2017): 70-78

Biochar–CH_4

T. Angst, *et al*., "Impact of Pine Char Biochar on Trace Greenhouse Gas Emissions and Soil Nutrient Dynamics in an Annual Ryegrass System in California," *Agriculture, Ecosystems and Environment 191* (2014): 17-26

B. Fang, *et al*., "Impacts of Straw Additions on Agricultural Soil Quality and Greenhouse Gas Fluxes in Karst Area, Southwest China," *Soil Science and Plant Nutrition 62* (2016): 526-533

Y. He, *et al*., "Effects of Biochar Application on Soil Greenhouse Gas fluxes: A Meta-Analysis*," Global Change Biology-Bioenergy 9* (2017): 743-755

J. Jia, *et al*., "Effects of Biochar Application on Vegetable Production and Emissions of N_2O and CH_4," *Soil Science and Plant Nutrition 5*8 (2012): 503-509

M. Johnson, *et al*. (2017) "Biochar Influences on Soil CO_2 and CH_4 Fluxes in Response to Wetting and Drying Cycles for a Forest Soil," *Scientific Reports 7*, 6780. doi.10.1038/s41598-017-07224-6

J. Junxiang, *et al*., "Effects of Biochar Application on Vegetable Production and Emissions of N_2O and CH_4," *Soil Science and Plant Nutrition 58* (2012): 503-509

K. Karhu, *et al*., "Biochar Addition to Agricultural Soil Increased CH_4 Uptake and Water Holding Capacity - Results from a Short-Term Pilot Field Study," *Agriculture, Ecosystems and Environment 140* (2011): 309-313

X. Song, *et al*. (2016) "Effects of Biochar Application on Fluxes of Three Biogenic Greenhouse Gases: A Meta-Analysis," *Ecosystem Health and Sustainability 2(2)*.e01202. doi: 10.1002/ehs2.1202

J. Wang, *et al*., "Effects of Biochar Amendment in Two Soils on Greenhouse Gas Emissions and Crop Production," *Plant Soil 360* (2012): 287-298

D. Woolf, *et al*. (2010) "Sustainable Biochar to Mitigate Global Climate Change," *Nature Communications 1*:56. doi.10.1038/ncomms1053

D. Zhang, *et al*., "Biochar Helps Enhance Maize Productivity and Reduce Greenhouse Gas Emissions under Balanced Fertilization in a Rainfed Low Fertility Inceptisol," *Chemosphere 142* (2016): 106-113

Biochar–Mean residence time-SOC/CO_2

T. Abbruzzini, *et al*., "Increasing Rates of Biochar Application to Soil Induce Stronger Negative Priming Effect on Soil Organic Carbon Decomposition," *Agricultural Research 6* (2017): 389-398

A. Budai, *et al*., "Biochar Persistence, Priming and Microbial Responses to Pyrolysis Temperature Series," *Biology and Fertility of Soils 53* (2016): 749-761

C. Cheng, *et al*., "Natural Oxidation of Black Carbon in Soils: Changes in Molecular Form and Surface Charge along a Climosequence," *Geochimica et Cosmochimica Act 72* (2008): 1,598-1,610

Y. Fang, *et al*., "Effect of Temperature on Biochar Priming Effects and Its Stability in Soils," *Soil Biology and Biochemistry 80* (2015): 136-145

J. Fargione, *et al*. (2018) "Natural Climate Solutions for the United States," *Science Advances.4.eaat1869.* doi:10.1126/sciadv.aat1869

J. Field, *et al*., "Distributed Biochar and Bioenergy Co-production: A Regionally Specific Case Study of Environmental Benefits and Economic Impacts," *Global Change Biology-Bioenergy 5* (2013): 177-191

B. Foereid, *et al*., "Modeling Black Carbon Degradation and Movement in Soil," *Plant Soil 211* (345): 223-236

Y. Kuzyakov, *et al*., "Black Carbon Decomposition and Incorporation into Soil Microbial Biomass Estimated by ^{14}C Labelling," *Soil Biology and Biochemistry 41* (2009): 210-219

J. Lehmann, *et al*., "Stability of Biochar in Soil," in J. Lehmann and S. Joseph, eds., *Biochar for Environmental Management*, chapter 11 (London: Earthscan, 2009)

S. Lutfalla, *et al*. (2017) "Pyrogenic Carbon Lacks Long-Term Persistence in Temperate Arable Soils," Frontiers in *Earth Science 5*:96.doi: 10.3389/feart.2017.00096

J. Major, *et al*., "Fate of Soil-Applied Black Carbon: Downward Migration, Leaching and Respiration," *Global Change Biology 16* (2010): 1,366-1,379

B. Nguyen, *et al*., "Turnover of Soil Carbon Following Addition of Switchgrass-Derived Biochar to Four Soils," *Soil Science Society of America Journal 78* (2014): 531-537

C. Preston and M. Schmidt, "Black (Pyrogenic) Carbon: A Synthesis of Current Knowledge and Uncertainties with Special Consideration of Boreal Regions," *Biogeosciences 3* (2006): 397-420

D. Rasse, *et al*. (2017) "Persistence in Soil of Miscanthus Biochar in Laboratory and Field Conditions," *PloS ONE 12*(9): e0184383.https//doi.org/10.1371/journal.pone.0184383

K. Roberts, *et al*., "Life Cycle Assessment of Biochar Systems: Estimating the Energetic, Economic and Climate Change Potential," *Environmental Science and Technology 44* (2010): 827-833

S. Shackley, *et al*., "Expert Perceptions of the Role of Biochar as a Carbon Abatement Option with Ancillary Agronomic and Soil-Related Benefits," *Energy and Environment 22* (2011): 167-187

B. Singh and A. Cowie (2014) "Long-Term Influence of Biochar on Native Organic Carbon Mineralisation in a Low-Carbon Clayey Soil," *Scientific Reports 4* article 3687.doi:10.1038/srep03687

J. Wang, *et al*., "Biochar Stability in Soil: Meta-Analysis of Decomposition and Priming Effects," *Global Change Biology Bioenergy 8* (2016): 512-523

C. Werner, *et al*., "Biogeochemical Potential of Biomass Pyrolysis Systems for Limiting Global Warming to 1.5C," *Environmental Research Letters 13* (2018) 044036.https://doi.org/10.1088.1748-9326.aabb0e

D. Woolf, *et al*. (2010) "Sustainable Biochar to Mitigate Global Climate Change," *Nature Communications 1:56.* doi.10.1038/ncomms1053 (2010)

D. Woolf and J. Lehmann, "Modelling the Long-Term Response to Positive and Negative Priming of Soil Organic Carbon by Black Carbon," *Biogeochemistry 111* (2012): 83-95

A. Zimmerman, "Abiotic and Microbial Oxidation of Laboratory-Produced Black Carbon (Biochar)," *Environmental Science and Technology 44* (2010): 1,295-1,301

A. Zimmerman and B. Gao, "The Stability of Biochar in the Environment," chapter 1 in N. Ladygina and F. Rineau, eds., *Biochar and Soil Biota* (Boca Raton: CRC Press, 2013), pp 1-40

Biochar: Crop residue removal-SOC/CO_2

R. Allmaras, *et al*., "Crop Residue Transformations in Root and Soil Carbon as Related to Nitrogen, Tillage, and Stover Management," *Soil Science Society of America Journal 68* (2004): 1,366-1,375

P. Buysse, *et al*., "Fifty Years of Contrasted Residue Management of an Agricultural Crop: Impacts on the Soil Carbon Budget and on Soil Heterotrophic Respiration," *Agriculture, Ecosystems and Environment 167* (2013): 52-59

E. Campbell, *et al*., "Assessing the Soil Carbon, Biomass Production, and Nitrous Oxide Emission Impact of Corn Stover Management for Bioenergy Feedstock Production Using DAYCENT," *Bioenergy Research 7* (2014): 491-502

K. Chan, *et al*., "Soil Carbon Dynamics under Different Cropping and Pasture Management in Temperate Australia: Results of Three Long-Term Experiments," *Soil Research 49* (2011): 320-328

D. Clay, *et al*., "Tillage and Corn Residue Harvesting Impact Surface and Subsurface Carbon Sequestration," *Journal of Environmental Quality 44* (2015): 803-809

C. Curtis, *et al*., "Perennialization and Cover Cropping Mitigate Soil Carbon Loss from Residue Harvesting," *Journal of Environmental Quality 47* (2018): 710-718

B. Dalzell, *et al*., "Simulated Impacts of Crop residue Removal and Tillage on Soil Organic Matter Maintenance," *Soil Science Society of America Journal 77* (2013): 1,349-1,356

C. Dell, *et al*., "Implications of Observed and Simulated Soil Carbon Sequestration for Management Options in Corn-Based Rotations," *Journal of Environmental Quality 47* (2018): 617-624

L. Dendooven, *et al*., "Global Warming Potential of Agricultural Systems with Contrasting Tillage and Residue Management in the Central Highlands of Mexico," *Agriculture, Ecosystems Environment 152* (2012): 50-58

B. Dimassi, *et al*., "Long-term Effect of Contrasted Tillage and Crop Management on Soil Carbon Dynamics during 41 years," *Agriculture, Ecosystems and Environment 188* (2014): 134-146

R. Follett, *et al*., "Soil Carbon Sequestration by Switchgrass and No-Till Maize Grown for Bioenergy," *Bioenergy Resources 5* (2012): 866-975

J. Guzman, *et al*., "Greenhouse Gas Emissions Dynamics as Influenced by Corn Residue Removal in Continuous Corn System," *Soil Science Society of America Journal 79* (2015): 612-625

C. Jones, *et al*., "The Greenhouse Gas Intensity and Potential Biofuel Production Capacity of Maize Stover Harvest in the US Midwest," *Global Change Biology-Bioenergy 9* (2017): 1,543-1,554

S. Kristiansen, *et al*., "Natural ^{13}C Abundance and Carbon Storage in Danish Soils under Continuous Silage Maize," *European Journal of Agronomy 22* (2005): 107-117

R. Lemke, *et al*., "Crop Residue Removal and Fertilizer N: Effects on Soil Organic Carbon in a Long-term Crop Rotation Experiment on a Udic Boroll," *Agriculture, Ecosystems and Environment 135* (2010): 42-51

M. Liebig, *et al*., "Tillage and Cropping Effects on Soil Quality Indicators in the Northern Great Plains," *Soil and Tillage Research 78* (2004): 131-141

C. Liu, *et al*., "Effects of Straw Carbon Input on Carbon Dynamics in Agricultural Soils: a Meta-Analysis," *Global Change Biology 20* (2014): 1,366-1,381

E. Lugato, *et al*., "Potential Carbon Sequestration of European Arable Soils Estimated by Modelling a Comprehensive Set of Management Practices," *Global Change Biology 20* (2015): 3,357-3,567

C. Poeplau, *et al*., "Qualitative and Quantitative Response of Soil Organic Carbon to 40 Years of Crop Residue Incorporation under Contrasting Nitrogen Fertilization Regimes," *Soil Research 55* (2017): 1-9

Z. Qin, *et al*., "Land Management Change Greatly Impacts Biofuels' Greenhouse Gas Emissions," *Global Change Biology-Bioenergy 10* (2018): 370-381

M. Schmer, *et al*., "Tillage and Residue Management Effects on Soil Carbon and Nitrogen under Irrigated Continuous Corn," *Soil Science Society of America Journal 78* (2014): 1,987-1,996

P. Smith, *et al*., "Carbon Sequestration Potential in European Croplands Has Been Overestimated," *Global Change Biology 11* (2005): 2,153-2,163

W. Smith, *et al*., "Crop Residue Removal Effects on Soil Carbon: Measured and Intermodel Comparisons," *Agriculture, Ecosystems and Environment 161* (2012): 27-38

C. Stewart, *et al*., "Nitrogen and Harvest Effects on Soil Properties under Rainfed Switchgrass and No-till Corn over 9 Years: Implications for Soil Quality," *Global Change Biology-Bioenergy 7* (2015): 288-301

M. Villamil and E. Nafiger, "Corn Residue and Nitrogen Rate Effects on Soil Carbon and Nutrient Stocks in Illinois," *Geoderma 253/254* (2015): 61-66

B. Wienhold, *et al*., "CQESTR Simulated Change in Soil Organic Carbon under Residue Management Practices in Continuous Corn Systems," *Bioenergy Research 9* (2016): 23-30

Biochar: Crop residue removal-N_2O

D. Abalos, *et al*., "Role of Maize Stover Incorporation on Nitrogen Oxide Emissions in a Non-Irrigated Mediterranean Barley Field," *Plant and Soil 364* (2013): 357-371

E. Campbell, *et al*., "Assessing the Soil Carbon, Biomass Production, and Nitrous Oxide Emission Impact of Corn Stover Management for Bioenergy Feedstock Production Using DAYCENT," *Bioenergy Research 7* (2014): 491-502

K. Congreves, *et al*., "Differences in Field-Scale N_2O Flux Linked to Crop Residue Removal under Two Tillage Systems in Cold Climates," *Global Change Biology-Bioenergy 9* (2017): 666-680

L. Dendooven, *et al*., "Global Warming Potential of Agricultural Systems with Contrasting Tillage and Residue Management in the Central Highlands of Mexico," *Agriculture, Ecosystems and Environment 152* (2012): 50-58

J. Guzman, *et al*., "Greenhouse Gas Emissions Dynamics as Influenced by Corn Residue Removal in Continuous Corn System" *Soil Science Society of America Journal 79* (2015): 612-625

V. Jin, *et al*., "Soil Greenhouse Gas Emissions in Response to Corn Stover Removal and Tillage Management across the US Corn Belt," *Bioenergy Research 7* (2014): 517-527

V. Jin, *et al*., "Long-Term No-Till and Stover Retention Each Decrease the Global Warming Potential of Irrigated Continuous Corn," *Global Change Biology 23* (2017): 2,848-2,862

T. Lehtinen, *et al*., "Effect of Crop Residue Incorporation on Soil Organic Carbon and Greenhouse Gas Emissions in European Agricultural Soils," *Soil Use and Management 30* (2014): 524-538

H. Li, *et al*., "Estimates of N_2O Emissions and Mitigation Potential from a Spring Maize Field Based on DNDC Model," *Journal of Integrative Agriculture 11* (2012): 2,067-2,078

C. Liu, *et al*., "Effects of Straw Carbon Input on Carbon Dynamics in Agricultural Soils: a Meta-Analysis," *Global Change Biology 20* (2014): 1,366-1,381

S. Mahli and R. Lemke, "Tillage, Crop Residue and N Fertilizer Effects on Crop Yields, Nutrient Uptake, Soil Quality and Nitrous Oxide Gas Emissions in a Second 4-yr Rotation Cycle," *Soil and Tillage Research 96* (2007): 269-283

J. Mutegi, *et al*., "Nitrous Oxide Emissions and Controls as Influenced by Tillage and Crop Residue Management Strategy," *Soil Biology and Biochemistry 42* (2010): 1701-1711

M. Wang, *et al*., "A Global Perspective on Agroecosystem Nitrogen Cycles after Returning Crop Residue," *Agriculture, Ecosystems and Environment 266* (2018): 49-54