Pathways for Agricultural Decarbonization in the United States

Brittany Staie,[1] Austin Kinzer,[2] Jordan Macknick,[1] Yong Wang,[1] Randy Cortright,[1] Thomas Foust,[1] Sami Ghantous,[1] Patrick Lamers,[1] and Darlene Steward[1]

1 National Renewable Energy Laboratory
2 American Farmland Trust

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5100-86071
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Suggested Citation
Staie, Brittany, Austin Kinzer, Jordan Macknick, Yong Wang, Randy Cortright, Thomas Foust, Sami Ghantous, Patrick Lamers, and Darlene Steward. 2024. *Pathways for Agricultural Decarbonization in the United States*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5100-86071. https://www.nrel.gov/docs/fy24osti/86071.pdf.

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National Renewable Energy Laboratory
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Golden, CO 80401
303-275-3000 • www.nrel.gov

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This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by NREL Planning and Assessment Funds and the Joint Institute for Strategic Energy Analysis Agricultural Decarbonization Catalyzer. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

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Acknowledgments

The authors wish to thank James McCall (NREL), Alicen Kandt (NREL), Carishma Gokhale-Welsh (NREL), Thomas Hickey (NREL), Caitlin Murphy (NREL), Jill Engel-Cox (NREL), Elizabeth Doris (NREL), Anelia Milbrandt (NREL), Dan Bilello (NREL), Zia Abdullah (NREL), Sherry Stout (NREL), Mark Ruth (NREL), Gian Porro (NREL), David Glickson (NREL), Jared Creason (United States Environmental Protection Agency), Chris Cassidy (United States Department of Agriculture), Eugene Kelly (Colorado State University), Steve Conrad (Colorado State University), Nathan L'Etoile (American Farmland Trust), Ethan Winter (American Farmland Trust), Bonnie McGill (American Farmland Trust), and Rachel Seman-Varner (American Farmland Trust) for their insightful comments and reviews. They also wish to thank NREL team members Alfred Hicks, Besiki Kazaishvili, Mike Meshek, Emily Horvath, and Thomas Hickey for their valuable contributions.

List of Abbreviations and Acronyms

3NOP	3-nitroxypropanol
CH_4	methane
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
GHG	greenhouse gas
GIS	geographic information system
INM	integrated nutrient management
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
K	potassium
MMT	million metric tons
N	nitrogen
N_2O	nitrous oxide
NI	nitrification inhibitor
P	phosphorous
PM	particulate matter
PRP	pastures, ranges, and paddocks
SDG	sustainable development goal
SOC	soil organic carbon
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

Executive Summary

In the United States, agricultural production is both a significant source of greenhouse gas (GHG) emissions (Environmental Protection Agency [EPA] 2023) and expected to be widely susceptible to climate change impacts (Vermeulen, Campbell, and Ingram 2012). Decarbonization solutions have been proposed for addressing agricultural GHG emissions; however, analysis to synthesize available literature on mitigation opportunities and quantify mitigation potential in the United States has been limited. Recent emphasis in literature has focused on agricultural decarbonization solutions for their potential to be some of the most cost-effective strategies for GHG mitigation across all sectors (IPCC 2022).

For this report, we focus on agricultural production GHG emissions (i.e., we do not include pre- or postproduction GHG emissions) and agricultural production solutions; we do not include social, policy, demand-side (e.g., transition to plant-based diets), or transformational (e.g., a sectorwide transition to cellular agriculture) solutions. Figure ES-1 illustrates the scope of our study as well as GHG sources in the broader food supply chain and mitigation solutions in the social, policy, and transformational fields.

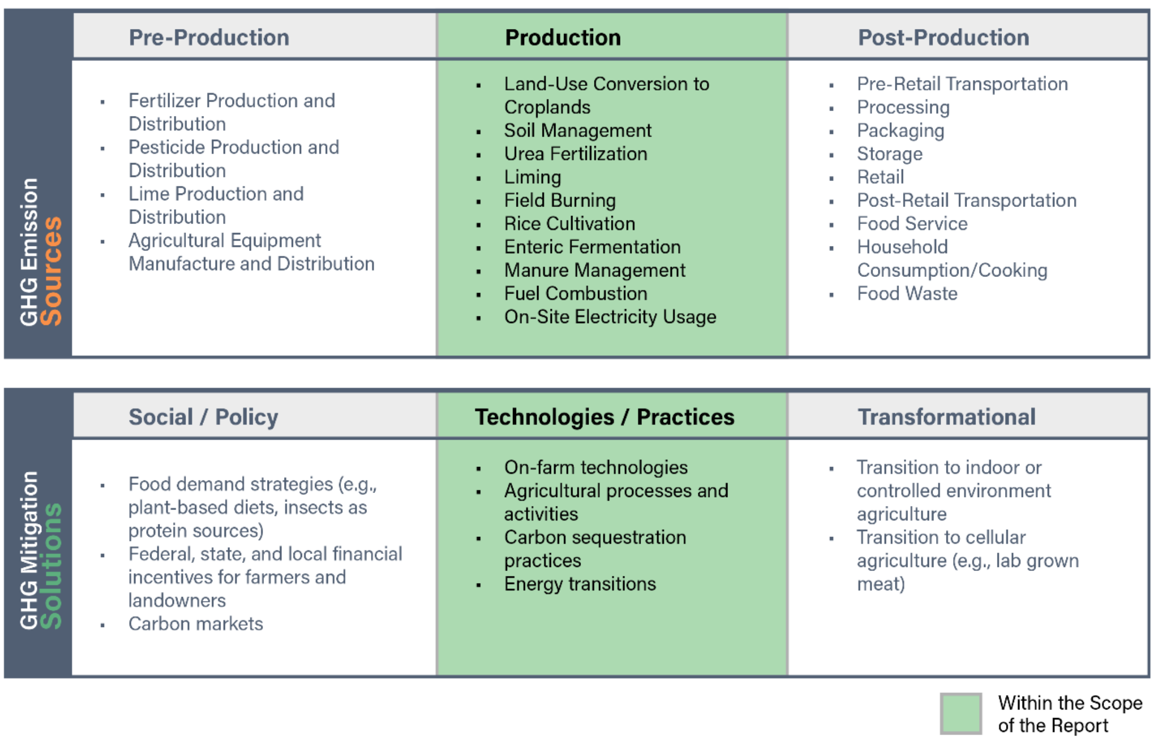

Figure ES-1. Study scope

The items listed in the center green boxes are included in the scope of this study. The items listed in the boxes on the left and right sides of the figures are outside the scope of the study.

This report builds on the Environmental Protection Agency's (EPA) (2023) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021* report to provide an initial analysis of available data on GHG mitigation solutions and establish a foundation for future agricultural decarbonization research. In this report, we assess the state of research literature on U.S. agricultural GHG emissions by activity and GHG source type and then quantify potential GHG emission mitigation for different technologies and agricultural practices based on a comprehensive review of available data. We also discuss additional agricultural-based carbon sequestration options for their key role in agricultural decarbonization. One challenge is that each GHG emission mitigation solution estimate is taken from separate studies that often use different methodologies. These estimates are used as a starting point; accompanying literature is referenced to show uncertainties and variance in current mitigation estimate potentials.

In the United States, agricultural production accounts for 12% of total annual GHG emissions, or 730 MMT CO_2e/yr (EPA 2023). Of these GHG emissions, 43% are nitrous oxide (N_2O), 38% are methane (CH_4), and 19% carbon dioxide (CO_2) emissions, distinguishing it from the predominantly CO_2-emitting fossil fuel sector (Lynch et al. 2021). In descending order of GHG emission magnitude, agricultural production includes GHG emissions from the following sources (Figure ES-1):

- Soil management (40%; 294 MMT CO_2e/yr of GHG)
- Enteric fermentation (27%; 195 MMT CO_2e/yr of GHG)
- Manure management (11%; 83 MMT CO_2e/yr of GHG)
- Land use conversion to croplands (8%; 59 MMT CO_2e/yr of GHG)
- Fossil fuel combustion (5%; 38 MMT CO_2e/yr of GHG)
- On-site electricity usage (5%; 36 MMT CO_2e/yr of GHG)
- Rice cultivation (2%; 17 MMT CO_2e/yr of GHG)
- Urea fertilization (0.7%; 5 MMT CO_2e/yr of GHG)
- Liming (0.4%; 3 MMT CO_2e/yr of GHG)
- Field burning (0.1%; 0.7 MMT CO_2e/yr of GHG)

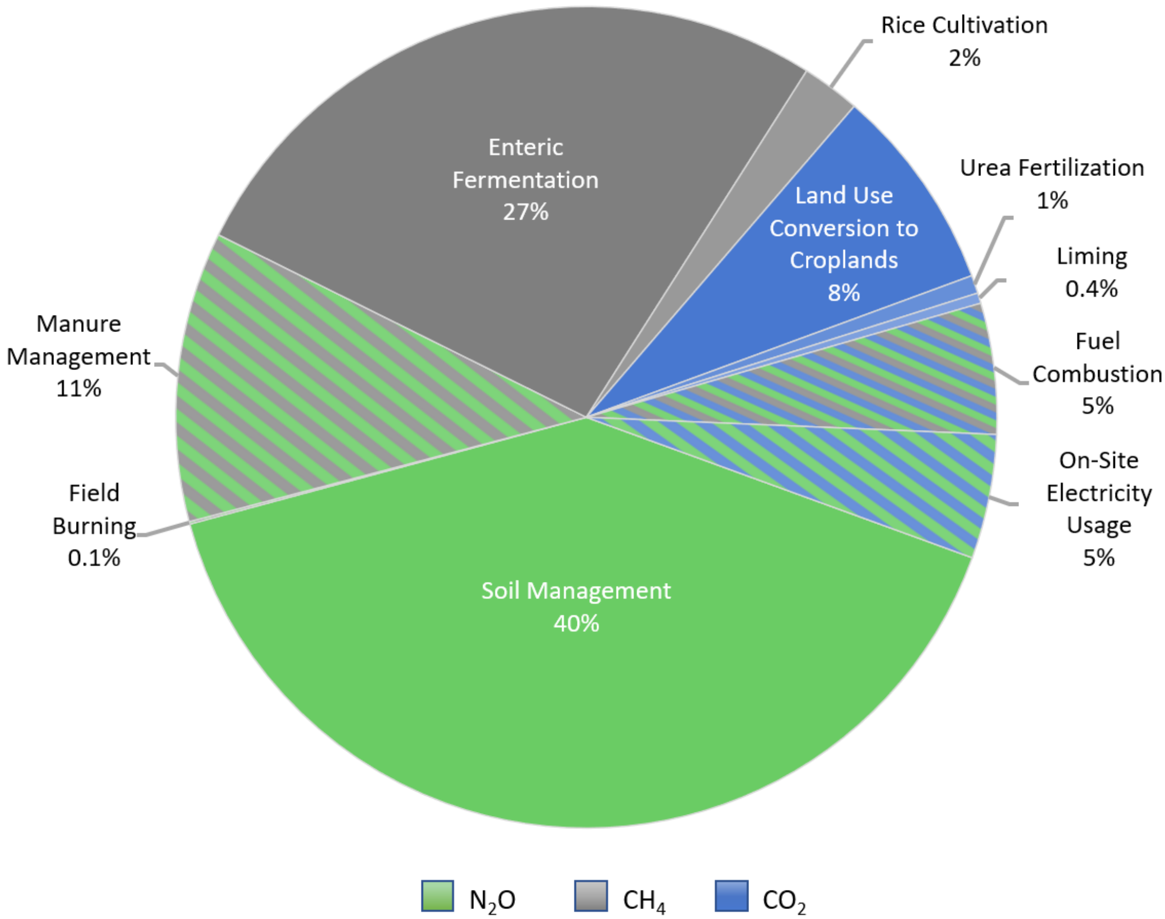

Figure ES-2. Agricultural production GHG sources in the United States (CO_2e)

Data from EPA (2023). Green/gray striping for manure management and field burning signifies that they are a combination of N_2O and CH_4. Green/gray/blue striping for fuel combustion signifies a combination of N_2O, CH_4, and CO_2. Green/blue striping for on-site electricity use signifies a combination of N_2O and CO_2.

Figure ES-3 illustrates our findings for potential agricultural GHG mitigation solutions in the United States based on available research literature. Our review found the following options to offer significant mitigation potential in the U.S. agricultural sector (i.e., each is equivalent to at least 10% of annual U.S. agricultural emissions or 73 MMT CO_2e/yr):

- Agroforestry (52%; 381 MMT CO_2e/yr of GHG mitigation)
- Biochar application (29%; 211 MMT CO_2e/yr of GHG mitigation)
- No-till systems (19%, 137 MMT CO_2e/yr of GHG mitigation)
- Cover crops (14%; 103 MMT CO_2e/yr of GHG mitigation)
- Grazing strategies (12%; 91 MMT CO_2e/yr of GHG mitigation)
- Feed additives for livestock (12%; 88 MMT CO_2e/yr of GHG mitigation)
- Renewable energy production (including installation of anaerobic digestors) (11%; 79 MMT CO_2e/yr of GHG mitigation)

Further, our review uncovered five crosscutting solutions that offer GHG mitigation or carbon sequestration potential for three or more GHG categories (Table ES-1, page x):

- Energy efficiency and renewable energy production
- Integrated nutrient management
- No-till systems
- Precision agriculture
- Biochar application

We found GHG emissions from soil management (e.g., N_2O from denitrification in agricultural soils) and enteric fermentation (CH_4 from digestive processes in ruminant animals) to be significant agricultural GHG contributors, but there was a lack of mitigation solutions that could substantially reduce emissions; these sources are difficult to mitigate fully due to being natural process-based (EPA 2023). Use of existing technologies, such as enhanced efficiency fertilizers and precision agriculture for soil management and feed additives for enteric fermentation, can mitigate some but not all of these hard-to-abate emissions. Further research is warranted in this area to uncover new technologies and methods for abating N_2O emissions from soil management and CH_4 emissions from enteric fermentation.

Substantial agricultural decarbonization will likely require carbon sequestration in agricultural soils using practices such as agroforestry, biochar application, and no-till. Significant carbon sequestration potential exists across the land sector through enhancing aboveground and belowground carbon sinks via management strategies of existing agricultural land. Our literature review indicates the potential to offset more GHG emissions through these practices than is currently emitted for the agricultural sector as a whole. However, current carbon sequestration potential estimates are rather uncertain because of variability in soils, climates, agricultural practices, soil organic carbon (SOC) saturation rates, SOC permanence, interaction among other sequestration activities, and lack of extensive empirical data. Future empirical research is warranted to address research gaps in different climates, soils, and agricultural systems and to increase confidence in the estimated GHG mitigation potentials.

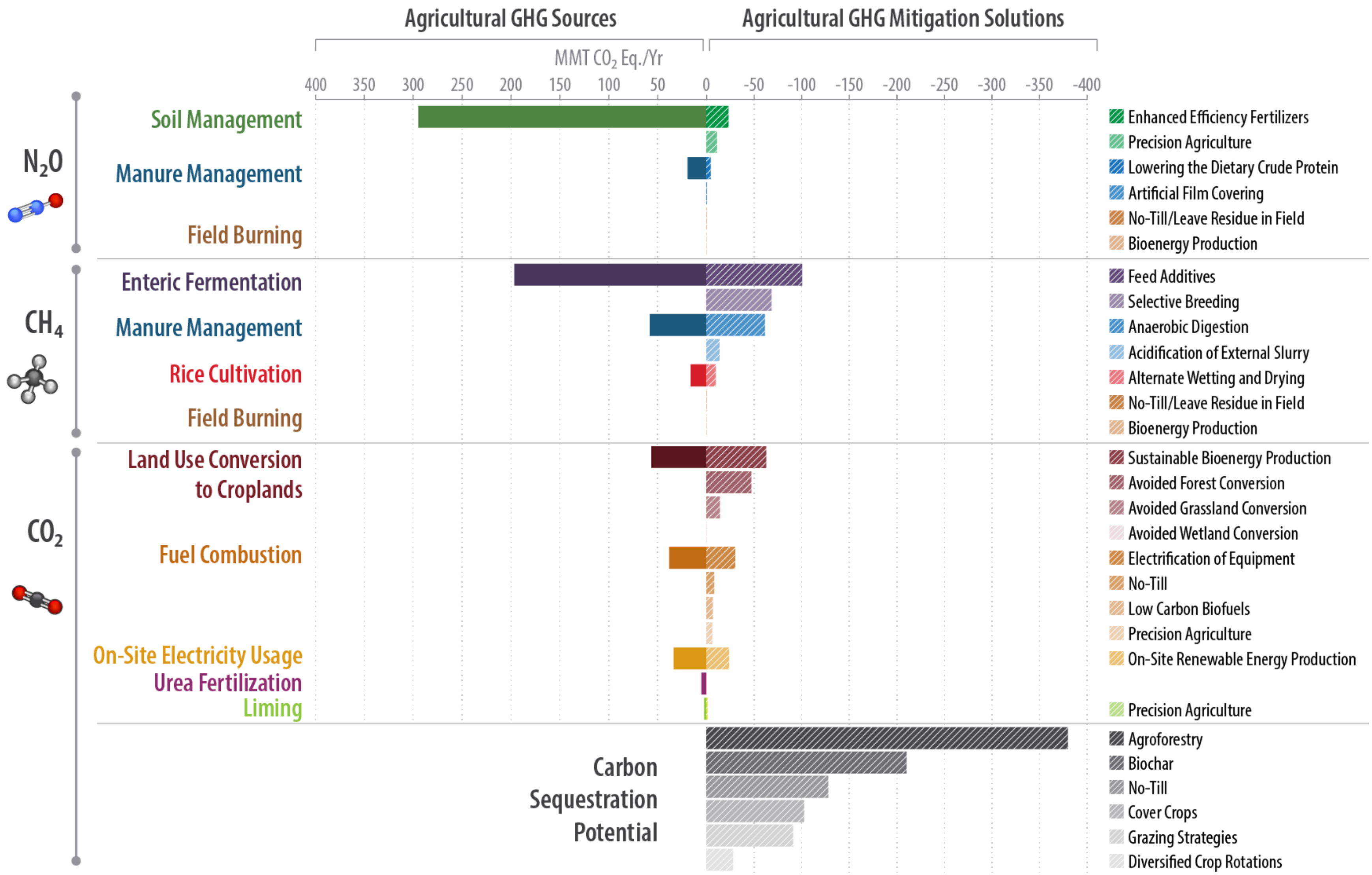

Figure ES-3. Estimated agricultural GHG emissions and mitigation potential by source in the United States (CO_2e)

Table ES-1. Crosscutting Solutions for Agricultural Decarbonization

	Energy Efficiency and Renewable Energy Production	Precision Agriculture	No-Till	Integrated Nutrient Management	Biochar
Fuel Combustion	X	X	X		
On-Site Electricity Use	X				
Manure Management	X				
Soil Management		X	X	X	X
Urea Fertilization		X		X	
Liming		X			X
Rice Cultivation			X		
Field Burning			X		
Soil Carbon Sequestration Potential			X	X	X

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Introduction

Agriculture is a source of three major greenhouse gases (GHGs): nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2) (Environmental Protection Agency [EPA] 2023). N_2O and CH_4, which comprise the largest proportion of agricultural GHGs, have 265 and 28 times the global warming potential of CO_2, respectively, over a 100-year time horizon. This high rate of non-CO_2 GHG emissions distinguishes agriculture from the mainly CO_2-emitting fossil fuel sector in its climate change contribution (Lynch et al. 2021). Although considerable attention has been given to reducing or eliminating fossil fuel combustion, relatively less emphasis has been placed on assessing agricultural GHG mitigation strategies.

Globally, the agricultural supply chain is estimated to contribute one-third of total anthropogenic GHG emissions (Tubiello et al. 2021). Agricultural production sources (e.g., soil management, manure management, and land use change) make up 65% of these GHGs, with 44% coming from within the farm gate and 21% from land use change (Tubiello et al. 2022). The remaining 35% comes from preproduction (e.g., fertilizer manufacturing) and postproduction agricultural processes (e.g., food processing, packaging, transportation). From 2000 to 2018, global agricultural emissions increased within the farm gate by 14% and decreased for land use change by 21%, mainly because of a reduction in deforestation (Food and Agriculture Organization (FAO) 2021). During the same timeframe, GHG emissions for all preproduction and postproduction processes increased, with retail activities contributing the highest increase (Tubiello et al. 2022).

Comparing global agricultural supply chain GHG emissions by country, the top five emitting countries per year in descending order are China, India, Brazil, Indonesia, and the United States (Tubiello et al. 2022). However, the breakdown of emissions by source or activity (e.g., production GHG emissions versus land use change GHG emissions) vary greatly within the agricultural supply chain for different countries. For crop and livestock production, the top five emitting countries in descending order are India, China, Brazil, the United States, and Indonesia. The top five emitting countries for land use change are Indonesia, Brazil, the Democratic Republic of the Congo, Canada, and Myanmar (FAO 2021).

To address agricultural GHG emissions, mitigation strategies and carbon sequestration opportunities have been proposed (Eagle et al. 2022; Fargione et al. 2018; Moore et al. 2023; Roe et al. ; Rosa and Gabrielli 2023). The Intergovernmental Panel on Climate Change (IPCC) (2022) recently reported "agriculture, forestry, and other land use" GHG mitigation solutions to be some of the most important and impactful options available. The IPCC also reports these solutions to be near-term and low-cost but that they should not be used to delay decarbonization of other sectors (e.g., fossil fuels). Average abatement costs for agricultural GHG mitigation are estimated to be \$0–\$100 USD per ton CO_2e, with natural land conversion avoidance and carbon sequestration in croplands showing the highest potential to reduce GHG emissions by 2030 (IPCC 2022).

Across developed countries, the United States shows the greatest potential for cost-effective GHG mitigation in the agricultural sector (Roe et al. 2021). The goal of this report is to assess available literature to identify agricultural GHG sources by magnitude in the United States, quantify technical GHG mitigation or carbon sequestration potentials of proposed solutions, and put those solutions into the context of the current state of research and necessary next steps. To this end, we (i) performed a literature review to uncover estimates and uncertainties associated with current GHG sources and potential mitigation solutions in the U.S. agricultural sector and (ii) conducted data analysis to quantify the mitigation potential of proposed solutions, uncover research gaps, and identify future research opportunities.

Methods

We reviewed more than 300 publications to understand current pathways for agricultural decarbonization in the United States and current research gaps. We used Google Scholar searches for all GHG sources (e.g., manure management), mitigation solutions (e.g., anaerobic digestion), and carbon sequestration potentials in U.S. agricultural lands to obtain relevant peer-reviewed journal articles and academic reports. Recently published U.S. government reports by the U.S. Department of Agriculture (USDA), the U.S. Environmental Protection Agency (EPA), and the U.S. Energy Information Administration (EIA) were also referenced. After we identified potential mitigation solutions for each agricultural GHG source as well as carbon sequestration potentials, we performed an initial quantitative analysis to estimate GHG mitigation potentials. Each solution estimate is taken from separate studies that often use different methodologies; we did not harmonize assumptions or boundary conditions across literature estimates other than through unit conversions. These estimates are used as a starting point; accompanying literature is referenced to show uncertainties and variance in current mitigation estimate potentials.

We define agricultural production categories based on EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021* (2023), with relevant agricultural GHG sources in the agriculture, energy, and land use; land use change; and forestry sections. The scope of the study is limited to agricultural GHG emissions and mitigation opportunities within the United States. Based on the EPA inventory, we classify agricultural GHG emissions to be those from agricultural production activities within the farm gate, including the cropland, livestock production, and energy-related activities shown in Figure 1.

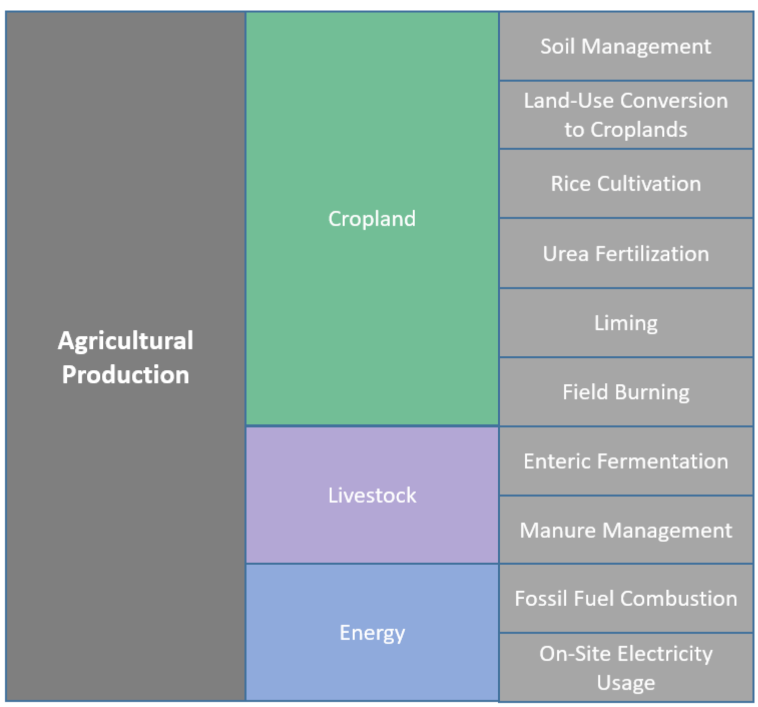

Figure 1. Scope of agricultural production for this study

Figure 2 illustrates GHG sources for the broader agricultural supply chain, including preproduction and postproduction activities, and GHG mitigation solutions options, including social, policy, and transformational strategies. For this study, we focus on production activities for their high GHG emission rates and their high potential for GHG mitigation through land-based solutions. GHG mitigation solutions listed in this study are technology-based to facilitate understanding of technologies and practices that can be used to mitigate GHG emissions for agricultural production activities. Though policy, social, consumer dietary preferences and demand (e.g., transition to plant-based diets), and transformational (e.g., a sectorwide transition to lab-grown food) solutions could offer significant GHG mitigation (Popp, Lotze-Campen, and Bodirsky 2010), they are out of scope for this study.

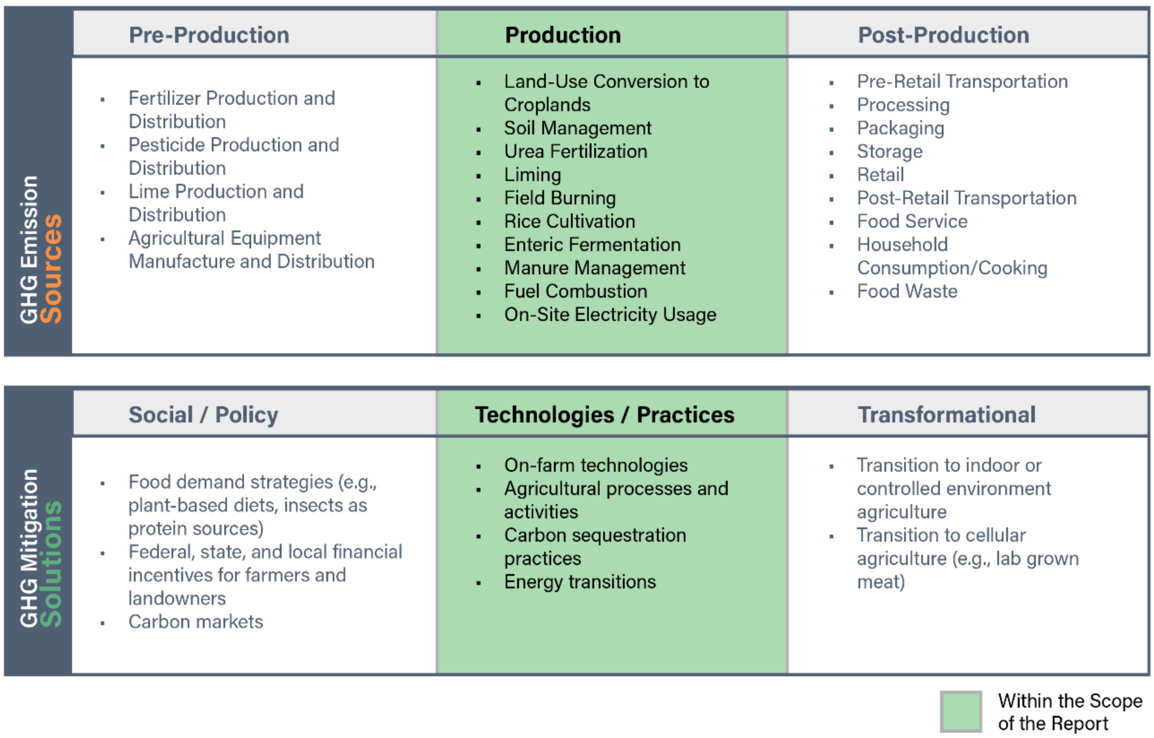

Figure 2. Study scope

The items listed in the center green boxes are included in the scope of this study. The items listed in the boxes on the left and right sides of the figures are outside the scope of the study. Production categories are adapted from EPA (2023).

GHG Emission Estimates

GHG emission rates for agricultural production activities used in this study are based on calculations from EPA's 2023 report, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021* (EPA 2023). For all emission estimates, EPA uses the internationally accepted estimation methods recommended by IPCC in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006). Emission rates for all GHGs are listed in MMT CO_2e. The global warming potentials used in this study for CH_4 and N_2O are 28 and 265, respectively, over a 100-year time horizon (EPA 2023; IPCC 2006). Total agricultural supply chain GHG emissions for the United States were estimated using a recent analysis by Tubiello et al. (2022)

and data from EPA (2023). GHG emissions for all categories of the agricultural supply chain were estimated from recently published analyses by Mohareb et al. (2018) and Heller (2017).

GHG Mitigation Solutions

For the quantitative analysis, we prioritized using meta-analyses from U.S.-based studies or meta-analyses that included partial U.S.-based data. If no such meta-analyses were available, individual field studies or analyses were used. International studies were not used for the quantitative analysis except in the case of selective breeding of cattle for CH_4 mitigation because of its global applicability. International studies were referenced only to show potential for adoption in the United States and to illustrate current research gaps. Mitigation potentials were then compared to current GHG emission rates in the United States to understand the degree of impact for individual solutions. For solutions with only one or a few applicable studies, estimates should be used only as a starting point for future research, and more-extensive U.S.-based studies are warranted to increase confidence.

Detailed methodologies for mitigation potential estimates of each solution can be found in Appendix A.

Agricultural GHG Emissions in the United States

In the United States, the agricultural supply chain (i.e., preproduction, production, and postproduction processes) is estimated to account for 21% of total GHG emissions (Tubiello et al. 2022). Limited studies exist on analyzing the breakdown of agricultural supply chain GHG emissions in the United States, with current studies differing on categorization, definitional boundaries, and allocation of emissions. Mohareb et al. (2018) found on-farm agricultural production to be the highest-emitting category within the agricultural supply chain, contributing 36%. They found the remainder in descending order to consist of waste, retail, household energy used for cooking and storage distribution, food service, processing, packaging, and grocery trips. Heller (2017) found cooking and storage to represent the majority of agricultural supply chain emissions at 31%, with the remainder consisting of agricultural production, processing, pre-retail transportation, packaging, commercial food services, post-retail transportation, and retail in descending order. These two approaches to estimating agricultural supply chain GHG emissions are shown in Figure 3.

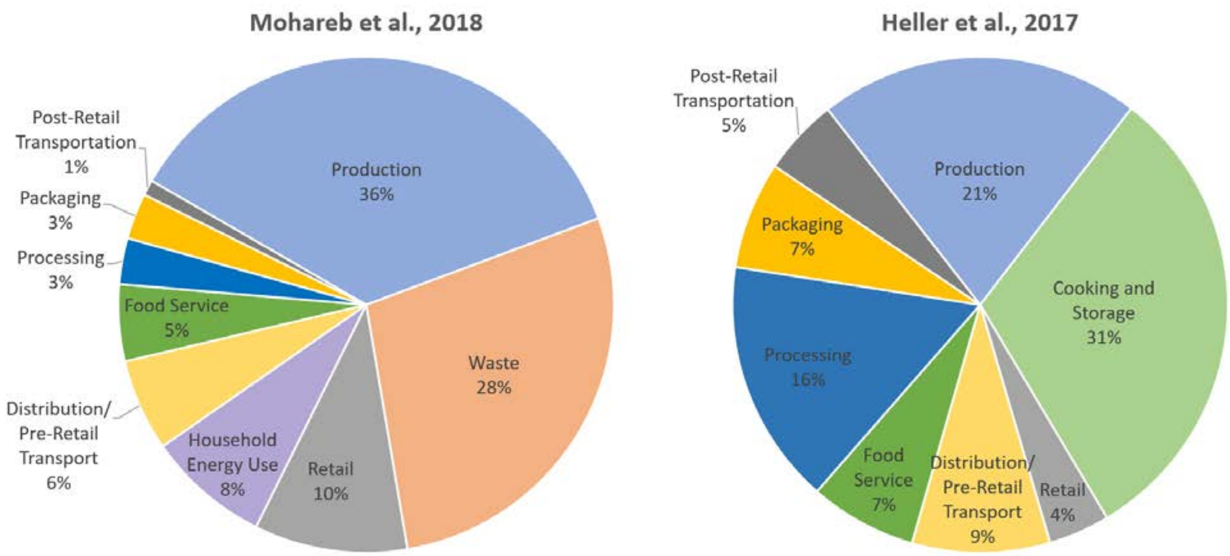

Figure 3. Agricultural supply chain GHG sources in the United States (CO_2e)

Agricultural Production GHG Emissions in the United States

For this study, we focus on agricultural production because it is a top contributor along the agricultural supply chain (Figure 3) and can potentially offer significant GHG mitigation potential opportunities (IPCC 2022). In 2021, agricultural production contributed 730 MMT CO_2e, or 12% of total U.S. GHG emissions (EPA 2023). Agricultural production emissions include N_2O emissions from soil management, manure management, fuel combustion, on-site electricity usage, and field burning; CH_4 emissions from enteric fermentation, manure management, rice cultivation, field burning, and fuel combustion; and CO_2 emissions from land use conversion to croplands, fuel combustion, on-site electricity usage, urea fertilization, and liming (Figure 4). When converted to CO_2e, emissions from agricultural production consist of 43% N_2O, 38% CH_4, and 19% CO_2 (Figure 5).

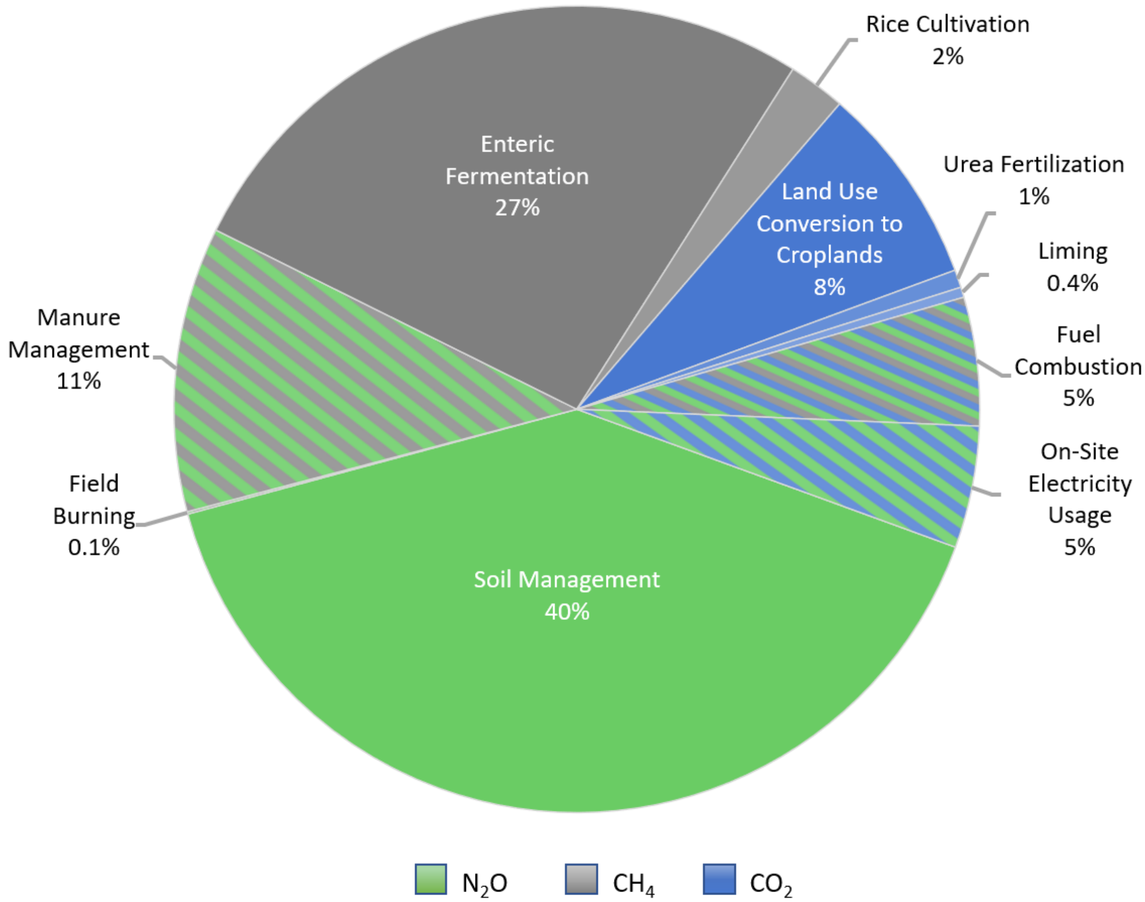

Figure 4. Agricultural production GHG sources in the United States in 2021 (CO_2e)

Data from EPA (2023). Green/gray striping for manure management and field burning signifies that they are a combination of N_2O and CH_4. Green/gray/blue striping for fuel combustion signifies a combination of N_2O, CH_4, and CO_2. Green/blue striping for on-site electricity use signifies a combination of N_2O and CO_2. All data are reported in CO_2e.

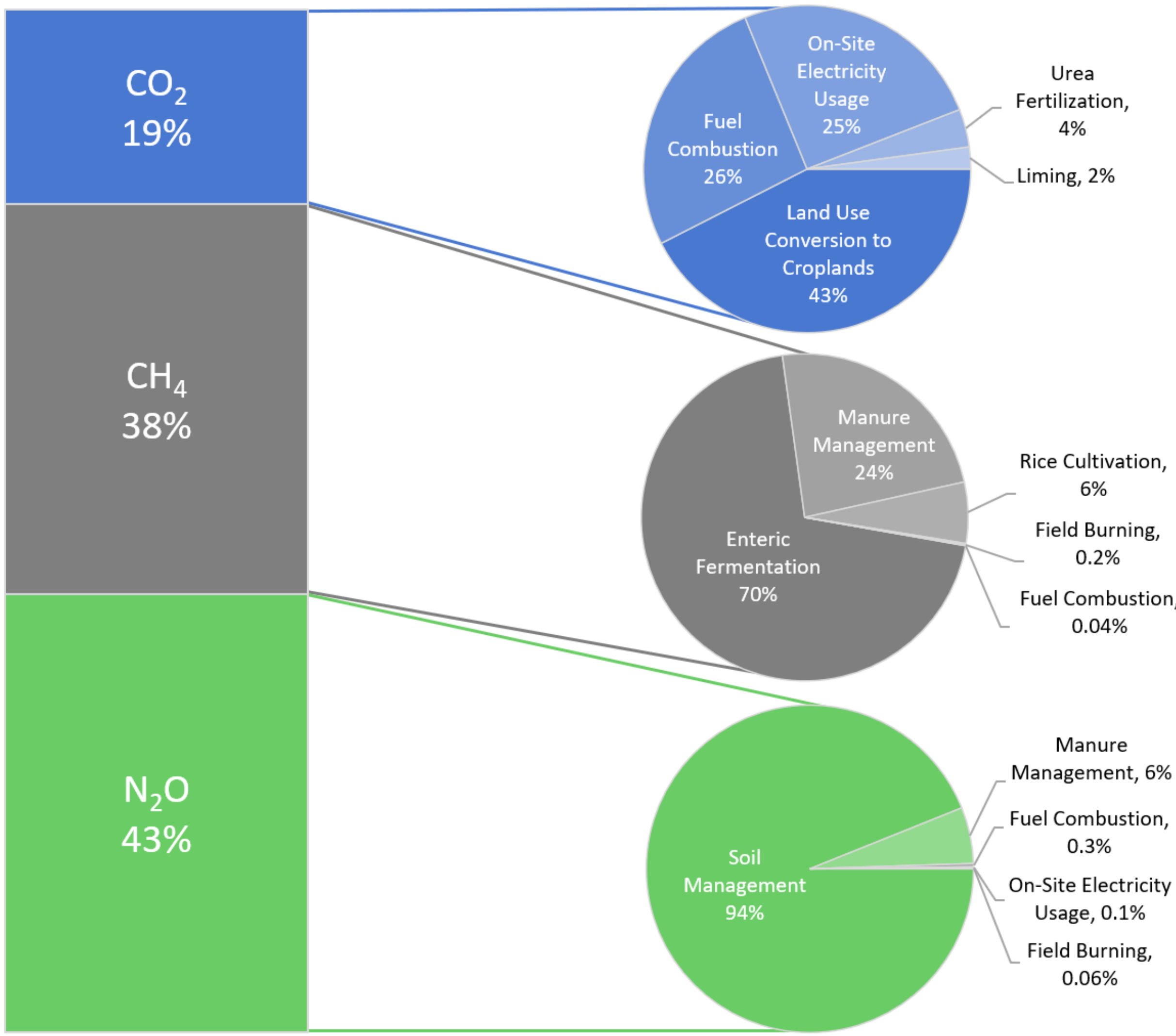

Figure 5. Agricultural production GHG sources by gas in the United States in 2021 (CO_2e)

Data from EPA (2023). All data are reported in CO_2e.

From 1990 to 2021, total agricultural production GHG emissions increased 7% (EPA 2023). During this same period, GHG emissions from croplands and livestock production in the United States increased 3% and 19%, respectively, while energy-related GHG emissions decreased 8%. Agricultural production GHG emissions are projected to grow from increased fertilizer consumption and crop and livestock production, mostly because of increased demand for animal products (USDA 2021). GHG emissions from livestock production and rice cultivation in the United States are expected to increase by the largest margins by 2030 (EPA n.d.). Regionally, the highest agricultural production GHG emissions are expected in Texas, followed by Iowa, California, Kansas, and Nebraska (USDA 2021).

Heavy Emitters

The three largest GHG emitter categories in terms of CO_2e are soil management, enteric fermentation, and manure management, which make up 40%, 27%, and 11% of agricultural production GHG emissions, respectively (Figure 4). Combined, they account for 79% of total agricultural production emissions in the United States or 17%–28% of total agricultural supply chain GHG emissions (Figure 3 and Figure 4). In 2021, agricultural soil management contributed 75% of total U.S. N_2O emissions (EPA 2023). Combined, enteric fermentation and manure management contributed 27% and 9% of total CH_4 and N_2O emissions, respectively. In 2021, enteric fermentation was the largest source of CH_4 emissions in the United States. From 1990 to 2021, soil management emissions increased 2%, enteric fermentation emissions increased 6%, and manure management emissions increased 62%.

Moderate Emitters

Moderate emitters in the U.S. agricultural sector include land use conversion to croplands (8%), fossil fuel combustion (5%), and on-site electricity usage (5%) (Figure 4). Combined, they account for 18% of agricultural production GHG emissions, or 4%–6% of total agricultural supply chain GHG emissions (Figure 3 and Figure 4). From 1990 to 2021, land use conversion to croplands GHG emissions increased 4%, fossil fuel combustion GHG emissions decreased 16%, and on-site electricity use GHG emissions increased 1% (EPA 2023).

Minor Emitters

Minor GHG emitters in the U.S. agricultural sector include rice cultivation (2%), urea fertilization (1%), liming (0.4%), and field burning (0.1%) (Figure 4). From 1990 to 2021, rice cultivation GHG emissions decreased 6%, urea fertilization GHG emissions increased 117%, liming GHG emissions decreased 36%, and field burning GHG emissions increased 40% (but only from 0.5% to 0.7%) (EPA 2023). Though these categories are minor contributors, current technologies and systems—some of which address GHG emissions in other categories—could be implemented to reduce annual GHGs.

Cropland, Livestock, and Energy Use

Agricultural production GHG emissions can be categorized by cropland, livestock, and energy use. Cropland-related GHG emissions make up 52% of total agricultural production GHG emissions in the United States, and livestock and energy make up 38% and 10%, respectively (Figure 6). Note that crop production for livestock consumption is included in cropland emissions. Cropland production activities emit all three GHGs (N_2O, CO_2, and CH_4), livestock production activities emit CH_4 and N_2O, and energy use primarily emits CO_2 but also small amounts of N_2O and CH_4.

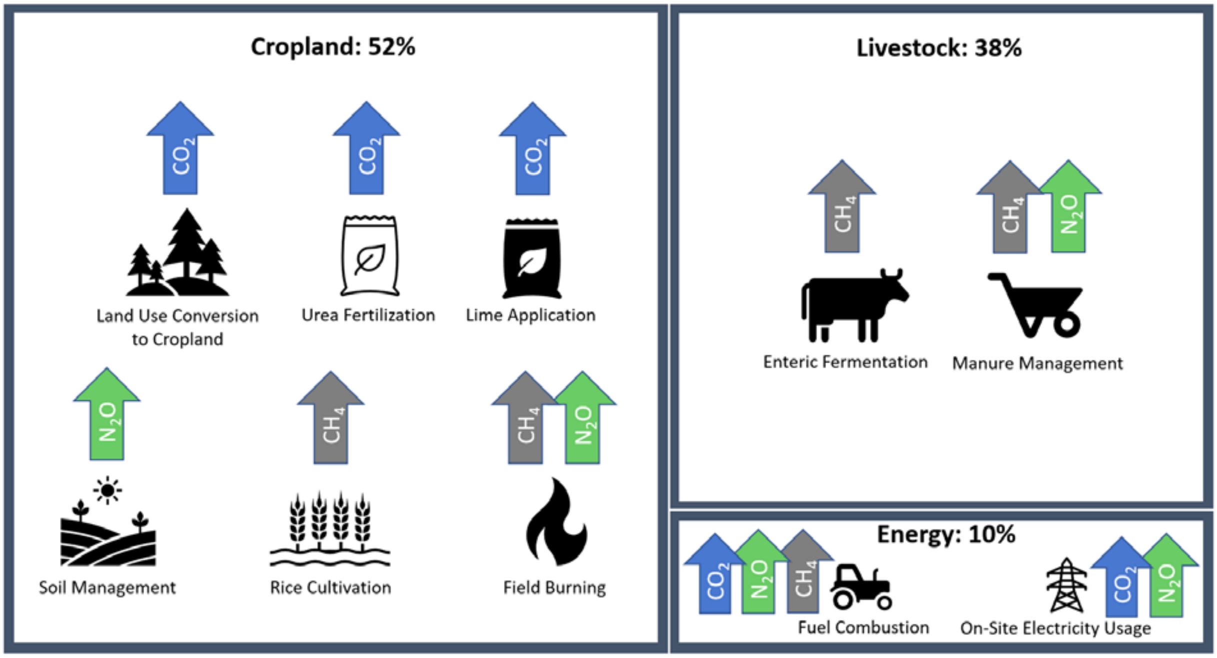

Figure 6. Agricultural production GHG sources by category in the United States in 2021

Data from EPA (2023). All data are reported in CO_2e.

Agricultural Decarbonization Pathways in the United States

In this section, we evaluate and compare available data on 1) GHG emission estimates across agricultural production systems in the United States, 2) potential technologies, agricultural practices, and systems that can be implemented to reduce emission rates, 3) potential barriers to adopting these technologies, and 4) research gaps in the literature. First, we show a quantitative summary of GHG mitigation solutions relevant to agricultural production. We next consider crosscutting solutions, given their potential to mitigate total emissions, and then evaluate solutions specific to croplands, livestock, and energy. For each category, we discuss emissions within that source category and summarize potential emission mitigation strategies for those categories.

Summary of Agricultural GHG Mitigation Solutions in the United States

Through a comprehensive literature review, we identified and quantified 23 individual solutions that show potential to mitigate agricultural production GHG emissions in the United States (Figure 7). These mitigation solutions also include practices that provide carbon sequestration in agricultural lands. Figure 7 provides a summary of our findings of available literature on agricultural GHG sources and potential mitigation solutions in the United States.

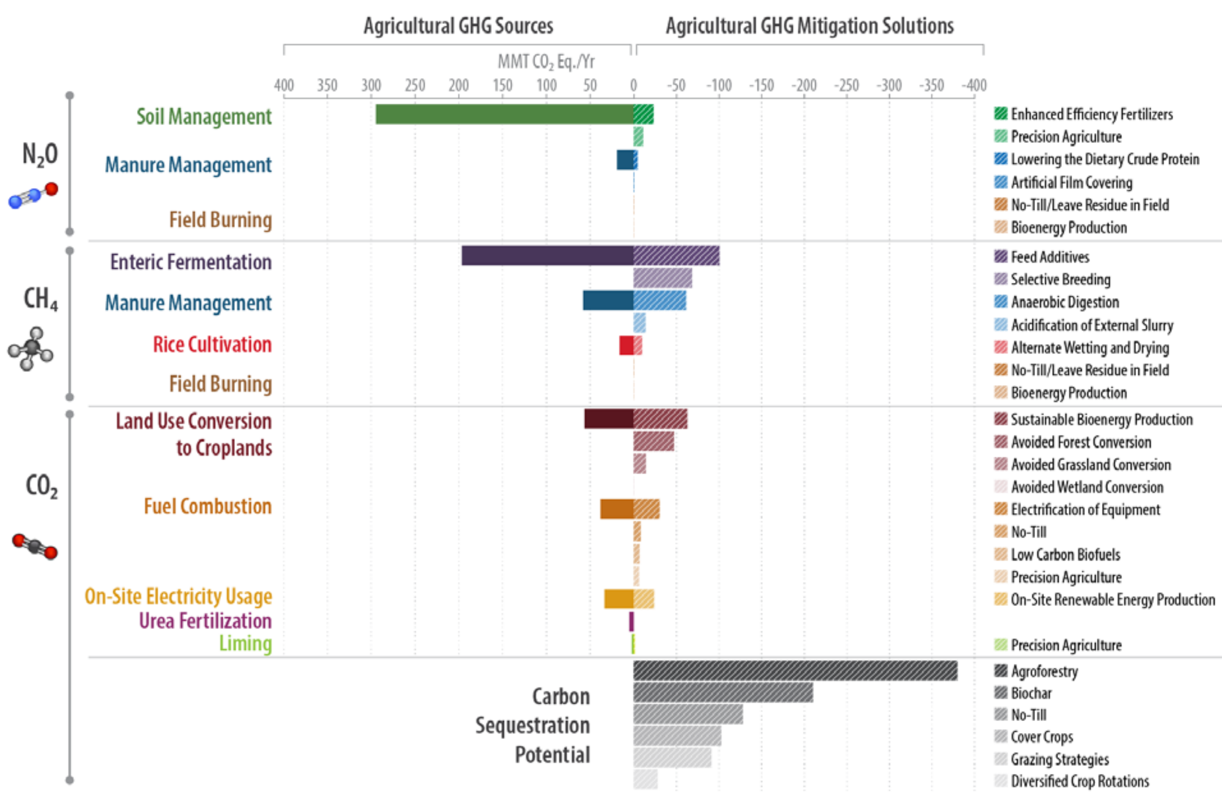

Figure 7. Estimated agricultural GHG emissions and mitigation potential by source in the United States (CO_2e)

All data are reported in CO_2e. Agricultural GHG sources are annual estimates from 2021 based on data from EPA (2023). Agricultural GHG mitigation solution estimates represent the average as reported in the literature.

We found the following solutions to offer significant mitigation potential in the U.S. agricultural sector (i.e., each is equivalent to at least 10% of annual U.S. agricultural emissions or 73 MMT CO_2eyr) (Figure 7):

- Agroforestry (381 MMT CO_2e/yr)
- Biochar application (211 MMT CO_2e/yr)
- No-till systems (137 MMT CO_2e/yr)
- Cover crops (103 MMT CO_2e/yr)
- Grazing strategies (91 MMT CO_2e/yr)
- Feed additives for livestock (89 MMT CO_2e/yr)
- Renewable energy production (including installation of anaerobic digestors) (79 MMT CO_2e/yr)

Carbon sequestration in agricultural lands was found to offer the greatest potential for agricultural GHG mitigation in the United States (943 MMT CO_2e/yr or 131% of total agricultural GHG emissions) (Figure 7). Though soil management and enteric fermentation generate the highest agricultural GHG emissions in the United States, current solutions show limited potential to offer full mitigation. For soil management, enhanced efficiency fertilizers show the highest mitigation potential (23 MMT CO_2e/yr or 7% of soil management GHG emissions), and for enteric fermentation, feed additives show the highest potential (89 MMT CO_2e/yr or 51% of enteric fermentation GHG emissions). The third-highest-emitting GHG category—manure management—shows a promising mitigation solution through adopting anaerobic digestors at large-scale swine and dairy operations (55 MMT CO_2e/yr or 69% of manure management GHG emissions). The moderate emitters—fuel combustion and on-site electricity usage—show the highest impact from electrification of farm equipment (30 MMT CO_2e/yr or 77% of fuel combustion GHG emissions) and renewable energy production (24 MMT CO_2e/yr or 70% of on-site electricity usage). Although minor GHG sources, rice cultivation GHG mitigation is most impactful from adopting alternate wetting and drying and other irrigation strategies (10 MMT CO_2e/yr or 64% rice cultivation GHG emissions) whereas liming shows greatest impact from precision agriculture (0.6 MMT CO_2e/yr or 25% of liming GHG emissions). Urea fertilization mitigation solutions showed quantitative research gaps in the United States.

GHG mitigation estimates and sources for each solution are shown in Table 1.

Table 1. Agricultural GHG Mitigation Potentials for Proposed Solutions in the United States

GHG	GHG Source/ Carbon Sequestration Practice	GHG Mitigation Solution	GHG Mitigation Potential Average (MMT CO_2e/yr)	Min (MMT CO_2e/ yr)	Max (MMT CO_2e/ yr)	Source(s)	n
N_2O	Soil management	Precision agriculture	11.2	7.8	14.6	(EPA 2023; Roe et al. 2021)	3
		Enhanced efficiency fertilizers	22.9	8.8	36.4	(Akiyama et al. 2009; EPA 2023)	36
	Manure management	Lowering dietary crude protein	0.5			(EPA 2023; Hou et al. 2015; Niles and Wiltshire 2019)	3
		Artificial film covering	3.9			(EPA 2023; Hou et al. 2015; Niles and Wiltshire 2019)	4
	Field burning	No-till/leave residues in field	0.2			(EPA 2023)	1
		Bioenergy production	0.2			(EPA 2023)	1
CH_4	Enteric fermentation	Feed additives	100.7	10.3	191.9	(EPA 2023; Honan et al. 2021)	210
		Selective breeding	68.2	48.7	87.7	(EPA 2023; Pickering et al. 2015)	2
	Manure management	Anaerobic digestion	61.6			(EPA 2018a)	1
		Acidification of external slurry	13.2			(EPA 2023; Hou et al. 2015; Niles and Wiltshire 2019)	4
	Rice cultivation	Alternate wetting and drying	10.8	10.4	11.2	(EPA 2023; Runkle et al. 2019)	2
	Field burning	No-till/leave residues in field	0.5			(EPA 2023)	1
		Bioenergy production	0.5			(EPA 2023)	1

GHG	GHG Source/ Carbon Sequestration Practice	GHG Mitigation Solution	GHG Mitigation Potential Average (MMT CO_2e/yr)	Min (MMT CO_2e/ yr)	Max (MMT CO_2e/ yr)	Source(s)	n
CO_2	Land use conversion to croplands	Sustainable bioenergy production	63.0	21.0	105.1	(Lemus and Lal 2005; USDA 2019a)	4
		Avoided forest conversion	48.5			(EPA 2023)	1
		Avoided grassland conversion	9.8			(EPA 2023)	1
		Avoided wetland conversion	0.7			(EPA 2023)	1
	Fuel combustion	Electrification of equipment	30.3	25.4	35.2	(EPA 2023; Northrup et al. 2021)	2
		No-till	8.3			(USDA NRCS 2022)	1
		Low-carbon biofuels	6.7			(EPA n.d.; IEA 2011; EIA 2023b; EIA 2023c; EIA 2023d; Jeswani et al. 2020; USDA NASS 2023)	179
		Precision agriculture/nutrient management	5.7	2.2	9.1	(EPA 2023; Finger et al. 2019)	2
	On-site electricity use	Renewable energy production	24.3	21.0	33.0	(EPA 2023; Shawhan et al. 2022)	2
	Liming	Precision agriculture	0.8			(EPA 2023; Northrup et al. 2021)	2
	Carbon sequestration potential	Grazing strategies	91.4	20.4	194.5	(Conant et al. 2017a; Fargione et al. 2018)	126
		Diversified crop rotation	28.1			(USDA 2019a; T. Wang et al. 2021; T. O. West and Post 2002)	69
		Cover crops	103.0			(Fargione et al. 2018)	30

GHG	GHG Source/ Carbon Sequestration Practice	GHG Mitigation Solution	GHG Mitigation Potential Average (MMT CO_2e/yr)	Min (MMT CO_2e/ yr)	Max (MMT CO_2e/ yr)	Source(s)	n
		Agroforestry	381.3			(Roe et al. 2021)	27
		Biochar	211.1	95.0	327.3	(Fargione et al. 2018; Roe et al. 2021)	5
		No-till	128.5			(Sperow 2016)	6

All data are reported in CO_2e and are for the United States; n = the number of original studies used for reference in the mitigation estimates.

Quantification Research Gaps: GHG Mitigation Solutions

During our literature review, we identified several technologies and agricultural practices that showed potential to mitigate agricultural GHG emissions in international/global studies but did not have any U.S.-based studies that quantified their potential. We therefore categorized these solutions as research gaps in the United States (Table 2). U.S.-based empirical studies would help close these research gaps to understand whether these technologies and/or agricultural practices could be used in a national decarbonization of agriculture effort. Increasing the number of empirical studies in the United States for all other mitigation solutions would also help decrease uncertainties in the estimated mitigation potentials.

Table 2. Research Gaps for Quantifying Agricultural GHG Mitigation Solutions in the United States

GHG	GHG Source/Carbon Sequestration Practice	GHG Mitigation Solution Research Gaps
N_2O	Soil management	Integrated nutrient management, biostimulants, no-till, grazing strategies, improved irrigation strategies, and biochar
	Manure management	Alternative flooring systems for livestock housing
CH_4	Enteric fermentation	Improved feed and forage quality
	Manure management	Composting
	Rice cultivation	Deepwater rice fields, straw management, and low-methane rice varieties
CO_2	Land use conversion to croplands	Sustainable intensification
	On-site electricity use	Energy efficiency and renewable-powered equipment
	Urea fertilization	Integrated nutrient management and precision agriculture
	Liming	Biochar
	Carbon sequestration potential	Intercropping, perennial crops

Crosscutting Solutions

We found that some GHG mitigation solutions showed potential to lower GHG emissions for more than one source and/or provide a carbon sequestration mechanism. These solutions include energy efficiency and renewable energy production, precision agriculture, no-till, integrated nutrient management, and biochar (Table 3). Combined, these five solutions show mitigation potential for 8 of 10 agricultural GHG categories (fuel combustion, on-site electricity usage, manure management, soil management, urea fertilization, liming, rice cultivation, and field burning). In this section, we discuss the GHG mitigation potential of these crosscutting solutions, adoption rates, and barriers to implementation before reviewing solutions for each agricultural GHG source. Detailed information on each of the agricultural GHG source categories are found in the later sections “Cropland Agricultural Greenhouse Gas Emissions and Mitigation Solutions” and “Livestock Production GHG Emissions and Mitigation Solutions.”

Table 3. Crosscutting Solutions for Agricultural Decarbonization

	Energy Efficiency and Renewable Energy Production	Precision Agriculture	No-Till	Integrated Nutrient Management	Biochar
Fuel Combustion	X	X	X		
On-Site Electricity Use	X				
Manure Management	X				
Soil Management		X	X	X	X
Urea Fertilization		X		X	
Liming		X			X
Rice Cultivation			X		
Field Burning			X		
Soil Carbon Sequestration Potential			X	X	X

Energy Efficiency and Renewable Energy Production

Energy efficiency and renewable energy production shows potential to lower emissions from fuel combustion, on-site electricity usage, and manure management. From the supply side, increased adoption of low-carbon electricity generation—including some on agricultural land—could contribute to broader decarbonization. On the demand side, there is substantial room for improvement of energy efficiency on farms to reduce energy consumption (Benedek, Rokicki, and Szeberényi 2023). Finally, there are opportunities to convert agricultural waste products into fuels for use on farms and elsewhere.

Fuel Combustion

Farmers have historically dealt with increased fuel prices by improving engine maintenance and reducing trips over their fields (Beckman, Borchers, and Jones 2013). The average age of a tractor in the United States exceeds 25 years, and the tractor fleet turnover rate is estimated at 1 to 2 percent per year (Bietresato, Calcante, and Mazzetto 2015; Murphy et al. 2010). Given the slow turnover of U.S. farm machinery, fuel efficiency improvements will have a muted effect on near-term emissions. New models of tractors should be expected to continue operating until mid-century, so near-term fuel efficiency improvements would have a lasting effect on long-term emissions. Though fuel efficiency alone cannot eliminate on-farm vehicle emissions, it can reduce emissions from farm machinery before technologies for full electrification are commercialized. Research gaps exist in the United States to quantify potential GHG mitigation from adopting fuel efficient tractors and farm machinery.

On-Site Electricity Usage

Energy Efficiency

Opportunities for on-farm energy efficiency improvements depend on the type of farm and equipment in use. Energy savings opportunities are primarily centered on end uses of irrigation, space conditioning, and lighting.

For irrigation, subsurface drip irrigation is the most efficient form of irrigation in terms of water and energy consumption, but it may be cost-prohibitive to install for many farmers. For center-pivot systems with end guns, corner extensions, or varied elevation, variable frequency drives can significantly improve energy efficiency for systems (Brar et al. 2019). Efficiency of center-pivot systems can also be improved by installing lower-elevation nozzles, which reduces water loss from drift, thereby reducing the volume of water that needs to be pumped.

Space conditioning for livestock is a major driver of agricultural energy consumption, but there are multiple opportunities for energy efficiency improvement. Generally, the energy efficiency of barns can be improved with insulation improvements and natural ventilation to reduce energy demand from fan motors (University of Massachusetts Amherst 2014). Passive design features to improve energy efficiency include placing large doorways on the south-facing side and planting trees along the north side of the barn to reduce energy losses from wind during the winter. Efficiency gains can also be made by choosing appropriately sized equipment for the ventilation requirements (larger fans are generally more efficient) and installing automated controls to adjust operating schedules (University of Massachusetts Amherst 2014). Space heating for barns is fueled by propane, natural gas, fuel oil, diesel, and electricity. In addition to efficiency improvements from building envelope upgrades, there is potential to decarbonize space heating by converting to electric heat pumps, though the potential for emissions savings from fuel switching for space heating in the agriculture sector has not been thoroughly investigated.

Lighting is a significant energy end use for a variety of agricultural operations, including livestock barns, supplemented greenhouses, and indoor agriculture (e.g., vertical farms). A 2017 report estimated potential annual electricity savings of 2.3 TWh—approximately a 40% reduction in electricity consumption for lighting—by retrofitting horticultural lighting (excluding livestock barns) with LEDs (Stober et al. 2017).

Renewable Energy Production

Renewable energy production does not need to be located on-farm to reduce GHG emissions associated with on-site electricity consumption. GHG mitigation will mainly depend on decarbonization of the U.S. energy sector through a transition to renewable and alternative energy sources. In the United States, Shawhan et al. (2022) estimate a 60%–79% conversion to clean energy by 2035 and a 93%–94% conversion by 2050 in the United States. Considering these two transition estimates, renewable energy production could mitigate an average of 24 MMT CO_2e/yr in the United States from agricultural on-site energy use (Table 2).

Farmland is generally attractive to renewable energy developers, and opportunities exist to integrate renewable energy production with agricultural production—including on-site solar, wind, geothermal, and renewable gas production.

On-Site Solar

Agrivoltaics, which involves the co-location of solar and agricultural production, is one potential solution to provide local, low-emission electricity in rural communities while still preserving agricultural operations. Agrivoltaics can combine solar with crop production, livestock grazing, or greenhouses and requires different degrees of design modification relative to conventional solar depending on the use case and location (Macknick et al. 2022).

The scale of agrivoltaic systems ranges from research projects in the tens of kilowatts to grazing operations in the hundreds of megawatts. If paired with energy storage, agrivoltaics may enable farmers to electrify a greater share of farm operations by mitigating grid congestion in rural areas and enabling charging during nonsolar hours. Livestock operations, which often feature grazing or feed production alongside significant energy demand for space conditioning, may be particularly well-suited to agrivoltaics and other forms of on-site solar (Macknick et al. 2022).

Barriers to the deployment of agrivoltaics include the high capital cost for farmers and solar developers, uncertain impacts on agricultural operations, and uncertain regulatory environments for zoning and permitting of agrivoltaic projects (Pascaris, Schelly, and Pearce 2022; Pascaris, Gerlak, and Barron-Gafford 2023). Beyond agrivoltaics, solar can also be sited on rooftops and other nonproductive land, which is often viewed more favorably in rural communities than solar sited on productive farmland (Crawford, Bessette, and Mills 2022; Nilson and Stedman 2022).

On-Site Wind

Wind turbines are already deployed on farmland across the United States, serving an important role in decarbonization of the electricity sector. In total, over 100 GW of wind power is currently sited on cropland and rangeland in the United States (Harrison-Atlas, Lopez, and Lantz 2022). Wind development presents a potentially significant source of income for rural landowners with a relatively small footprint that minimally impacts farm operations. An average modern wind farm sited on farmland in the United States requires only about 2% of the land parcel area to be removed from production to accommodate roads, turbine pads, and other infrastructure (Diffendorfer et al. 2019).

One major concern for wind development is pushback from rural communities against new turbines and transmission infrastructure, which can manifest in costly lawsuits and difficult permitting processes (Baxter, Morzaria, and Hirsch 2013). Farmers can also consider smaller, distributed wind turbines instead of utility-scale projects, but distributed wind is relatively more expensive per unit of energy produced (NREL 2023).

On-Site Geothermal

Geothermal heat pumps may be an effective solution for on-farm heating and cooling needs, such as for livestock barns, greenhouses, aquaculture, and drying grains, fruit, and vegetables (Lund 2003; Lund and Toth 2021). As of 2017, geothermal was used on only approximately 1% of farms in the United States (USDA 2017). Most geothermal capacity (98%) in the United States is in the form of geothermal heat pumps (Lund and Toth 2021). For agricultural uses, most geothermal energy is used for greenhouse heating (730.2 TJ/yr) followed by agricultural drying (97.5 TJ/yr) and animal farming (59.0 TJ/yr).

On-Site Renewable Gas Production

Anaerobic digestion is a natural process in which microorganisms break down organic matter (e.g., livestock manure) to generate gaseous products, such as CH_4 (Mohankumar Sajeev, Winiwarter, and Amon 2018). This gas can then be used as a renewable energy source. According to EPA (2018), estimated 8,100 U.S. dairy and swine operations could support anaerobic digestors. EPA estimates that installing these digestors could provide 16 million megawatt-hours of electricity per year. In 2018, only 250 digestors were in operation on farms in the United States, illustrating a large opportunity for renewable gas production. The top 10 states for biogas production from swine farms are Illinois, Indiana, Iowa, Kansas, Minnesota, Missouri, Nebraska, North Carolina, Ohio, and Oklahoma (EPA 2018). The top 10 states for biogas production on dairy farms are Arizona, California, Colorado, Idaho, Michigan, New Mexico, New York, Texas, Washington, and Wisconsin. Biogas production from livestock manure could provide on-site energy needs as well as energy to neighboring communities from surplus; however, barriers to adoption exist—including high investment costs, increased labor requirements, and costs to maintain and manage the system (Nevzorova and Kutcherov 2019).

Manure Management

According to EPA (2018), installing anaerobic digestors at large-scale U.S. dairy and swine operations can reduce their CH_4 emissions by 85%. Using this reduction rate, EPA found a 2.2 MMT of CH_4 mitigation potential from installing these digestors, or equivalent to a 62 MMT CO_2e/yr mitigation potential in the United States. Mohankumar Sajeev, Winiwarter, and Amon (2018) suggest a lower mitigation potential (29%, on average) but with a large mitigation range (±116%). Uncertainties are because of variances in existing manure management practices, storage durations, and temperatures, which affect GHG emission rates.

Co-benefits of using digestors include odor control, improved water quality, land conservation, reduction in the need for chemical fertilizers from digestate usage, and economic benefits for farmers (EPA 2018). Use of digestates for field-applied fertilizer also lowers N_2O emissions by 25%, on average, compared to untreated manure (Hou, Velthof, and Oenema 2015).

Adoption Rates and Barriers to Adoption

As of 2017, the adoption rate of any type of renewable energy production on farms was 7% (USDA 2019a), including 4% adoption for solar, 1% for wind, and 1% for geothermal. Though this represents a small share of farms, the number of farms with on-site renewable energy production more than doubled from 2017, increasing at a compound annual growth rate of 18%. While anaerobic digestors are only sited at 0.03% of all farms, their adoption rate at large-scale swine and dairy operations is orders of magnitude higher at 3% (EPA 2018). The low penetration and rapid growth rates of on-farm renewable energy illustrate a significant opportunity for GHG mitigation by increasing renewable energy production at farms in the United States.

Precision Agriculture

Precision agriculture practices and technologies can lower GHG emissions by targeting site-specific spatial and temporal needs and reducing agricultural inputs (Balafoutis et al. 2017).

Balafoutis et al. (2017) classify precision agriculture technologies into three categories: 1) guidance technologies (e.g., machine guidance, driver assistance, controlled traffic framing), 2) recording technologies (e.g., soil mapping, soil moisture sensing, canopy sensing), and 3) reacting technologies (e.g., variable rate technologies for nutrients, pesticides, seeding, weeding, and irrigation). When farmers use precision agriculture technologies, GHG emissions under the categories of soil management, urea fertilization, fuel combustion, and liming could be reduced.

Soil Management and Urea Fertilization

In several studies, increasing nitrogen fertilizer application rates was found to be correlated to increasing N_2O soil management emissions (EPA 2023; B. L. Ma et al. 2010). In the United States, especially in row-crop farming in the Midwest, overapplication of nitrogen fertilizer is common (Millar et al. 2010a). Globally, the United States is responsible for 11% of excess nitrogen use (P. C. West et al. 2014). Using precision agriculture technologies, such as variable rate technology, can decrease nitrogen fertilizer application by improving the timing, placement, and rate (Millar et al. 2010a; Roberts et al. 2010). An increase in nitrogen use efficiency lowers associated soil management (N_2O) and urea fertilization (CO_2) emissions. Roe et al. (2021) found precision agriculture to offer a mitigation potential of 11 MMT CO_2e/yr for soil management in the United States. Although a minor agricultural GHG source, research gaps exist in the United States for quantifying potential CO_2 mitigation potential for urea fertilization.

Liming

Similar to fertilizer application, using precision agriculture for lime application also shows potential to decrease associated GHG emissions (Northrup et al. 2021). Northrup et al. (2021) estimate a 25% reduction in liming GHG emissions from adopting precision agriculture in row-crop systems. However, because liming is a minor emitter, using precision agriculture for liming offers only a 0.8 MMT CO_2e/yr GHG mitigation potential in the United States (Table 1).

Fuel Combustion

Because precision agriculture reduces the application of agricultural inputs, it can also lead to lower tractor and fuel usage (Plant, Pettygrove, and Reinert 2000). Finger et al. (2019) estimate a 6%–25% reduction in fuel combustion GHG emissions when adopting precision agriculture or equivalent to a 5.7 MMT CO_2e/yr average mitigation potential in the United States (Table 1).

Adoption Rates and Barriers to Adoption

In a national survey by Purdue University (Erickson and Lowenberg-DeBoer 2020), agricultural dealers estimated precision agriculture adoption rates and found five precision agriculture technologies adopted by more than 50% of farmers: yield monitors (69% adoption rate), guidance/auto steer (66%), field mapping with geographic information system (GIS) (58%), sprayer section controllers (56%), and grid or zone soil sampling (52%). Variable rate technologies were most adopted for lime application (41%), followed by fertilizer application (39%), seeding (19%), and irrigation (4%). For imagery, an estimated 26% of farmers used satellite or aerial imagery, and 8% used drone or unmanned aerial vehicle imagery. Robotics and/or automation for weeding or harvesting were found to have limited adoption.

Erickson and Lowenberg-DeBoer (2020) report the following barriers to adoption for precision agriculture technologies: cost outweighing benefits; soil, topography, or crop types limiting use;

time requirements for use of precision agriculture technologies; and data privacy concerns. Shafi et al. (2019) report additional barriers, including variable weather, high-speed connectivity requirements, and inability for data sharing between precision agriculture machines. Further research is warranted to quantify potential GHG reductions for each precision agriculture technology and to identify methods for decreasing barriers to entry for farmers in the United States.

No-Till

No-till has been defined as "the practice of direct-seeding of crops in a field without ploughing" (Ogle et al. 2019). It was originally introduced for erosion control but was found to offer other benefits, such as reducing energy and labor and improving fertilizer and water use efficiency (Triplett and Dick 2008). No-till can also reduce nitrogen leaching and offers the potential for optimizing crop productivity while also providing lower energy costs and providing greater environmental benefits compared to systems with tillage practice (Sainju et al. 2006). The impact of tillage on crop yields, however, varies. Implementing no-till practices, which increase soil moisture content, has been recorded to increase seed germination rate, enhance root growth, and ultimately improve crop production in some cases (Blevins et al. 1971; Pittelkow et al. 2015). On the other hand, no-till systems can lead to delayed emergence and maturity, reduced crop yields because of decreased maximum soil temperature and challenges with root penetration and weed and pest control (Pittelkow et al. 2015; Toliver et al. 2012). No-till shows potential to lower emissions from fuel combustion, soil management, rice cultivation, and field burning as well as sequester carbon.

Fuel Combustion

Farmers who currently adopt no-till decrease potential farm machinery fuel combustion emissions by reducing the number of times a field must be passed over during agricultural production (USDA Natural Resource Conservation Service [NRCS] 2022). NRCS (2022) reports that almost 87% of all cropland uses a form of conservation tillage for at least one crop per rotation. Continuous no-till is used on 33% of acres and contributes 48% of the total fuel GHG reduction. Geographically, the North Central and Midwest, Northern Plains, and Southern and Central Plains comprise 80% of fuel combustion GHG emission reductions from no-till. Depending on the crop, this may have the trade-off of increased herbicide usage (Hitaj and Suttles 2016). An alternative to herbicide application may be the use of roller-crimpers or other methods of mechanical weed management. NRCS (2022) estimates that if the remaining cropland was farmed using no-till, 8.3 MMT of CO_2e/yr could be mitigated.

Soil Management

Studies have shown that no-till systems can often decrease N_2O emissions; however, some studies have reported inconsistencies based on soil characteristics (e.g., no-till shows potential to increase N_2O emissions in poorly aerated soils) (Rochette 2008). No-till shows improved potential to increase total nitrogen stocks when coupled with increased cropping frequency (i.e., harvesting more than one crop per field per year) and use of legumes (Nicoloso and Rice 2021).

Rice Cultivation

In an international study, no-till in rice paddies showed potential to lower CH_4 emissions by 30% (X. Zhao et al. 2016). However, increases in N_2O emissions (82%) were found, showing a potential to offset CH_4 emission decreases from no-till. Further research is warranted to lessen uncertainties and to understand the full GHG flux of no-till in rice production. We find this area to be a research gap within the United States.

Field Burning

Instead of burning crop residues, farmers can transition to retaining the residues in the fields and/or use no-till systems. When these systems are used as an alternative to field burning, total estimated GHG emissions from field burning can be eliminated, or 0.7 MMT CO_2e/yr (EPA 2023). Although this strategy offers minimal GHG mitigation to total agricultural emissions, crop residues can also play a vital role as valuable sources of soil organic carbon (SOC) and essential nutrients. Plant residues facilitate the accumulation of SOC by enhancing soil aggregation, which enhances soil structure that has higher water-holding capacity and aeration (Husain and Dijkstra 2023; Six and Paustian 2014). Different rates of residue return in various cropping systems have been associated with higher levels of total and active SOC pools and improved soil structure (Gupta Choudhury et al. 2014; Martens 2000; H. Zhao et al. 2018). However, the breakdown of residues also has potential to emit N_2O emissions, and total GHG flux should be analyzed. Crop residues also contribute to erosion control and enhance soil temperature and moisture, potentially improving crop production (Wilhelm, Doran, and Power 1986).

Carbon Sequestration Potential

No-till systems have been recognized for their potential to increase SOC (Lal 2004) and reduce SOC losses by up to 63% compared to conventional tillage systems (Cillis et al. 2018). However, recent studies show that increases in SOC may be limited across the full soil profile when implementing no-till systems alone (Ogle et al. 2019; Powlson et al. 2014). No-till often shows higher carbon sequestration potential when combined with other agricultural practices, such as increased cropping frequency and integrating legumes into the crop rotation (Nicoloso and Rice 2021). Sperow (2016) estimates no-till to offer a mitigation potential of 128 MMT CO_2e/yr in the United States, but further research is needed on the impact of no-till along the full soil profile to reduce uncertainties of this estimate.

Adoption Rates and Barriers to Adoption

In the United States, 26% of cropland uses no-till systems, with an additional 25% using reduced till systems (USDA National Agricultural Statistics Service 2019). Barriers to adoption include increased weed pressure, soil compaction, initial decrease in water infiltration rates, and inability to incorporate residues and fertilizers into the soil (Triplett and Dick 2008). Crop productivity can also change under no-till systems and can depend on climate conditions (Ogle et al. 2012). No-till systems have been found to decrease crop productivity in cooler, wetter climates and increase productivity in warmer, drier climates (e.g., southwestern United States).

Integrated Nutrient Management

Integrated nutrient management (INM) is designed “to maximize the use of soil nutrients to improve crop productivity and resource-use efficiency” (Wu and Ma 2015). Emphasis is placed on using organic fertilizer, reducing nitrogen losses, and optimizing soil conditions. Practices can include cover cropping, manure or compost application, intercropping, crop rotation, conservation tillage, and efficient irrigation systems. INM shows potential to lower emissions from soil management, urea fertilization, and liming and to increase soil carbon sequestration. INM has also been shown to improve yield, soil health, water and nutrient use efficiency, and farmer profits compared to conventional production methods (Jat et al. 2015).

Soil Management

Limited research exists on the impact of INM on N_2O emissions; however, in a few studies, INM has been shown to decrease N_2O emissions compared to sole use of inorganic fertilizers (Graham, Wortman, and Pittelkow 2017). Individual practices of INM—such as cover cropping, intercropping, and conservation tillage—have shown potential to decrease N_2O emissions and/or increase soil nitrogen. Intercropping has been found to increase nitrogen fixation and/or reduce N_2O losses compared to monocropping (Cong et al. 2015). Though there is a research gap for studies evaluating intercropping impact in the United States, international studies have found that intercropping can reduce N_2O soil emissions by 37.2% (J. Huang et al. 2014) to 300% (Beaudette et al. 2010). Cover crops can also significantly lower nitrogen leaching (Abdalla et al. 2019). To understand the N_2O mitigation potential of INM in the United States, studies could include multiple practices (e.g., cover cropping, conservation tillage, organic amendment application) to evaluate the system as a whole.

Urea Fertilization

INM decreases the amount of synthetic fertilizer used through replacement with organic fertilizers (Wu and Ma 2015). This then decreases the rate of urea fertilizer applied as well as associated GHG emissions. Quantification of this GHG reduction potential is a current research gap in the United States. Empirical studies are recommended in the United States in a variety of climates, soils, and agricultural systems to provide data for estimating mitigation potential.

Carbon Sequestration Potential

Although limited studies analyze the potential for INM to sequester SOC as a system, individual practices of INM—such as cover cropping, intercropping, and diversified crop rotation—have been shown to increase SOC in multiple studies (Cong et al. 2015; Jian et al. 2020; McClelland, Paustian, and Schipanski 2021; K. Zhang, Maltais-Landry, and Liao 2021). We found estimating carbon sequestration potential of INM as a system to be a research gap in the United States with most studies focusing on individual practices. We evaluate the carbon sequestration potential of these individual practices discussed later in the section titled, "Agricultural Carbon Sequestration Potential in Croplands and Grasslands."

Adoption Rates and Barriers to Adoption

Little data exist on the adoption of INM as a system in the United States; however, some data are available on the adoption rates of individual practices, which are discussed in later sections (e.g., cover crops, intercropping, diversified crop rotation). Barriers to adopting INM include current uncertainties on the overall effectiveness to reduce GHG emissions (Graham, Wortman, and Pittelkow 2017) as well as similar barriers to other sustainable agricultural systems, including cultural barriers (e.g., beliefs, attitudes, and moral values), workforce/technical training, cooperation (e.g., farmer networking), incentives (e.g., policy and advertising), and laws and regulations (Barbosa Junior et al. 2022).

Biochar

Biochars are a carbon-rich material produced through the pyrolysis of biomass (e.g., crop residues, forestry residues, and municipal waste fractions). Biochars vary in physical and chemical properties based on feedstock, pyrolysis process (slow vs. fast, temperature, residence time at high temperature, oxidation), and postproduction processes. Biochars have shown positive effects on crop yield through various mechanisms and can improve nutrient retention in the soil, enhancing nutrient availability for plants and promoting crop growth (Schmidt et al. 2021). Research studies have demonstrated that biochar amendments significantly increase nutrient levels—including nitrogen, phosphorus, and potassium—leading to improved crop yield (Lehmann et al. 2011; Jeffery et al. 2011). Biochar can also enhance soil water-holding capacity by improving soil porosity, which reduces water runoff and increases water infiltration. This allows crops to access water during dry periods, increasing crop resilience to drought and yield stability. Biochar application also shows potential to lower GHG emissions from soil management and liming as well as sequester carbon in soil.

Soil Management

Biochar applications have the potential to reduce N_2O emissions from soil, contributing to further GHG mitigation. Studies have shown that biochar amendments can suppress denitrification and reduce N_2O emissions by altering soil conditions and microbial processes (Zhang et al. 2010; Cayuela et al. 2014). In addition, biochar can enhance nitrogen use efficiency and minimize nitrogen losses, reducing the availability of nitrogen for N_2O production (Clough et al. 2013; Liu et al. 2014). Furthermore, biochar's high surface area enables it to adsorb and immobilize nitrogen, further mitigating N_2O emissions (Cayuela et al. 2014; Liu et al. 2014). However, the effectiveness of biochar in reducing N_2O emissions can vary depending on soil type, biochar properties, and environmental conditions (Liu et al. 2013; Pang et al. 2017). Overall, biochar application shows promise as a potential strategy for N_2O emission mitigation, but further research is needed to fully understand its effects in different contexts, representing a research gap.

Liming

Similar to liming agents, biochar has shown potential to increase soil pH (Chintala et al. 2014; Jeffery et al. 2011). The pH of biochar generally increases with increases in pyrolysis temperature, and therefore ash content, but also depends on feedstock material (Chintala et al. 2014; Gezahegn, Sain, and Thomas 2019). In one study, corn stover biochar showed greater soil pH increases than switchgrass biochar (Chintala et al. 2014). However, little data exist in the United States for quantifying the potential GHG emission reduction for biochar as a pH adjustment tool replacement for lime in agricultural systems. This area represents a research gap.

Carbon Sequestration Potential

Research studies have demonstrated that biochar amendments can significantly increase SOC content in various soil types and agricultural systems (Luo et al. 2017; Spokas et al. 2012). The addition of biochar to soil can contribute to SOC sequestration through multiple mechanisms. The effect of biochar on SOC includes the addition of stable carbon directly from the biochar amendments and the potential negative priming effect. Schmidt et al. (2021) found that biochar enhanced soil carbon through long-term carbon storage and increasing soil microbial carbon. Biochar can also improve soil aggregation, creating a protective environment for organic matter and enhancing its persistence in the soil (Biederman and Harpole 2013; Major et al. 2012). In one study, SOC stocks increased by more than twice within a 6-year period (Blanco-Canqui et al. 2020). This negative priming effect has the potential to also enhance the carbon storage capacity from other conservation practices such as no-till and cover cropping.

Further research is warranted to understand the long-term impact and stability of varying types of biochar in different environments and agricultural systems (Leng et al. 2019). Roe et al. (2021) estimate that biochar application has the potential to mitigate 327 MMT CO_2e/yr in the United States; Fargione et al. (2018) reported a lower mitigation potential of 95 MMT CO_2e/yr. These estimates are based on the potential to apply biochar to about 10% of production acres in the United States and from biochars produced from crop residues. Given the variability of regional conditions and estimates, we used the average of the Roe et al. (2021) and Fargione et al. (2018) estimates for a U.S. average GHG mitigation potential of 211 MMT CO_2e/yr.

Adoption Rates and Barriers to Adoption

Little data are available on farmer adoption of biochar application in the United States. Barriers to adoption can include access to feedstock, lack of market research, low profit and high cost, farmer perceptions and knowledge and decision support, and environmental and human health impacts from particulate emissions and waste (Thengane et al. 2021). As a higher cost agricultural amendment, some studies have evaluated the economic feasibility for farmers. Keske et al. (2020) found biochar application to increase yields for beets and potatoes and to be profitable for beet production but not potato production. Trippe and Phillips (2018) created a biochar atlas for farmers in the Pacific Northwest to run cost-benefit analyses for soils and crops grown in that area. Further studies on economic evaluation for various crops, soils, and climates would help to understand if biochar can be both implemented as a GHG mitigation strategy and a profitable agricultural amendment for farmers across the United States.

Cropland Agricultural GHG Emissions and Mitigation Solutions

Agricultural GHG sources in croplands include soil management, land use conversion to croplands, urea fertilization, liming, and field burning. Potential carbon sequestration in croplands and grasslands is also considered. In this section, we evaluate the potential of noncrosscutting solutions for their impact on mitigating GHG emissions in crop production in the United States.

Soil Management

Table 4 presents a soil management summary.

Table 4. Soil Management Summary

Annual Emission Rate	294 MMT CO_2e/yr
Percentage of Agricultural GHG Emissions	40% (heavy emitter)
GHG	N_2O
Most Impactful Solution	Enhanced efficiency fertilizers
Other GHG Mitigation Solutions	• Precision agriculture • Integrated nutrient management • No-till • Biostimulants • Grazing strategies • Improved irrigation technologies
Research Gaps for Quantifying GHG Mitigation Potential in the United States	• Integrated nutrient management • No-till • Biostimulants • Grazing strategies • Improved irrigation technologies
Takeaways	• Soil management is based on natural nutrient cycling processes and is currently a hard-to-fully-abate GHG source. • Decreasing the impact of synthetic nitrogen fertilizer application (e.g., enhanced efficiency fertilizers and precision agriculture) shows the greatest mitigation potential. • Closing research gaps on mitigation strategies to increase soil nitrogen (e.g., grazing strategies and improved irrigation technologies) could improve confidence in implementing land-based strategies to lower N_2O emissions.

In 2021, agricultural soil management was the highest contributor to agricultural production emissions in the United States (40%) (EPA 2023). Soil management includes direct N_2O sources from croplands and grasslands, including mineralization and asymbiotic fixation; synthetic fertilizers; residue nitrogen; organic amendments; drained organic soils; pastures, ranges, and paddocks manure; and biosolids and indirect N_2O source from croplands and grasslands, including surface leaching and runoff along with volatilization and atmospheric deposition (Figure 8). Soil management of croplands accounted for 69% of associated N_2O emissions, while grasslands accounted for 31%.

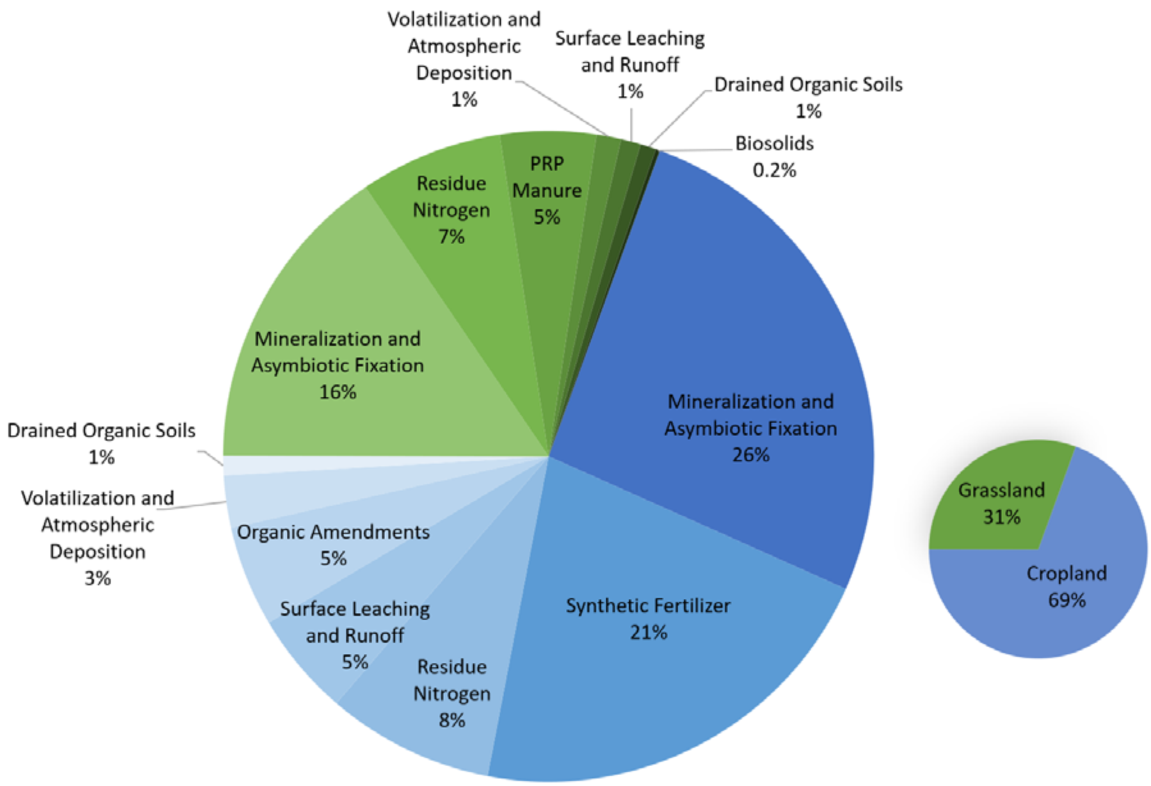

Figure 8. N_2O emissions from soil management in 2021

Data from EPA (2023). Blue = Cropland, Green = Grassland. PRP = Pastures, ranges, and paddocks.

Climate change shows potential to increase agricultural N_2O emissions by 19% and nitrogen mineralization by 24% while decreasing nitrogen fixation and yields (Elli et al. 2022). Solutions for decreasing soil management GHG emissions include precision agriculture, INM, no-till, enhanced efficiency fertilizers, biostimulants, grazing strategies, and improved irrigation technologies.

Soil Management GHG Mitigation Solutions

Crosscutting Solutions: Precision agriculture, integrated nutrient management, no-till, and biochar

Enhanced Efficiency Fertilizers

Enhanced efficiency fertilizers, such as nitrification inhibitors (NI), polymer-coated fertilizers, and urease inhibitors, have been proposed as effective strategies for decreasing soil management N_2O emissions (Akiyama, Yan, and Yagi 2009). In a meta-analysis, NIs were found to decrease N_2O emissions by 38% and were effective for both inorganic and organic fertilizers and across various land uses and soils (Akiyama, Yan, and Yagi 2009). NIs have also been found to be effective at increasing yields (Thapa et al. 2016). Polymer-coated fertilizers were found to decrease N_2O by 35%, but results varied across land uses and soils (Akiyama, Yan, and Yagi 2009). Both NIs and polymer-coated fertilizers are most effective at decreasing N_2O emissions when used in grassland systems. Additional research is needed to understand if urease inhibitors can lower N_2O emissions because results are inconsistent (Akiyama, Yan, and Yagi 2009; T. Li et al. 2018). Based on data from Akiyama, Yan, and Yagi (2009) and EPA (2023), we then estimate enhanced efficiency fertilizers to provide a mitigation average of 23 MMT CO_2e/yr in the United States.

Biostimulants

Biostimulants and other microbial inputs have been suggested as a replacement for agricultural chemicals to provide nutrient availability, sequester carbon, and combat disease (Northrup et al. 2021). With the addition of beneficial bacteria to the soil (a type of biostimulant), one international study found that wheat farmers can reduce fertilizer application 25% without a reduction in available nitrogen, phosphorous, or potassium or yield (Juanjuan Wang et al. 2020). These reductions in nitrogen fertilizer application would offer mitigation by lowering associated N_2O emissions. Research gaps exist in the United States on quantifying the potential for biostimulants to provide N_2O mitigation because many of the products are newer technologies.

Grazing Strategies

Grazing strategies, such as adaptive multipaddock systems, have been shown to increase soil nitrogen (Mosier et al. 2021). These systems use multiple fenced-in paddocks where livestock graze for short periods and are rotated to avoid overgrazing and allow for pasture regrowth (Teague et al. 2013). Mosier et al. (2021) found adaptive multipaddocks to offer a 9% increase in soil nitrogen compared to conventional grazing system. However, research quantifying the impact on total N_2O soil management flux from using alternative grazing strategies in U.S. agricultural systems is limited.

Improved Irrigation Technologies

Research indicates that irrigation can both increase and decrease N_2O emissions, depending on various factors such as soil moisture content, fertilizer application rate, and irrigation method. Overirrigation or waterlogging can create anaerobic conditions, promoting denitrification processes and resulting in increased N_2O emissions (Kritee et al. 2018). On the other hand, proper irrigation management, such as optimized water and nutrient application, can reduce N_2O emissions by minimizing nitrogen losses and optimizing nitrogen use efficiency.

Improved irrigation strategies, such as the use of subsurface drip irrigation and intermittent irrigation, show potential to decrease N_2O emissions (Sapkota et al. 2020). In one study in California, drip and subsurface drip irrigation was shown to decrease N_2O emissions by 55% and 67%, respectively, compared to surface gravity irrigation (Deng et al. 2018). Although many studies show potential to decrease N_2O emissions, some results have been inconsistent or vary based on soils, climate, or agricultural system. The interaction between irrigation and N_2O emissions is complex and context-dependent, highlighting the importance of considering site-specific conditions and adopting sustainable irrigation practices to mitigate N_2O emissions in agricultural systems. Further research is warranted to lower uncertainties and understand the potential for improved irrigation technologies to decrease N_2O emissions in the United States.

Land Use Conversion to Cropland

Table 5 presents a summary of land use conversion to cropland.

Table 5. Land Use Conversion to Cropland Summary

Annual Emission Rate	59 MMT CO_2e/yr
Percentage of Agricultural GHG Emissions	8% (moderate emitter)
GHG	CO_2
Most Impactful Solution	Sustainable bioenergy production (sustainable bioenergy feedstocks and use of degraded land perennial bioenergy crops)
Other GHG Mitigation Solutions	• Sustainable intensification • Forest conversion avoidance • Grassland conversion avoidance • Wetland conversion avoidance
Research Gaps in the United States	Sustainable intensification
Takeaways	• Forest conversion currently makes up most land use conversion to cropland GHG emissions. • Grasslands conversion GHG emissions are increasing and make up the majority of newly converted land. • Trade-offs exist between food production, native protection, and bioenergy production.

Throughout agricultural history in the United States, forestland, grasslands, and wetlands have been converted to croplands. When considering all current cropland that has been converted from another use over the last 20 years, 59 MMT CO_2e of GHG emissions were emitted (EPA 2023). The intensity of soil carbon loss and GHG emissions from land use change depends on previous land use (Fritsche, Sims, and Monti 2010). GHG emission rates are greater when land with high carbon stocks (e.g., forests) is converted to agricultural production. From 1990 to 2021, forestland converted to cropland accounted for 86% of carbon loss from land use change to cropland (EPA 2023). This includes aboveground and belowground live biomass, dead wood, litter, and mineral and organic soils. Aboveground biomass made up 60% of carbon losses in 2021.

Although forests made up the majority of land use change emissions from 2008 to 2012, 77% of all newly converted cropland in the United States was converted from grasslands (Lark, Meghan Salmon, and Gibbs 2015). Throughout history, in the Great Plains of the United States alone, approximately 120 million hectares of tall, mixed, and shortgrass prairies have been plowed and converted to croplands, leaving less than 3% of the original tallgrass prairies (DeLuca and Zabinski 2011). Wright et al. (2017) found that 3.6 million acres of recently converted grassland were within 100 miles of ethanol refineries, suggesting that bioenergy production is potentially accelerating grassland conversion.

Wetlands are the only category of land use change to croplands that decreased from 1990 to 2021. Over that period, GHG emissions from wetland conversion decreased 13%, while land use change from grasslands and forests increased 23% and 1%, respectively (EPA 2023). Wetlands also make up the lowest proportion of land use conversion to cropland GHG emissions (1%). However, from the 1780s to 1980s, approximately 53% of all wetlands—or 208 million acres—

were lost in the lower 48 states (Dahl 1990). In states with high agricultural activity (e.g., California, Iowa, Illinois, Missouri, Ohio, Indiana), over 80% of historical wetlands have been lost (Zedler 2004). Current U.S. policy (i.e. the Clean Water Act) also enforces a no net loss of wetlands during permitting processes.

For this study, we categorized potential GHG mitigation solutions for land use change to croplands into resource use efficiency solutions (addressing unproductive farmland and land use for bioenergy production) and CO_2 abatement solutions (forest conversion avoidance, grassland conversion avoidance, and wetland conversion avoidance). We consider nonagricultural land use practices (i.e., maintaining the natural ecosystems) for their ability to preserve carbon in the soils and aboveground and belowground biomass. Trade-offs for food production may exist for these strategies, although increasing yields on current agricultural lands is possible through various management strategies discussed next and in later sections (e.g., sustainable intensification).

Land Use Conversion to Croplands GHG Mitigation Solutions: Resource Use Efficiency

From 2008 to 2016, croplands expanded by more than a million acres per year, and 69.5% of the newer croplands showed below-average yields (Lark et al. 2020). Corn was the most common crop planted on newly converted cropland. Together, corn, soybeans, and wheat made up 78% of all newer croplands in the United States from this time frame (2008–2016). Lower yields were found to correlate with lower soil quality of newly converted lands, lower water availability, poorer slope gradients, and a decrease in nearby natural areas (Lark et al. 2020).

Another aspect of resource use efficiency is the trade-off between using agricultural land for food and for renewable energy production. Bioenergy, though it is an important part of clean energy production in the United States, can lead to land competition from food and fiber production and to an increase in GHG emissions during land use change and production (Fritsche, Sims, and Monti 2010; Sands et al. 2017). Approximately 33 million acres in the United States are used for corn production that is eventually turned into ethanol, a bioenergy product (Sands et al. 2017). Proposed solutions for improving the sustainability of bioenergy production include the use of sustainable feedstocks and degraded lands.

Next, we evaluate sustainable intensification and sustainable bioenergy production as potential solutions for improving the resource use efficiency of cropland.

Sustainable Intensification

Sustainable intensification has been defined as “producing more from the same area of land while conserving resources, reducing negative environmental impacts and enhancing natural capital and the flow of environmental services” (Wezel et al. 2015). Sometimes interchangeably used terms include ecological intensification and agroecological intensification. Weltin et al. (2018) classified sustainable intensification into four “fields of action”: agronomic development, resource use efficiency, land use allocation, and regional integration. Sustainable intensification practices can include reducing agricultural inputs, increasing water use efficiency, mixing crop-livestock operations, and focusing on agronomic improvements. By decreasing GHG emissions from inputs and improving yields without increasing land use, sustainable intensification shows potential to slow land use change and decrease associated GHG emissions. However, research quantifying potential GHG mitigation from sustainable intensification in the United States is limited. Similar to INM, most studies focus on one practice within INM (e.g., reducing agricultural inputs), so systemwide studies are needed to close the research gap.

Sustainable Bioenergy Feedstocks

Second-generation bioenergy feedstocks can be sustainably obtained from agricultural systems when the rate of removal is considered (Qin et al. 2018; Xu et al. 2019). Second-generation feedstocks are nonedible food byproducts or other residual or waste products from agriculture or industry (e.g., corn stover). Xu et al. (2019) found that high removal of corn stover (>75%) reduces SOC by an average of 8.7% and moderate removal (<50%) has no significant difference in SOC changes from nonremoval sites. Qin et al. (2018) found that SOC could be increased with bioenergy production in a conventional till system when only 30% of stover was removed and cover cropping and manure application were added to the system. Bioenergy feedstocks can also be obtained from nonagricultural sources—such as forest thinning byproducts, wood and food processing residues, organic waste, and algae—to lessen the impact on land use change from bioenergy production (Fritsche, Sims, and Monti 2010).

Use of Degraded Lands for Perennial Bioenergy Crops

Over 2 million hectares of previous agricultural land are unused in the northeastern United States mainly because of deteriorated soil quality and use of more productive lands in the midwestern states (Stoof et al. 2015). This marginal land could provide for potential bioenergy feedstock production without competition for food production. Use of marginal lands would then lower land use conversion to cropland and associated GHG emissions. Perennial grasses and short-rotation woody crops show potential for carbon sequestration on marginal lands. However, crop yields will also likely be lower on degraded lands than on productive agricultural land (Fritsche, Sims, and Monti 2010). Lemus and Lal (2007) estimate bioenergy production in degraded soils to sequester a range of 0.6 to 3.0 Mg C ha/yr. Using data from Lemus and Lal (2007) and USDA NASS (2019), we then estimate sustainable bioenergy production on degraded lands to offer a mitigation potential of 63 MMT CO_2e/yr in the United States.

Land Use Conversion to Croplands GHG Mitigation Solutions: Land Management

Land management solutions involve evaluating general land use strategies and the trade-offs of using land for agricultural production, native forests, grasslands, or wetlands. Solutions include conversion avoidance strategies for forests, grasslands, and wetlands.

Forest Conversion Avoidance

Because most land use to cropland conversion emissions result from forest conversion (EPA 2023), decreasing forest conversion rates will be the most impactful conversion avoidance GHG mitigation strategy. When compared to reforestation of croplands, conversion avoidance will be more successful in the near term because reforestation can require 50 years for carbon equilibrium to occur (Lefebvre et al. 2021). If all forest acres avoided cropland conversion, an estimated 49 MMT CO_2e/yr could be mitigated in the United States (EPA 2023).

Although out of scope of the study, Niu and Duiker (2006) found that marginal agricultural lands around the midwestern United States show a high potential for carbon sequestration from afforestation with the carbon stored in soils, roots, forest floor, and aboveground biomass. Potter et al. (2007) found that the top states for GHG mitigation through cropland afforestation in descending order were Texas, Minnesota, Iowa, Illinois, and Missouri and the top states for GHG mitigation through rangeland afforestation were Texas, California, Montana, New Mexico, and Colorado.

Grassland Conversion Avoidance

Avoiding grassland conversion to cropland shows a higher GHG mitigation potential than grassland restoration of croplands (Fargione et al. 2018). For the United States, EPA (2023) estimates grassland conversion avoidance to offer a mitigation potential of 10 MMT CO_2e/yr. Although out of scope of the study, grassland restoration can still offer many additional co-benefits, including water regulation, erosion control, soil formation, pollinator habitat, climate regulation, and air quality regulation (Y. Zhao, Liu, and Wu 2020).

Wetland Conversion Avoidance

Because wetlands are the least converted ecosystem to croplands in the United States, wetland conversion avoidance offers minimal agricultural GHG mitigation. For the United States, EPA (2023) estimates wetland conversion avoidance to offer a mitigation potential of 0.7 MMT CO_2e/yr.

Rice Cultivation

Table 6 presents a summary of rice cultivation.

Table 6. Rice Cultivation Summary

Annual Emission Rate	16.8 MMT CO_2e/yr
Percentage of Agricultural GHG Emissions	2% (minor emitter)
GHG	CH_4
Most Impactful Solution	Alternate wetting and drying
Other GHG Mitigation Solutions	• Deepwater rice fields • Straw management • Low-methane rice varieties • No-till
Research Gaps for Quantifying GHG Mitigation Potential in the United States	• Deepwater rice fields • Straw management • Low-methane rice varieties • No-till
Takeaways	• Trade-offs exist between CH_4 and N_2O emissions based on anaerobic or aerobic conditions of the growing conditions. • Irrigation strategies show the greatest potential for GHG mitigation. • Closing research gaps in the United States could help show potential for nonirrigation solutions (straw management, no-till, and low-methane rice varieties).

In the United States, most rice production occurs in six states across four regions: the Arkansas Grand Prairie (Non-Delta), the Mississippi Delta (parts of Arkansas, Mississippi, Missouri, and Louisiana), the Gulf Coast (Texas and Southwest Louisiana), and the Sacramento Valley (California) (McBride, Skorbiansky, and Childs 2018). All rice grown in the United States produces CH_4 emissions, but levels can vary based on chosen cultivation practices (EPA 2023). For example, in the southeastern United States, many rice farmers produce ratoon crops, or a second harvest of the original rice crop, which produces more CH_4 than the original harvest. Although all rice production in the United States uses flooded fields that promote CH_4 emissions by creating anaerobic conditions, this irrigation method also produces some of the highest yields in the world (McBride, Skorbiansky, and Childs 2018). Solutions for decreasing rice cultivation GHG emissions include no-till, alternate wetting and drying, deepwater rice fields, straw management, and low-methane rice varieties.

Rice Cultivation GHG Mitigation Solutions

Crosscutting Solution: No-till

Alternate Wetting and Drying

Alternate wetting and drying and similar irrigation systems have been proposed as methods for lowering CH_4 production. This intermittent irrigation method consists of drying and reflooding rice fields. In an international study, mild alternate wetting and drying was found to lower CH_4 emissions by 87%; however, N_2O emissions increased 280% (Liao et al. 2020). Using mid-season drainage instead was found to lower CH_4 without impacting N_2O emissions. In an international meta-analysis, J. Wang et al. (2018) found that fields with single drainage produced 71% fewer CH_4 emissions than continuously flooded fields. In a U.S.-based study, Runkle et al. (2019) found a 65% reduction in CH_4 from implementing alternate wetting and drying. Using data from Runkle et al. (2019) and EPA (2023), we estimate alternate wetting and drying to provide a mitigation potential of 9 MMT CO_2e/yr. Because the data set we used is small, further studies should be carried out in the United States to increase confidence in this estimate. Alternate wetting and drying has also been shown to impact rice yields. Some studies show a decrease in yields from severe alternate wetting and drying; however, moderate alternate wetting and drying has been found to overall increase yields and still lower methane emissions and water use (Yang, Zhou, and Zhang 2017).

Deepwater Rice Fields

In limited studies, deep water rice fields (>50 cm of water depth) were found to emit only 6% of the CH_4 emissions that continuously flooded rice fields emit (J. Wang et al. 2018). However, because data are limited or nonexistent in the United States, further research is needed to lower uncertainties of current analyses and to understand GHG mitigation potential in the United States.

Straw Management

Applying rice straw during the preseason can lower CH_4 emissions compared to applying straw close to transplanting (J. Wang et al. 2018). In one international study, J. Wang et al. (2018) found a 50% decrease in CH_4 when straw mulching is incorporated into rice production. In addition, straw mulch can increase SOC sequestration in rice production (Rahman et al. 2022). However, research is limited in the United States, and additional data are needed to understand the GHG mitigation potential of straw management.

Low-Methane Rice Varieties

Different cultivars of rice can emit different levels of CH_4 under the same practices (Gogoi, Baruah, and Gupta 2008). In an international study of 10 cultivars, Gogoi Baruah, and Gupta (2008) found that CH_4 emissions ranged from 8.8 to 18.6 g/m^2 over a 3.5-month experiment. This large range shows the potential to choose low CH_4-emitting rice varieties as well as selective breeding potential. Using a different cultivar would not require farmers to change their management practices, making it a practical choice for lowering CH_4 rice cultivation emissions. Research is limited, and further data are needed to understand GHG mitigation potential in the United States.

Urea Fertilization

Table 7 provides a summary of urea fertilization.

Table 7. Urea Fertilization Summary

Annual Emission Rate	5.3 MMT CO_2e/yr
Percentage of Agricultural GHG Emissions	1% (minor emitter)
GHG	CO_2
Most Impactful Solution	N/A
Other GHG Mitigation Solutions	• Integrated nutrient management • Precision agriculture
Research Gaps for Quantifying GHG Mitigation Potential in the United States	• Integrated nutrient management • Precision agriculture
Takeaways	• Application of urea as a nitrogen fertilizer is increasing on U.S. farms. • Mitigation strategies focus on decreasing fertilizer application and overlap with solutions for lowering N_2O in soil management.

Urea ($CO(NH_2)_2$), which contains 46% nitrogen, has surpassed ammonium nitrate as a nitrogen fertilizer in the United States (University of Minnesota Extension 2021). When applied, urea fertilizer emits CO_2 that was fixed during production processes (EPA 2023). The volatility of urea depends highly on soil temperature, moisture, and pH (University of Minnesota Extension 2021). Urea fertilization is a minor agricultural GHG source; however, emissions increased 118% from 1990 (3.3 MMT) to 2021 (7.2 MMT) because of increased annual application rates (EPA 2023). In some states, urea has replaced traditionally used nitrogen fertilizers (e.g., anhydrous ammonia) as the main source of agricultural nitrogen (University of Minnesota Extension 2021). Advantages of urea include its application as a solid or liquid and its decreased explosion hazard, high nitrogen percentage, decreased pollutants, and increased crop yields compared to other forms of nitrogen (University of Minnesota Extension 2021). Solutions for decreasing urea GHG emissions include crosscutting solutions, INM, and precision agriculture—all of which are research gaps in the United States.

Urea Fertilization GHG Mitigation Solutions

Crosscutting Solutions: Precision agriculture and integrated nutrient management

Liming

Table 8 presents a summary of liming.

Table 8. Liming Summary

Annual Emission Rate	3 MMT CO_2e/yr
Percentage of Agricultural GHG Emissions	0.4% (minor emitter)
GHG	CO_2
Most Impactful Solution	Precision agriculture
Other GHG Mitigation Solutions	Biochar
Research Gaps for Quantifying GHG Mitigation Potential in the United States	Biochar
Important Notes	• Liming is a decreasing GHG source in the United States. • The most impactful solution (precision agriculture) is also a crosscutting solution for fuel combustion, soil management, and urea fertilization.

Long-term use of inorganic nitrogen fertilizers can acidify soils (Schroder et al. 2011). Crushed limestone and/or dolomite are often added as an amendment to correct and increase soil pH (EPA 2023). The amount of nitrogen applied is directly correlated with the level of acidity (Schroder et al. 2011). Liming is a minor source of agricultural GHG emissions in the United States, and it saw a significant downward trend (36%) in emissions from 1990 to 2021(EPA 2023). Solutions for decreasing liming GHG emissions include the crosscutting solutions precision agriculture and biochar.

Liming GHG Mitigation Solutions

Crosscutting Solutions: Precision agriculture and biochar

Field Burning

Table 9 presents a summary of field burning.

Table 9. Field Burning Summary

Annual Emission Rate	0.6 MMT CO_2e/yr
Percentage of Agricultural GHG Emissions	0.08% (minor emitter)
GHG	N_2O, CH_4
Most Impactful Solution(s)	• No-till • Bioenergy production
Other GHG Mitigation Solutions	N/A
Research Gaps for Quantifying GHG Mitigation Potential in the United States	N/A
Takeaways	• Field burning is the smallest source of agricultural GHG emissions in the United States. • Solutions include alternative agricultural practices to field burning. • The co-benefits of solutions include decreasing ozone and particulate matter emissions.

Agricultural residues are a byproduct of crop production (EPA 2023). Farmers manage these residues in various ways, including by field burning. In 2014, approximately 1.5 million acres of cropland were burned in bluegrass, corn, cotton, rice, soybeans, sugarcane, and wheat cropping systems in the United States (Pouliot et al. 2017). An additional 1.6 million acres classified as grasslands or pasture were also burned in 2014. Field burning is a minor source of agricultural GHG emissions in the United States and contributes both CH_4 (0.5 MMT CO_2e/yr) and N_2O (0.2 MMT CO_2e/yr) (EPA 2023). In other countries, such as India, field burning is a much greater source of GHGs (Shyamsundar et al. 2019). In addition to GHGs, an estimated 49,600 short tons of $PM_{2.5}$ were emitted through agricultural burning of croplands and grasslands in the United States in 2014 (Pouliot et al. 2017). Through alternative residue management methods, such as no-till and bioenergy production, agricultural emissions (GHGs, ozone, and particulate matter) from field burning can be eliminated. This offers a minimal GHG potential of 0.7 MMT CO_2e/yr (EPA 2023). However, it is important to understand the potential barriers to implementation for alternative methods and potential increases in other GHG emissions from implementation (e.g., N_2O from crop residue breakdown).

Field Burning GHG Mitigation Solutions

Crosscutting Solution: No-till

Bioenergy Production

Another option for residue management is to use the material as second-generation feedstock for bioenergy production. As stated in the "Land Use Conversion to Croplands" section, bioenergy can be sustainably produced from agricultural residues (in corn production) if less than 50% is removed (Xu et al. 2019). Use for bioenergy production would eliminate the need for farmers to burn the excess residues, resulting in an estimated annual mitigation potential of 0.7 MMT CO_2e/yr (EPA 2023).

Livestock Production GHG Emissions and Mitigation Solutions

Agricultural GHG emissions in livestock production include enteric fermentation and manure management. In this section, we evaluate the potential of noncrosscutting solutions for their impact on mitigating GHG emissions in livestock production in the United States.

Enteric Fermentation

Table 10 presents a summary of enteric fermentation.

Table 10. Enteric Fermentation Summary

Annual Emission Rate	194.9 MMT CO_2e/yr
Percentage of Agricultural GHG Emissions	27% (heavy emitter)
GHG	CH_4
Most Impactful Solution	Feed additives
Other GHG Mitigation Solutions	• Selective breeding • Improved feed and forage quality
Research Gaps for Quantifying GHG Mitigation Potential in the United States	Improved feed and forage quality
Takeaways	• Enteric fermentation is based on a natural ruminant animal digestive process and is a hard-to-fully-abate GHG source. • Beef and dairy cattle make up most emissions (96%). • Strategy effectiveness can vary across ruminant animal species and subspecies. • The effectiveness and safety of feed additives must be verified across all applicable livestock. • Selective breeding is the longest-term solution to enteric fermentation (up to 30 years).

Ruminant animals, such as cattle, sheep, and goats, emit CH_4 through a microbial digestive process known as rumen or enteric fermentation (Newbold and Ramos-Morales 2020). Dry matter intake, or the rate of feed eaten per day, has been found to be the most reliable predictor of CH_4 production rates in dairy cattle (M. Niu et al. 2018). Other nonruminant livestock, such as swine and horses, produce small amounts of CH_4 (EPA 2023). Enteric fermentation is the second-largest source of GHG emissions within agricultural production in the United States. In 2021, beef cattle contributed 71% of enteric fermentation-related CH_4 emissions and dairy cattle contributed 25% (Figure 9). The remaining 4% of emissions came from swine, horses, sheep, goats, American bison, and mules and asses.

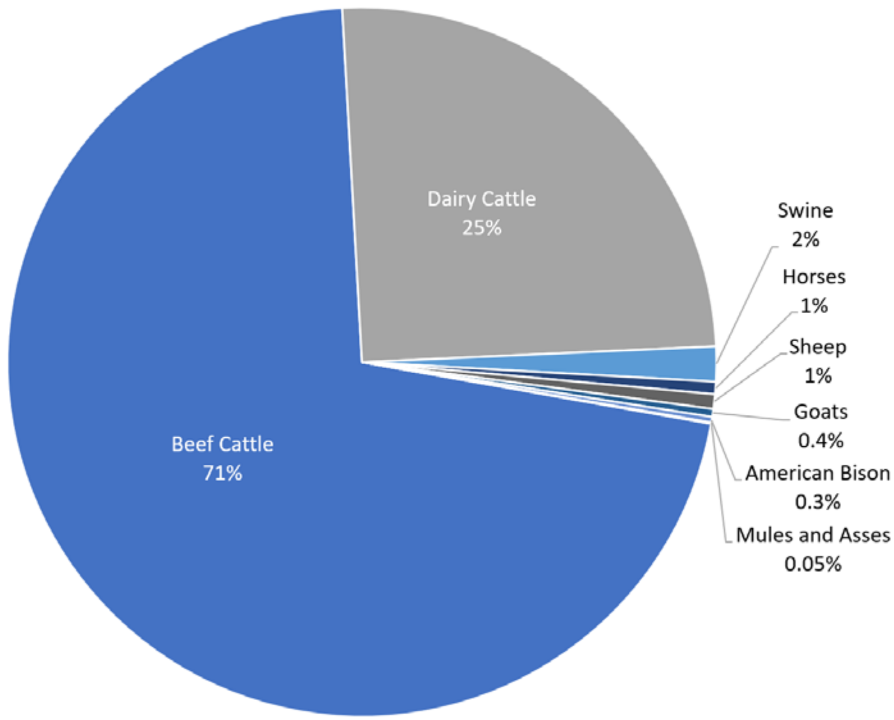

Figure 9. Enteric fermentation emissions by livestock in 2021

Data from EPA (2023)

From 1990 to 2021, GHG emissions from enteric fermentation increased 6% across all livestock types. During this time, GHG emissions from beef cattle increased 5% because of an increase in their populations. GHG emission rates for dairy cattle increased 13% from 1990 to 2021, even though overall populations decreased by 4%, mainly because of a decrease in feed digestibility (EPA 2023). Though per-head GHG emissions increased over that period for dairy cattle, milk production increased 62%, decreasing the GHG emissions per unit of product. GHG mitigation solutions have been proposed for improvements in livestock production and feed sources. Demand-side strategies (e.g., dietary changes) are not in the scope of this study.

Enteric Fermentation GHG Mitigation Solutions

Selective Breeding

Selective breeding can include direct selection of low CH_4-emitting animals or indirect selection of traits correlated to lowered CH_4 emissions (de Haas et al. 2021; Fouts et al. 2022; Pickering et al. 2015). In an international study, including CH_4 mitigation as a trait in selective breeding showed a 24% mitigation potential by 2050 (de Haas et al. 2021). Similarly, in another international study, Pickering et al. (2015) found a possible 25% decrease in CH_4 emissions when CH_4 yield was considered as the desired breeding trait and a potential 45% decrease if low residual feed intake traits were included. Residual feed intake is a measurement of feed efficiency and is the difference between the animal's actual feed intake and expected feed intake needed for weight and growth maintenance. Based on estimates from Pickering et al. (2015) and EPA (2023), we found selective breeding to offer a 68 MMT CO_2e/yr GHG mitigation potential;

however, selective breeding is still in early research phases and would be a long-term strategy for enteric fermentation mitigation.

Feed Additives

Feed additives that have shown potential to decrease methane production in ruminant animals include 3-nitroxypropanol (3NOP), macroalgae, lipids, nitrates, plant secondary compounds, and essential oils (Honan et al. 2021). However, some additives show inconsistent results or show potential to have adverse side effects on livestock. For example, nitrates show potential to decrease CH_4 from rumen methanogenesis but may also accumulate in the blood and become toxic to ruminant animals.

When analyzing the effectiveness of 90 feed additives, Kebreab and Feng (2021) found that 3NOP, bromochloromethane, chestnut, coconut, distillers dried grains and solubles, eugenol, grape pomace, linseed, monensin, nitrate, nitroethane, saifoin, fumaric acid, and tannins were all significantly effective at reducing CH_4, including that 3NOP (41% reduction in dairy cattle, 22% reduction in beef) and nitrates (14.4% reduction) were the two most effective additives. Feed additives have shown to be similarly effective with dairy cattle, beef cattle, and sheep (van Gastelen et al. 2019).

In several studies, red seaweed (*Asparagopsis taxiformis*) was found to be extremely effective at decreasing CH_4 from enteric fermentation (Kinley et al. 2020; Stefenoni et al. 2021). In one experiment, red seaweed decreased CH_4 emissions in beef cattle up to 98% without negatively impacting rumen function or feed conversion efficiency (Kinley et al. 2020). Stefenoni et al. (2021) also found a 98% CH_4 reduction in their first experiment but found decreasing effectiveness of CH_4 reduction over time, likely because of the decreasing bromoform rates in red seaweed during storage. Bromoform is the bioactive compound in red seaweed that is responsible for inhibiting CH_4 production in ruminant animals (Glasson et al. 2022). In a few studies, red seaweed has shown low potential toxicology risks, but further research is recommended to confirm this finding. Other barriers to adding red seaweed to ruminant diets include palatability, potential decreases in animal productivity (e.g., milk production for dairy cattle), and lack of long-term studies (Glasson et al. 2022).

Because a wide range of feed additives have been studied for lowering enteric fermentation GHG emissions, mitigation potential for this category also has a wide range. Based on estimates from Honan et al. (2021) and EPA (2023), we found feed additives to offer an average 101 MMT CO_2e/yr GHG mitigation potential. Red seaweed was found to offer the highest mitigation potential for a feed additive (191 MMT CO_2e/yr), but it is relatively new, and more data are needed to increase confidence in its mitigating abilities.

Improved Feed and Forage Quality

Feed and forages can be categorized into fresh (e.g., grazed grasses) or conserved (e.g., silage), and they can greatly vary in quality (Hristov et al. 2013). Quality is highly correlated with digestibility. In a review paper, Hristov et al. (2013) found improving forage quality and the overall efficiency of dietary nutrient use to be one of the most effective methods for decreasing CH_4 in ruminant animals, but their results were somewhat inconsistent. van Gastelen et al. (2019) studied the variance of forage quality interventions among different ruminant livestock and found that interventions were most effective for dairy cattle, somewhat effective for beef cattle, and not effective for sheep. Data on the impact of feed and forage quality on CH_4 emissions are limited for the United States, and this represents a current research gap. In addition, barriers to increasing studies exist because accurately examining CH_4 impacts of grazing livestock is difficult.

Manure Management

Table 11 presents a summary of manure management.

Table 11. Manure Management Summary

Annual Emission Rate	83.4 MMT CO_2e/yr
Percentage of Agricultural GHG Emissions	11% (heavy emitter)
GHG	CH_4, N_2O
Most Impactful Solution	Anaerobic digestors
Other GHG Mitigation Solutions	• Alternative flooring • Lowering the dietary crude protein • Acidification of external slurry • Artificial film covers • Composting
Research Gaps for Quantifying GHG Mitigation Potential in the United States	• Alternative flooring • Composting
Takeaways	• Dairy cattle and swine make up 81% of emissions. • Manure management shows an increasing trend toward higher GHG-emitting liquid storage systems (e.g., anaerobic lagoons and liquid slurry storage). • Trade-offs exist between CH_4 and N_2O emissions based on anaerobic or aerobic conditions of the manure. • After the use of anaerobic digestors, acidification of external slurry offers the greatest mitigation potential in manure management.

Livestock manure can be stored in a solid state (e.g., manure piles from solids scraped from housing surfaces or solids separated from slurry) or a liquid state (e.g., anaerobic lagoons and slurry tanks/ponds) (Owen and Silver 2015). Livestock manure produces varying levels of CH_4 and N_2O based on management and storage practices (EPA 2023). CH_4 emissions are promoted through anaerobic conditions in liquid systems. N_2O emissions occur both directly through nitrification and denitrification of manure and urine (higher in solid/aerobic storage of manure), and indirectly through runoff, leaching, and volatilization. Manure management systems are trending toward liquid storage systems or higher CH_4-emitting systems in the United States (EPA 2023; Figure 10). In 2014, most farms in the United States used anaerobic lagoons (39%), followed by liquid slurry (23%); solid storage (20%); daily spread (13%); unmanaged manure in pastures, ranges, and paddocks (5%); and deep pit storage (2%) (Figure 10).

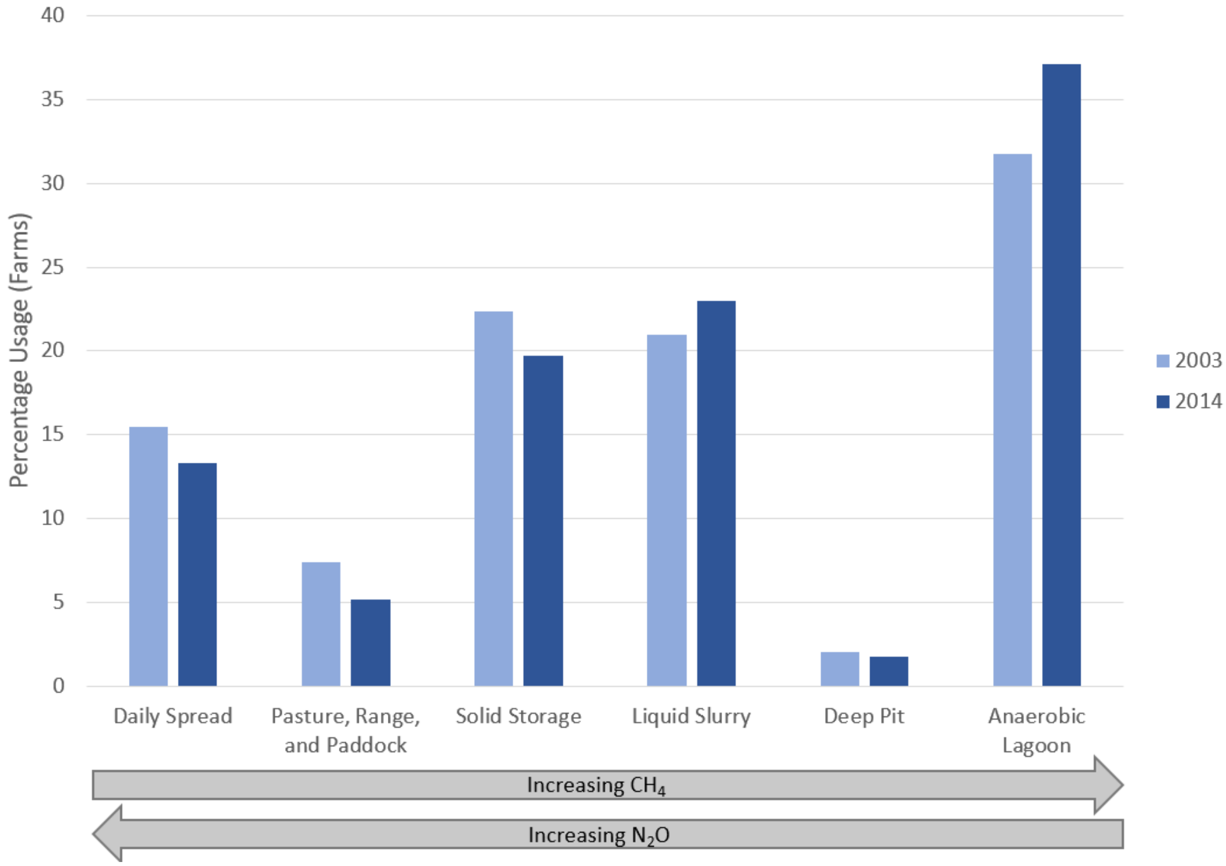

Figure 10. Manure management systems for dairy cattle in the United States

Data from Niles and Wiltshire (2019)

Manure composition, which is related to animal type and diet, can also impact the rate of CH_4 and N_2O associated with manure management. The main factors that influence CH_4 emissions in manure composition are energy content and digestibility of feed. N_2O emissions from manure composition can be influenced by the type of bacteria involved and the oxygen content of the manure. Research on the impact of leaching on GHG emissions from manure management operations is limited (EPA 2023). GHG emissions are expected to be minimal and are often coupled with runoff rates. Runoff rates would be correlated to housing or manure storage that is exposed to weather events.

In 2021, manure management was the third-highest-emitting category and consisted of 79% CH_4 and 21% N_2O (EPA 2023). Manure management contributed 9% of total U.S. CH_4 emissions and 5% of total N_2O emissions. From 1990 to 2021, total manure management emissions increased 62%. This included a 69% increase in CH_4 emissions and a 40% increase in N_2O emissions. Dairy cattle and swine production contribute the largest proportion of manure management emissions at 50% and 31%, respectively (Figure 11). From 1990 to 2021, dairy cattle manure management emissions increased 101% and swine manure management emissions increased 39% (EPA 2023). The main contributing factors to this growth include increasing dairy cattle and swine operation sizes and a shift toward liquid storage.

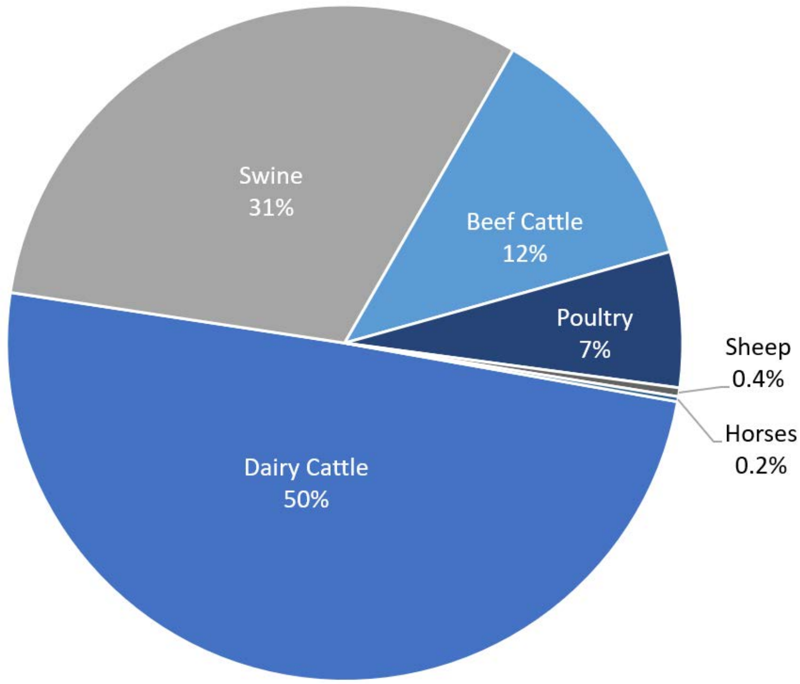

Figure 11. Manure management emissions by livestock in the United States in 2021

Data from EPA (2023)

We categorize potential GHG mitigation solutions into the following stages of manure management and/or storage system type: livestock production and housing, liquid/slurry manure storage, and solid manure heaps.

Manure Management GHG Mitigation Solutions

Crosscutting Solution: Energy efficiency and renewable energy production (on-site renewable gas production)

Livestock Production and Housing

Alternative Flooring

Both slatted-floor housing and deep litter mulch systems show lower manure management GHG emissions than standard concrete flooring systems (Hou, Velthof, and Oenema 2015). Slatted-floor housing has been shown to significantly reduce N_2O emissions associated with manure, but it does create conditions that might increase CH_4 emissions. Deep litter mulching can reduce CH_4 emissions, but it shows potential to increase N_2O emissions. Further research is recommended to understand total GHG fluxes when comparing alternative flooring and housing methods. We classify alternative flooring as a research gap in the United States.

Lowering Dietary Crude Protein

In one meta-analysis, decreasing the dietary crude protein of livestock was found to reduce direct and indirect N_2O emissions and overall GHG emissions by 5% from the manure chain (Hou, Velthof, and Oenema 2015). Mohankumar Sajeev, Winiwarter, and Amon (2018) found that lowering dietary crude protein decreased N_2O by 30% but increased CH_4 emissions by 71%.

Limited studies exist on evaluating GHG changes from dietary crude protein levels, but some show inconsistent changes to GHG emissions (Hou, Velthof, and Oenema 2015). Based on data from Hou et al. (2015) and EPA (2023), we estimate lowering the dietary crude protein to offer a mitigation potential of 0.5 MMT CO_2e/yr in the United States, and we recommend further research to lower the uncertainty of the strategy.

Liquid/Slurry Manure Storage (Anaerobic Decomposition)

Anaerobic lagoons and slurry storage systems emit significantly more GHG emissions per head than solid manure storage (Owen and Silver 2015). On average, anaerobic lagoons and slurry storage systems have a 20-fold higher global warming potential than solid storage. On a per-acre basis, slurry storage emits a slightly higher GHG rate than lagoons but has a lower GHG rate when compared on a per-head basis. With U.S. livestock manure systems trending toward these liquid/slurry systems, total manure management GHG emissions are likely to increase (EPA 2022a; Figure 10, page 44).

Acidification

Acidification of external slurry storage to around 5.5 inhibits methanogenesis and decreases CH_4 emissions by 87%, on average (Hou, Velthof, and Oenema 2015). Acids used in this process can include mineral acids (e.g., sulfuric acid and hydrochloric acid) or organic acids (e.g., lactic, acetic, and citric acid) (Overmeyer et al. 2021). Sulfuric acid is the most commonly used acid, but it can lead to high inputs of sulfur into soils. Overmeyer et al. (2021) suggest that organic acids can be used to replace mineral acids; however, they may require a higher application rate and more frequent addition and thus may increase overall acidification costs. When compared to combined CH_4 and N_2O emission from manure management, overall GHG can be decreased by 50% through acidification (Hou, Velthof, and Oenema 2015). Based on data from Hou et al., (2015) and EPA (2023), we estimate acidification of external slurry systems to offer a mitigation potential of 13 MMT CO_2e/yr in the United States. As a co-benefit, slurry acidification also shows potential to decrease ammonia (NH_3) emission in the manure chain by 83% (Hou, Velthof, and Oenema 2015).

Artificial Film Covers

One proposed solution for decreasing emissions associated with external slurry storage is the addition of various coverings (e.g., straw, granules, or artificial film). In a meta-analysis, Hou et al. (2015) found artificial film covers to be the most impactful of covers. N_2O emissions decreased by 98% and CH_4 emissions were also slightly decreased, but not significantly—resulting in an overall GHG decrease of 24%. Based on data from Hou et al. (2015) and EPA (2023), we estimate artificial film covers to offer a mitigation potential of 4 MMT CO_2e/yr in the United States. As a co-benefit, artificial film covers also show the potential to decrease NH_3 emission in the manure chain by 98% (Hou et al. 2015).

Solid Manure Heaps

Composting

Compared to stockpiling manure heaps, composting has been found to significantly lower CH_4 emissions, although results have been inconsistent across studies (Hou, Velthof, and Oenema 2015). Vanotti et al. (2008) found that the addition of aerated composting and cleaner aerobic technologies (e.g., treatment of liquid using aerobic biological nitrogen removal, chemical disinfection, and soluble phosphorous removal) reduced CH_4 by 99% and N_2O by 75% compared to untreated liquid lagoon storage. However, research on quantifying impact of composting on total GHG in the U.S. manure management chain is limited and is therefore classified as a research gap.

Agricultural Energy Usage GHGs and Mitigation Solutions

In this section, we evaluate the potential impact on mitigating GHGs in agricultural energy usage in the United States from additional opportunities beyond the crosscutting solutions discussed previously in the report. The main drivers of emissions from agricultural energy usage are fossil fuel combustion and on-site electricity consumption. Both GHG sources have a range of mature and emerging technologies to form the solution set for decarbonization.

Fossil Fuel Combustion

Table 12 presents a summary of fossil fuel combustion.

Table 12. Fossil Fuel Combustion Summary

Annual Emission Rate	39.1 MMT CO_2e/yr
Percentage of Agricultural GHGs	5% (moderate emitter)
GHG	CO_2
Most Impactful Solution	Renewable energy production
Other GHG Mitigation Solutions	• No-till • Precision agriculture • Electrification of farm equipment • Low-carbon biofuels
Research Gaps for Quantifying GHG Mitigation Potential in the United States	N/A
Takeaways	• Existing technologies can address on-farm fuel combustion for heating and irrigation. • Further research is needed to electrify tractors and other specialized farm machinery. • Further research is needed to quantify the potential for switching from liquid and gaseous fuels to electricity across the broad range of on-farm end uses.

On-farm fossil fuel combustion accounts for 5% of total agricultural GHG emissions and 26% of CO_2 emissions from the agricultural sector in the United States (EPA 2023). Direct energy consumption, including electricity and on-farm fuel combustion, comprises about 60% of agricultural energy consumption (Hitaj and Suttles 2016). Diesel and gasoline are widely used in trucks, tractors, and agricultural machinery used in farm operations. Natural gas and liquefied petroleum gas are both used to operate farm machinery, power irrigation systems, and provide heat for greenhouses, livestock operations, and grain dryers. Figure 12 illustrates the breakdown of farm fuel expenses by fuel type from 2013 to 2021. Diesel makes up the majority of farm fuel usage, followed by gasoline and liquified petroleum gas. On-farm fuel use varies by principal commodity, with rice and peanut producers having the highest fuel expenses per acre of production (Hitaj and Suttles 2016).

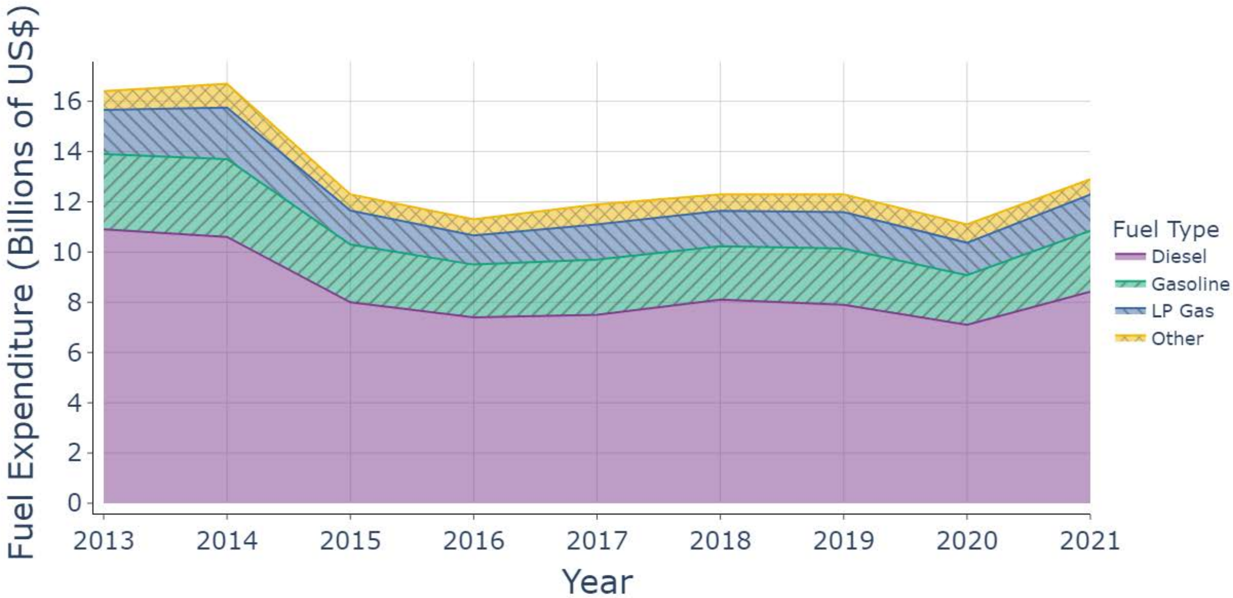

Figure 12. Farm fuel expenses by year (2013–2021)

Data from EIA (2023b, 2023c, 2023d); EPA (n.d.); USDA NASS (2023)

Fossil Fuel Combustion GHG Mitigation Solutions

Crosscutting Solutions: Energy efficiency, precision agriculture, and no-till

Electrification of Farm Vehicles/Equipment

Electrification of farm machinery is one option to reduce on-farm fuel combustion (Scolaro et al. 2021). The necessary technologies to achieve farm electrification range in maturity from widely commercialized to practically nonexistent, with many emerging technologies in early commercialization stages. Irrigation pumps and space heating can easily be converted to electric motors and heat pumps with existing technology. Electric trucks are now commercially available and capable of replacing internal combustion engine trucks. In contrast, electric versions of tractors and other specialized farm machinery (e.g., maple sap evaporators, grain dryers) are not widely available.

Northrup et al. (2021) estimate a 65% to 90% reduction in farm machinery tailpipe emissions from electrification of farm machinery and equipment. Based on data from Northrup et al. (2021) and EPA (2023), we estimate electrification of farm vehicles and equipment to provide 28 MMT CO_2e/yr of mitigation potential.

Barriers to equipment electrification include rural electric infrastructure limitations, high capital costs to switch, and reluctance of farmers to bear technology risk for vehicle lifespan and charging times. Another issue is that fleet turnover is extremely slow for tractors, with the average age of a tractor in the United States exceeding 25 years (Murphy et al. 2010).

To switch from fossil-fuel-powered to electrified farm equipment, approximately 55,000 to 67,000 GWh of electricity would be required (Clark 2018). This transition offers an additional $4.4 to $5.4 billion in potential annual revenue for rural electricity co-ops. These estimates include electrification of tractors, space heating, irrigation, grain dryers, evaporators, and water heaters.

Low-Carbon Biofuels

Replacing on-farm fuel use with low-carbon biofuels can at least partially mitigate the emissions impact of farm machinery. The use of biofuels makes the most sense for heavy machinery which is difficult to decarbonize, such as combine harvesters. The IEA Technology Roadmap: Biofuels for Transport (2011) estimates that biofuels will provide 27% of transport fuel by 2050. Using data from EIA (2023b, 2023c, 2023d), IEA (2011), and USDA NASS (2023) we estimate low-carbon biofuels to provide 7 MMT CO_2e/yr of mitigation potential (Table 1).

On-Site Electricity Usage

Table 13 presents a summary of on-site electricity usage.

Table 13. On-Site Electricity Usage Summary

Annual Emission Rate	34.4 MMT CO_2e/yr
Percentage of Agricultural GHGs	5% (moderate emitter)
GHG	CO_2
Most Impactful Solution	Renewable energy production
Other GHG Mitigation Solutions	• Energy efficiency technologies • Renewable-powered equipment
Research Gaps for Quantifying GHG Mitigation Potential in the United States	• Energy efficiency technologies • Renewable-powered equipment
Takeaways	• Mitigation potential is highly correlated to general grid decarbonization. • Potential constraints exist with current rural infrastructure.

Decarbonization of on-farm electricity consumption depends on general decarbonization of the electricity sector combined with on-site distributed energy resources and energy efficiency measures. Compared to the U.S. grid as whole, rural electric cooperatives have slightly higher dependence on coal, though there is significant regional variation (NRECA 2022; EIA 2023a). This regional variance in emission intensity has implications for emissions reductions pathways; incentivizing farm electrification produces greater emissions reductions in areas with lower carbon intensity of electricity. Farm electrification is an important strategy to reduce emissions from the agricultural sector but may be constrained by rural electric infrastructure. A large increase in demand from farms to accommodate charging of heavy farm machinery will require significant investment in capacity upgrades and distributed energy resources.

Data collection from farmers is very detailed for commodities, expenditures, and production but does not adequately capture energy consumption by end use. This makes it difficult to identify specific areas for energy efficiency improvement on farms, especially related to fuel switching for farm electrification. More research is needed to understand the potential emissions savings from farm electrification, including heat pumps for livestock space heating, electric irrigation pumps, and other emerging technologies, such as radio wave energy grain dryers. Future research should also characterize the barriers and constraints to farm electrification from rural electric infrastructure and should identify solutions to ensure reliability for farmers who invest significant capital into farm electrification.

On-Site Electricity Usage GHG Mitigation Solutions

Crosscutting Solutions: Renewable energy production and energy efficiency

Renewable-Powered Equipment

Equipment can be powered directly from renewable energy sources with or without interconnection to the grid. Solar generation can be paired with batteries to power motors for applications, such as irrigation or ventilation. Solar thermal heat can be used in applications such as space heating and grain drying, but it has not yet seen widespread adoption. Because of limited studies in the United States, we list renewable-powered equipment as a research gap.

Agricultural Carbon Sequestration Potential in Croplands and Grasslands

Table 14 presents a summary of agricultural carbon sequestration.

Table 14. Agricultural Carbon Sequestration Summary

Annual Emission Rate	N/A
Percentage of Agricultural GHGs	N/A
GHG	N/A
Most Impactful Solution	Agroforestry
Other GHG Mitigation Solutions	• No-till • Cover crops • Intercropping • Diversified crop rotation • Organic amendments • Grazing strategies • Perennial crops
Research Gaps for Quantifying GHG Mitigation Potential in the United States	• Intercropping • Organic amendments • Grazing strategies • Perennial crops
Takeaways	• Most agricultural carbon sequestration technologies are near-term and low-cost. • They offer high GHG mitigation impact (potentially over 100% of annual agricultural GHG emissions). • Significant barriers exist to widescale research, estimates, and implementation.

Evidence shows a significant GHG mitigation potential from carbon sequestration in agricultural soils (Chambers, Lal, and Paustian 2016). EPA (2023) estimates that in 2021, U.S. croplands had a net negative carbon flux of 19 MMT CO_2e; however, studies suggest a much greater potential for using agricultural soils as a carbon sink (Bai et al. 2019; Bossio et al. 2020; Paustian et al. 2016; Roe et al. 2021). Carbon cycling in the soils is also highly tied to nitrogen cycling, making it an important factor for managing N_2O from soil management.

Climate-smart agriculture practices, such as no-till, cover cropping, biochar application, and optimal grazing, have shown positive results for promoting soil carbon sequestration (Paustian et al. 2016). Evidence shows that soil carbon sequestration has an upper limit; however, agricultural systems will likely be unable to meet the saturation point with current soil disturbance practices (Stewart et al. 2007). Saturation levels and carbon sequestration potential depend on soil type, climate, agricultural practices, and cropping systems. Here, we evaluate the soil carbon sequestration/GHG mitigation potential of no-till, cover crops, intercropping, diversified crop rotation, organic amendment application, agroforestry, grazing strategies, and perennial crops. We also address current barriers to estimating and implementing SOC sequestration in croplands and grasslands.

Chambers, Lal, and Paustian (2016) found that U.S. croplands and grasslands could sequester enough carbon to offset 277 MMT CO_2e/yr. Annual potential included 45–98 MMT C/yr from croplands, 13–70 MMT C/yr from grasslands, 25–60 MMT C/yr from soil restoration, and 21–77 MMT C/yr from land conversion. Roe et al. (2021) found that the United States could sequester 1,024 MMT CO_2e/yr in agricultural land, with 547 MMT CO_2e/yr as cost-effective. Sperow (2016) estimated a 235 MMT CO_2e/yr mitigation potential with the use of no-till, the elimination of summer fallow, the incorporation of winter cover crops, and the removal of highly erodible land from crop production. Although carbon sequestration estimates have large ranges, Janzen et al. (2022) suggest that many current estimates overestimate the carbon sequestration potential in croplands. In our review, agroforestry showed the highest carbon sequestration in agricultural lands, followed by biochar, no-till, and cover crops (Table 1). Sequestration potentials should not be viewed as indefinite estimates because soils do saturate (Swan et al. 2022).

Carbon Sequestration Solutions

Crosscutting Solutions: No-till, integrated nutrient management, and biochar

Cover Crops

Research studies have demonstrated that incorporating both legume and nonlegume cover crops into agricultural systems can significantly enhance SOC levels (Jian et al. 2020). Legume cover crops, such as clover or hairy vetch, contribute to increased SOC through nitrogen fixation and subsequent deposition of nitrogen-rich residues (Jarecki and Lal 2003). The nitrogen input stimulates microbial activity, leading to enhanced organic matter decomposition and carbon sequestration in the soil. Furthermore, legume cover crops contribute to increased root biomass, adding to the organic carbon content of the soil (Rasse, Rumpel, and Dignac 2005). Nonlegume cover crops also play a vital role in SOC accumulation by providing aboveground and belowground biomass, which contributes to organic matter inputs (Six et al. 2002) . The decomposition of this biomass by soil microorganisms promotes SOC buildup over time (Gregorich et al. 1994). Moreover, nonlegume cover crops enhance soil structure, microbial activity, and organic matter stabilization, facilitating carbon sequestration (Dungait et al. 2012).

Jian et al. (2020) found cover crops to increase soil carbon, on average, by 15.5%, mostly because of a decrease in soil erosion and an increase in mineralizable carbon. Continuous cover crops and fall-planted cover crops have the potential to increase SOC stocks 20%–30% more compared to other time frames for growing cover crops (summer and overwintering) (McClelland, Paustian, and Schipanski 2021). Cover cropping in no-till systems has also been shown to enhance SOC sequestration compared to conventional till systems without cover crops. In a meta-analysis, Poeplau and Don (2015) estimate potential carbon sequestration saturation for winter cover crops to occur after 155 years of implementation. Abdalla et al. (2019) found that cover crops can be used to sequester SOC without significantly impacting direct N_2O emissions. For the United States, Fargione et al. (2018) estimate cover cropping to offer a mitigation potential of 103 MMT CO_2e/yr.

As of 2017, the adoption rate of cover crops in the United States is 5% of all harvested cropland, excluding alfalfa (USDA 2019; Wallander et al. 2021). This is an adoption increase of 50% from 2012. From 2012 to 2017, adoption rates vary greatly by state, with mostly eastern states having both high adoption and growth rates (e.g., Maryland, Pennsylvania, Virginia, and Georgia). Cover crop adoption declined over the same period in New Mexico, Colorado, Washington, and

Wyoming. The overall low adoption rate shows the high potential for carbon sequestration from adding cover crops into farmers' rotations across the United States.

Intercropping

Intercropping in maize-wheat, maize-fava bean, and wheat-fava bean productions has been found to increase SOC compared to monocropping systems (Cong et al. 2015). In an international study, Cong et al. (2015) found a potential increase in SOC of 184 ±86 kg C ha^{-1} yr^{-1} from intercropping. Intercropping has also been found to increase both aboveground and belowground biomass as well as improve land use efficiency for yields. Because no U.S.-based studies quantify carbon sequestration potential from intercropping, we list it as a current research gap. Because it is a relatively new practice, no data were found on the adoption rate of intercropping in the United States.

Diversified Crop Rotation

By promoting soil biodiversity and enhancing aboveground/belowground interactions, diversified crop rotation can also improve carbon cycling and increase SOC storage (K. Zhang, Maltais-Landry, and Liao 2021). For corn production, switching from 2-year to diversified 4-year rotations can increase SOC content (Jarecki et al. 2018). Maiga et al. (2019) found that diversified, no-till corn systems increased SOC, on average, more than 15% compared to a 2-year no-till rotation. West and Post (2002) estimate an 81 ±49 kg C per acre/yr sequestration potential of diversified crop rotation in the United States. Based on data from West and Post (2002), USDA (2019), and T. Wang et al. (2021), we estimate diversified crop rotation to offer a 28 MMT CO_2e/yr mitigation potential in the United States.

Bowles et al. (2020) found that increasing crop rotation diversity increased yields in a variety of growing conditions in North America—including drought—thus improving climate resilience without negative effects to food security. In the United States, 56.9% of farmers state that they use diversified crop rotation, and only 18.7% use continuous diversified crop rotation instead of 2-, 3-, or 4-year diversified crop rotations (T. Wang et al. 2021).

Organic Amendments

Organic amendments are a source of organic carbon, and they improve the SOC pool by increasing net primary production (i.e., fixing carbon through photosynthesis) (Tiefenbacher et al. 2021). However, organic amendments may stimulate SOC biodegradation and thus contribute to carbon loss. Organic amendments contribute to carbon sequestration when the material is not displaced from another system and subsequent erosion is prevented. Three organic amendments show potential to sequester SOC: compost, manure, and crop residues (Tiefenbacher et al. 2021).

In a meta-analysis of organic amendments in croplands, Tiefenbacher et al. (2021) found compost to sequester the highest rate of SOC followed by farmyard manure and then crop residues (e.g., corn stover and wheat straw). Compost has also been found to provide additional agronomic benefits, such as pest and disease suppression, soil moisture and erosion benefits, and improved crop yields and biodiversity (Martínez-Blanco et al. 2013). Solid farmyard manure was found to provide greater carbon sequestration benefits than liquid slurry (Zavattaro et al. 2017). The sequestration rates of crop residues depend on the C:N ratio of the residue, with a higher C:N ratio increasing SOC and a lower C:N ratio stimulating microbial decomposition

(Tiefenbacher et al. 2021). For example, a corn residue can increase SOC, but a lower C:N ratio crop in rotation (e.g., legumes) can potentially reverse the overall carbon contribution of crop residue (J. Chen et al. 2018).

The addition of organic amendments can also enhance carbon sequestration in rice paddies, and organic amendments such as poultry manure, rice straw, and cow manure all had greater increases in SOC than inorganic chemical fertilizers (Rahman et al. 2022). Poultry manure showed the greatest difference (50%) compared to inorganic fertilizers (27%) in a 5-year experiment (Rahman et al. 2022).

The potential for organic amendments to sequester SOC in the United States is found in limited publications in the United States and thus represents a research gap. Adoption rates for organic amendments in the United States are also a current data gap. To understand the potential for agricultural GHG mitigation of organic amendments in U.S. croplands and grasslands, widescale empirical studies and adoption rates will be needed.

Agroforestry

Agroforestry is the integration of trees and/or shrubs into cropland and grasslands. Practices can include windbreaks, alley cropping, and silvopasture. Mayer et al. (2022) found that 70% of agroforestry systems in temperate climates show a higher SOC than controls in the topsoil (top 20 cm), and 81% show a higher SOC in the subsoil (20–40 cm). Hedgerows and alley cropping systems showed the highest mean increase of SOC sequestration for agroforestry systems, and silvopasture showed a slight mean decrease. In a global meta-analysis, Ma et al. (2020) found that, on average, agroforestry systems have 46.1 Mg/ha more carbon than sole cropland or pasture systems. Ma et al. (2020) also found a higher initial carbon accumulation rate with young trees but a higher overall biomass carbon stock and change in SOC stock in agroforestry systems with older trees. Multiple tree species systems were found to have a higher SOC sequestration rate than single-species tree systems. Roe et al. (2021) estimate a mitigation potential of 381 MMT CO_2e/yr from agroforestry systems in the United States. The current adoption rate of agroforestry in the United States is 1.7% of farms (USDA 2019a). Because agroforestry shows a high potential for carbon sequestration and the current adoption rate is low, the United States shows high GHG mitigation potential for adopting agroforestry practices.

Grazing Strategies

Conant et al. (2017) found that improved grazing strategies, conversion from cultivation to grass, fertilization, sowing legumes, improved grass species, and improved irrigation all led to an increase in SOC. In grazing systems, SOC has shown to be strongly correlated with root production, root mass, and turnover (W. Chen et al. 2015). W. Chen et al. (2015) found that grazing strategies had varying effects on these variables. Constant moderate grazing showed the highest root production and highest SOC for all grazing treatments. Constant high-pressure grazing and reduced grazing pressure in the last grazing stage showed the lowest root production, root mass, and turnover and therefore the lowest rate of SOC. In a meta-analysis, adaptive multipaddock farms had, on average, 13% more SOC than conventional grazing farms (Mosier et al. 2021). Results from individual experiments demonstrated long-term SOC storage through a transition to more persistent soil organic matter. Based on data from Conant et al. (2017) and Fargione et al. (2018), we estimate grazing strategies to offer a mitigation potential of 91 MMT CO_2e/yr. However, some studies show inconsistent results, and further U.S.-based empirical studies are recommended to increase confidence in the GHG mitigation potential of alternative grazing strategies.

Perennial Crops

Using annual monocultures has led to ecosystem disservices, such as organic carbon loss, soil erosion, nutrient contamination and loss, and increased disease and pest pressure (T. Crews and Cattani 2018). Use of perennial crops has been proposed to lessen these negative impacts and improve SOC sequestration in agricultural systems. One study found that a transition from annual crops to perennials increased SOC 20% in the top 30 cm of soil and 10% over a 100 cm soil profile (Ledo et al. 2020). Limited studies have been carried out in the United States with current research focused on perennial grains (T. E. Crews, Carton, and Olsson 2018). Further research is needed to quantify the potential SOC increase and/or erosion prevention from perennial crops in the United States. A transition to a perennial food system would likely involve a long-term strategy with breeding trials and decreasing barriers to widescale farmer adoption.

Barriers to SOC Sequestration Estimations and Implementation

Though the United States shows high potential for soil carbon sequestration in agricultural soils, barriers exist for estimating sequestration potentials and for implementation of SOC-increasing practices. Barriers include variance in agricultural systems, current research gaps, decreasing SOC measurement uncertainties, and implementation obstacles (Table 15).

Table 15. Barriers to SOC Sequestration Estimations and Implementation

Agricultural Variance	Research Gaps	SOC Measurement	Implementation
• Variety of soil types • Diverse range of agricultural systems and practices • Varying climates • Different base levels of SOC • Field-level variance	• Lack of widescale research infrastructure • Shortage of long-term experiments • Lack of agricultural land management data • Need for further understanding C-N cycling dynamics, soil microbiology, and deep soil carbon stability • Lack of consensus on SOC storage potential	• High cost and time requirements of widescale field sampling • Lack of full soil profile measurements (~1 m) • SOC impermanence • Failure to monitor changes in N_2O emissions	• Cost to farmer to implement practices • Farmer learning curve • Potential to increase labor needs • Lack of land ownership (40% lease rate) • High requirement for other nutrients (N, P)

Agricultural Variance

SOC saturation levels are highly dependent on local pedoclimatic conditions as well as land use and land management practices (Rumpel et al. 2020). Sperow (2016) found 90% of total SOC sequestration potential in the United States occurs in moist climatic regions, mainly cold and warm temperate regions. Irrigation methods also influence SOC sequestration rates; however, the initial soil carbon content and climate have varying impacts on SOC storage when combined with irrigation methods (McGill et al. 2018; Rumpel et al. 2020). Current models also show soil organic matter (and therefore SOC) losses are higher when agricultural productivity is increased (Sanderman et al. 2017).

Irrigation can also have contrasting effects on SOC levels. Proper irrigation practices can increase SOC through enhanced plant growth, increased organic inputs, and improved soil moisture conditions (Y. Li et al. 2018; J. Zhang et al. 2021). However, excessive irrigation or poor water management can lead to waterlogging, poor drainage, and soil erosion, resulting in SOC loss (G. Lal et al. 2019). Soil texture and composition also play a role, with sandy soils potentially experiencing less SOC accumulation. Effective irrigation management—considering factors such as water application, drainage, and soil characteristics—is crucial for maintaining or increasing SOC levels.

Research Gaps

Uncertainties exist for estimating SOC sequestration potential in agricultural systems. Barriers to close these gaps include a lack of research infrastructure and agricultural land management data, a shortage of long-term experiments, and a need for better understanding of C-N cycling dynamics, soil microbiology, deep soil carbon stability, and SOC storage potential.

SOC Measurement

SOC monitoring, reporting, and verification face challenges for accurately representing SOC sequestration potential and permanence. Factors that may influence storage include SOC stability, reversibility if agricultural practices are not maintained, and varying SOC saturation rates (Rumpel et al. 2020). SOC saturation may occur after 20–120 years depending on pedoclimate conditions and climate change impacts. Effects from climate change will also influence the permanence of stored SOC in agricultural soils (Fargione et al. 2018). Accounting for SOC losses because of climate change, erosion, or future agricultural management practices will be needed for accurate GHG mitigation estimates.

Though the scientific consensus is that many suggested practices increase SOC, little research includes the impact these practices have on N_2O emissions. Because carbon and nitrogen cycles are highly connected, it is important to measure and report the full C-N dynamic for all proposed sequestration practices (Guenet et al. 2021). For example, although no-till may provide SOC sequestration benefits, it may also increase N_2O emissions (Guenet et al. 2021). Using leguminous cover crops may have similar impacts on SOC and N_2O (Lugato, Leip, and Jones 2018a). Irrigation can also increase SOC sequestration rates at the expense of increasing N_2O emissions (Trost et al. 2013). Ignoring the impact on N_2O emissions may cause overestimations of GHG mitigation potential of agricultural practices.

Implementation

Farmers are likely to implement SOC sequestration practices only if there is potential to increase long-term profits and productivity (Rumpel et al. 2020). Currently, 40% of farm acres are leased in the United States (USDA 2019a). Lack of land ownership presents barriers to implementation because farmers will not engage in long-term investments (e.g., agroforestry) if leases are short-term or management practices are limited.

The need for other nutrients (e.g., nitrogen and phosphorous) to increase SOC sequestration has also been raised as a concern (Rumpel et al. 2020). Because nitrogen and phosphorous are needed for plant production and carbon input, several articles have deemed the high rate of nutrient requirements unrealistic. Furthermore, the application of nitrogen fertilizers increases N_2O emissions, potentially offsetting the GHG benefits.

Discussion

U.S.-Based Agricultural Decarbonization

Various U.S. agencies have funded decarbonization efforts and climate-smart agricultural practices to push toward low GHG-emitting agricultural systems (Department of Energy [DOE] 2022; USDA 2022). However, for some proposed agricultural GHG mitigation technologies, the rate of adoption has been limited because of various implementation barriers for farmers (e.g., a 5% cover crop adoption [USDA 2019; Wallander et al. 2021]). EPA (2019) estimates the mitigation potential of total annual agricultural GHG emissions to be 15% by 2030. This reduction lowers total annual non-CO_2 GHG emissions by 26% in the United States and consists of reductions of livestock emissions (27%), cropland emissions (3%), and rice cultivation emissions (55%). Roe et al. (2021) suggest that the United States could mitigate 93 MMT CO_2e/yr in agricultural lands (or 13% of total GHG emissions) with 72 MMT CO_2e/yr (10%) being cost-effective. They estimate the addition of SOC sequestration in croplands to offer an additional mitigation potential of 1,024 MMT CO_2e/yr (or 142% of total emissions). Sperow (2016) estimates a lower SOC sequestration potential of a 55% mitigation rate of agricultural emissions in the United States.

With 79% of U.S. agricultural production emissions originating from soil management, enteric fermentation, and manure management (EPA 2023), these represent important categories to address for achieving substantial levels of agricultural decarbonization. GHG emissions from soil management were found to be the hardest to abate with currently available solutions showing minimal mitigation potential (Table 1). Future research is warranted in this area to uncover higher-impact GHG mitigation solutions to address the largest source of agricultural GHG emissions. Enteric fermentation was found to be mostly correlated to livestock populations, with some long-term solutions showing mitigation potential by 2050. To move decarbonization efforts forward, improving mitigation solutions, decreasing uncertainties, and closing research gaps in these areas will be important.

Near-Term Opportunities: Existing Technologies

Current technologies can largely address GHGs associated with manure management (e.g., anaerobic digestion, slurry acidification, and artificial film covers), land use conversion to croplands (forest, grassland and wetland conversion avoidance, and sustainable bioenergy production), on-site electricity usage (energy efficiency and renewable energy production), rice cultivation (alternate wetting and drying), urea fertilization (precision agriculture and INM), liming (precision agriculture and biochar), and field burning (no-till and bioenergy production). In addition, current practices are ready for adoption for increasing carbon sequestration in croplands (grazing strategies, diversified crop rotation, intercropping, cover crops, agroforestry, biochar, no-till, and organic amendments). Although many proposed solutions do not require further technological advancements, barriers to adoption for farmers exist, slowing adoption rates. Further research is warranted to better understand and address these barriers and improve certainty of the mitigation potential of proposed solutions.

Long-Term Opportunities: Technology and Practice Improvement

Long-term opportunities involve widespread research on lowering research gaps and uncertainties for decreasing GHGs from the two highest and hardest-to-abate agricultural GHG sources: N_2O emissions from soil management and CH_4 emissions from enteric fermentation. Though some technologies exist for partial mitigation (e.g., precision agriculture and enhanced efficiency fertilizers for soil management and feed additives for enteric fermentation), substantial mitigation of these GHG sources is likely not possible with currently available solutions.

For enteric fermentation, selective breeding of livestock will likely require decades before it can be an impactful and widespread solution through requiring lengthy breeding trials (Pickering et al. 2015). Other proposed solutions for enteric fermentation, such as feed additives, require that they be safe for animal consumption and that new supply chains are created. Historically, enteric fermentation GHG emissions have been correlated to livestock populations and will likely continue to be.

N_2O emissions from soil management are also difficult to abate because many emission-producing processes are part of natural biogeochemical cycles. Application of nitrogen fertilizers, however, does significantly increase N_2O emissions in agricultural systems (EPA 2023). Some enteric fermentation and soil management GHGs may need to be offset through other agricultural mitigation efforts (e.g., carbon sequestration in agricultural lands) until new technologies are uncovered. Though carbon sequestration practices exist and can be implemented in the short term, it will likely take decades of implementation for full carbon sequestration potential to be realized.

Importance of Accounting for Total GHG Fluxes

Carbon-Nitrogen Cycle

Soils can be either a carbon source or a carbon sink for atmospheric CO_2, depending on which field management operations are adopted. The carbon-nitrogen cycle starts with photosynthesis, which provides biomass that will be either harvested or left in the field. The dead biomass from rooting systems or aboveground biomass is the main source for SOC formation via microbial decomposition, which is moderated by soil temperature and moisture. Of the nutrients plants require, nitrogen is the most important from agronomic, environmental, and economic perspectives.

Nitrogen fertilization exerts a significant influence on the cycling of carbon and nutrients. Being the primary macronutrient that determines crop yield, nitrogen fertilizer can enhance the productivity of various crops (Linquist et al. 2013; X. Zhang et al. 2015). However, it is important to note that nitrogen fertilization is typically a major contributor to GHG emissions, particularly N_2O. Agricultural N_2O emissions generally increase as nitrogen fertilization rates increase (Maaz et al. 2021; Millar et al. 2010b; Y. Wang et al. 2020). Therefore, although nitrogen fertilization plays a positive role in enhancing production and carbon sequestration, its benefits may be counteracted by N_2O emissions.

Tillage, use of cover crops, and crop residues can impact both carbon-nitrogen cycling and rate of GHG emissions. For example, tillage exposes sequestered SOC to air and makes it accessible for soil microbes. The adoption of conservation tillage practices is considered an effective means for reducing increase rate of atmospheric CO_2 by minimizing SOC decomposition (R. Lal 1997). Many field empirical studies have demonstrated that reduced till or no-till increases both total and active SOC (Dou, Wright, and Hons 2008; Dou and Hons 2006; A. L. Wright and Hons 2005). However, reports indicate that increased N_2O emissions attributed to enhanced soil moisture content and available SOC may offset the benefits obtained from conservation tillage (Ball, Scott, and Parker 1999; Shahidi et al. 2020). Nonetheless, Six et al. (2004) and Plaza-Bonilla et al. (2014) have suggested that maintaining long-term no-till practices may lead to reduced N_2O emissions, potentially because of soil structure improvements. In some cases, short-term no-till systems have shown either the same or lower N_2O emissions (Malhi and Lemke 2007; Pelster et al. 2011).

Although cover crops can increase SOC, legume cover crops can increase N_2O emissions and nonlegume cover crops can decrease N_2O emissions (Lugato, Leip, and Jones 2018b). Legume cover crops, by fixing atmosphere nitrogen into soil systems, increase the nitrogen pool for potential losses. Nonlegume cover crops could contribute to N_2O reduction by improving soil health and nutrient cycling, minimizing nitrogen losses and potential N_2O production (Malik et al. 2013). However, studies have demonstrated that incorporating both legume and nonlegume cover crops in agricultural systems can effectively mitigate N_2O emissions by adjusting synthetic nitrogen rate. Legume cover crops, such as clover or alfalfa, provide a natural nitrogen source through nitrogen fixation, reducing the need for synthetic nitrogen fertilizers and subsequently decreasing N_2O emissions (Hansen et al. 2013). Similarly, crop residue return increases SOC but also has the potential to increase soil microbial activities and associated GHG emissions (Saffigna et al. 1989; Y. Wang et al. 2017). Generally, the return of residue leads to increased emissions of CO_2 and N_2O, with the magnitude of increase influenced by residue carbon/nitrogen ratios, nitrogen fertilization, and tillage practices (Baggs et al. 2003; Y. Huang et al. 2004). However, exceptions exist where residue incorporation results in similar or lower N_2O emissions (Baker, Fassbinder, and Lamb 2014; Hao et al. 2014).

N_2O-CH_4 Relationship

In several proposed GHG mitigation solutions, trade-offs existed when decreasing N_2O or CH_4 emissions. Instances of these trade-offs were found in the GHG source categories of manure management and rice cultivation. For example, when analyzing alternative flooring systems for manure management, slatted-floor housing decreased N_2O and increased CH_4 emissions whereas deep litter mulch systems decreased CH_4 and increased N_2O emissions (Hou, Velthof, and Oenema 2015). Lowering the dietary crude protein for livestock was found to decrease N_2O but increase CH_4 emissions in manure management (Mohankumar Sajeev, Winiwarter, and Amon 2018). For rice cultivation, alternate wetting and drying was found to decrease CH_4 but also significantly increase N_2O (Liao et al. 2020). In one study, using no-till systems in rice cultivation also showed a decrease in CH_4 but an increase in N_2O (X. Zhao et al. 2016). Many studies focus on either N_2O or CH_4 but do not evaluate the full GHG flux, potentially overestimating the mitigation potential of different solutions.

Food-Energy-Water Nexus

When evaluating the effectiveness and practicality of proposed GHG mitigation solutions, it is important to understand how they relate to the food-energy-water nexus. The food-energy-water nexus can be described as "the complex and inter-related nature of our global resources systems… It is about balancing different resource user goals and interests – while maintaining the integrity of ecosystems" (FAO 2014, p. 3). For example, cover crops show potential to increase soil carbon sequestration but will require irrigation in many parts of the United States. To determine whether cover crops are an effective strategy, understanding water availability as well as carbon sequestration potential is important. Another trade-off to consider is between growing food crops and bioenergy crops. Both crops require land, energy, and water but contribute benefits to different sectors. Avoiding conversion of natural ecosystems to cropland may decrease available land for food production; however, using strategies such as sustainable intensification can increase food production per acre of farmland.

Some agricultural GHG mitigation solutions provide co-benefits to the food-energy-water nexus. For example, agrivoltaics has the potential to provide benefits to farms, reduce water use, and increase renewable energy production. Agrivoltaics has been found to decrease plant drought stress, increase food production, and reduce stress on photovoltaic panels in arid regions (Barron-Gafford et al. 2019). In a field study in Oregon (United States), Hassanpour Adeh et al. (2018) found that agrivoltaic sheep pastures increased water efficiency by 328% and late season biomass by 90%. Dinesh and Pearce (2016) found that if lettuce cultivation in the United States were converted to agrivoltaic systems, an additional 40–70 GW of solar photovoltaic power could be generated. Studies have found varying impacts on crop yields depending on crop type and climate (Macknick et al. 2022). In some locations, shade-tolerant crops would need to be considered to prevent crop yield reduction and increase farmer adoption (Dinesh and Pearce 2016). Agrivoltaics can produce further benefits by incorporating other GHG mitigation strategies; for example, INM has been shown to increase crop productivity and water use efficiency (Jat et al. 2015).

Decreasing food waste is out of scope for this study but could lessen stress on the food-water-energy nexus in the United States. In 2010, food loss and waste accounted for 35% of energy use, 34% of blue water use, 34% of GHGs, 31% of land use, and 35% of fertilizer use for an individual's food footprint in the United States (Birney et al. 2017).

Co-Benefits and Trade-Offs

Climate-smart agriculture practices, such as no-till, intercropping, cover crops, and precision agriculture can provide benefits beyond GHG mitigation and carbon sequestration. These benefits can include direct farmer benefits, ecosystem services and ecological benefits, and socioeconomic benefits. Trade-offs also exist for implementation of these agricultural practices, especially to farmers. Further understanding and quantifying potential synergies and trade-offs could assist in the adoption of climate-smart agricultural practices that provide benefits to farmers.

Farmer Benefits

Many proposed GHG mitigation solutions have shown to offer further benefits to farmers. For example, precision agriculture has shown potential to increase crop yields, lower fertilizer and pesticides costs, and lessen pest resistance (Balafoutis et al. 2017). A study from the USDA illustrates the profitability of precision agriculture but states that the impact is often small, with studies showing inconsistent results (Schimmelpfennig and Schimmelpfennig 2016).

Cover crops have also been shown to provide benefits, such as improving cash crop productivity, nutrient cycling efficiency, soil and water quality, and pest suppression. One study showed that early-season cover crops were more effective at preventing pest damage than integrated pest management and preventative pest management (Rowen et al. 2022). Cover crops also reduced weed biomass and increased beneficial predator abundance. No-till has shown additional benefits, such as improving crop water availability and resistance to drought, decreasing erosion and land degradation, and decreasing fuel costs and labor requirements (Derpsch et al. 2010).

Farmer Trade-offs and Barriers

In some instances, implementation of agricultural GHG mitigation solutions shows potential to negatively impact farmer profits and/or crop yields. For example, in a meta-analysis of 678 studies, no-till systems led to 5% lower yields, on average (Pittelkow et al. 2015). However, when examining no-till in dry climates under rainfed conditions, there was no difference in yields compared to traditional systems. The addition of cover crops has also shown to impact farmer economics. The costs of seeds, necessary equipment, and labor are additional expenses for the farmer without certainty that they will lead to higher yields or profits (Bergtold et al. 2019). In one study, no-till was less profitable than conventional; however, no-till became the more profitable choice when cover crops were integrated into the system (Zhou et al. 2017).

Although precision agriculture has shown to be profitable in some studies, farmers still frequently report that the cost of adopting precision agriculture outweighs the benefits, leading to their decision to not adopt the technology (Erickson and Lowenberg-DeBoer 2020). Time requirements for using and learning new technologies, availability of high-speed connectivity, and data privacy concerns also present additional barriers (Shafi et al. 2019). Similarly, agroforestry has shown barriers to farmer adoption, such as costs and time requirements establishing and managing trees, lack of tree management expertise, and uncertainties in profitability (Valdivia, Barbieri, and Gold 2012). Although many of these agricultural systems and technologies show the ability to mitigate GHGs, it is important to understand the barriers to entry for farmer implementation.

Ecosystem Services and Ecological Benefits

Some proposed solutions can provide ecosystem services. For example, carbon sequestration in croplands and grasslands can have a positive impact on the physical, chemical, biological, and ecological qualities of soil (R. Lal 2014). Carbon sequestration can reduce erosion and improve water retention, water quality, soil biodiversity, aeration, nutrient cycling, and productivity. Climate-smart agricultural practices can also improve climate regulation and resiliency to climate change, including severe weather events such as flooding and drought (Lipper et al. 2014). Smith et al. (2019) add further potential ecosystem service benefits of carbon sequestration, such as habitat creation; air quality regulation; disease regulation; medicinal, biochemical, and genetic resources; learning opportunities; and inspiration. These increases in ecosystem services also offer potential economic benefits to farmers through payments from opportunities such as carbon credits, carbon maintenance fees, and payments for ecosystem services (R. Lal 2014).

Socioeconomic Benefits

Some agricultural GHG mitigation solutions can offer socioeconomic benefits. Climate-smart agricultural practices can improve food security by improving crop yields and climate resiliency of agricultural systems (Lipper et al. 2014). Carbon sequestration practices show potential to contribute toward many of the United Nations Sustainable Development Goals (SDGs). Smith et al. (2019) found that agricultural carbon sequestration helped work towards 11 SDGs:

- SDG 1: End poverty in all forms everywhere
- SDG 2: End hunger, achieve food security and improved nutrition, and promote sustainable agriculture
- SDG 3: Ensure healthy lives and promote well-being at all ages
- SDG 6: Ensure availability and sustainable management of water and sanitation for all
- SDG 8: Promote sustained, inclusive and sustainable economic growth, full and productive employment, and decent work for all
- SDG 9: Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation
- SDG 11: Make cities and human settlements inclusive, safe, resilient, and sustainable
- SDG 12: Ensure sustainable consumption and production patterns
- SDG 13: Take urgent action to combat climate change and its impacts
- SDG 14: Conserve and sustainably use the oceans, seas, and marine sources for sustainable development
- SDG 15: Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably managed forests, combat desertification, halt and reverse land degradation, and halt biodiversity loss.

Research Gaps and Future Studies

This study is meant to establish a foundation for future agricultural decarbonization research, present initial estimates for agricultural decarbonization solutions in the United States based on available data, and provide guidance for addressing relevant research gaps. Future empirical research and meta-analyses are recommended to close the research gaps listed in Table 2 (reproduced here as Table 16) and to improve accuracy of quantifying mitigation potential for all agricultural decarbonization solutions in the United States. Empirical studies that include different climates, soils, and agricultural systems will help improve confidence in estimates. Recent collaborative efforts by the USDA also point to the opportunities to translate scientific research and insights into solutions that support more sustainable land use, agricultural production practices, and community-engaged research (Colorado State University and Meridian Institute 2023)

Table 16. Research Gaps for Quantifying Agricultural GHG Mitigation Solutions in the United States

GHG	GHG Source/Carbon Sequestration Practice	GHG Mitigation Solution Research Gaps
N_2O	Soil management	Integrated nutrient management, biostimulants, no-till, grazing strategies, improved irrigation strategies, and biochar
	Manure management	Alternative flooring systems for livestock housing
CH_4	Enteric fermentation	Improved feed and forage quality
	Manure management	Composting
	Rice cultivation	Deepwater rice fields, straw management, and low-methane rice varieties
CO_2	Land use conversion to croplands	Sustainable intensification
	On-site electricity use	Energy efficiency and renewable-powered equipment
	Urea fertilization	Integrated nutrient management and precision agriculture
	Liming	Biochar
	Carbon sequestration potential	Intercropping, perennial crops

Significant research gaps exist for mitigation solutions of N_2O emissions for soil management, the largest source of agricultural GHG emissions in the United States. Developing new technologies and systems will help increase mitigation options to work toward more substantial decarbonization of the sector. Integrated nutrient management—a crosscutting solution—also showed large research gaps for quantifying mitigation potential in the United States. For agricultural carbon sequestration, focusing on decreasing uncertainties in SOC saturation potentials, variance of SOC along the full soil profile, and permanence of SOC in soils will help to better understand the potential for using carbon sequestration as a significant GHG mitigation solution. For farm energy usage, collection of data for on-farm end-use energy consumption will enable research to better uncover technologies that address the highest energy consumption and estimate their mitigation potential. Little data also exist on evaluating agricultural GHG emissions across the entire supply chain (i.e., including pre- and postproduction GHG emissions).

The collection of individual studies does not account for potential trade-offs of a particular GHG mitigation solution on other GHG emission sources, and the individual mitigation strategies are not necessarily additive—meaning that the actual total potential mitigation opportunity will be less than the sum of the individual mitigation solutions added together. Because many of the reviewed studies use different methodologies, boundary conditions, and input data sets to estimate GHG mitigation potential, there are high uncertainties when comparing decarbonization solutions. Regional variations in soil, climate conditions, and agricultural practices can also affect the national applicability of these results. Standardization of methodologies and assumption harmonization across different studies combined with increasing empirical data collection will help lessen these uncertainties.

Conclusions

Addressing agricultural emissions has been identified as an important aspect of mitigating anthropogenic climate change. Abatement of N_2O, CH_4, and CO_2 emissions through technology adoption and increasing carbon sequestration in agricultural soils would significantly lower the current GHG contribution of agriculture in the United States. High-impact mitigation solutions (agroforestry, biochar application, no-till systems, cover crops, grazing strategies, livestock feed additives, and renewable energy production) and crosscutting solutions (energy efficiency and renewable energy production, precision agriculture, INM, no-till, and biochar) show the greatest potential for agricultural decarbonization based on available data from U.S.-based studies. Continued research efforts for reducing the two largest agricultural GHG sources (soil management and enteric fermentation) will be crucial for improving mitigation strategies for these hard-to-abate sources. Emphasis on lowering barriers to entry for farmers will improve the rate of adoption and implementation. To increase confidence in mitigation potentials across the United States, on-farm data should be collected and analyzed across varying climates, soils, agricultural systems, and land management techniques. Further understanding the co-benefits and/or trade-offs of proposed technologies or practices and their impacts on the food-water-energy nexus, food security, and farmer profitability would create a better understanding of the full benefits of, or barriers to, adopting each solution.

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Appendix A. Individual Methodologies for Agricultural GHG Mitigation Solutions and Sinks—Table 1

N_2O

Soil Management

Precision Agriculture/Nutrient Management

Roe et al. (2021) estimate nutrient management to mitigate 11.2 MMT CO_2e/yr (7.7–14.6 CO_2e/yr) in the United States. They use per hectare GHG mitigation reduction potential from both Griscom et al. (2020) and Beach et al. (2015) multiplied by applicable hectares in the United States (160,436,800 ha) to get the average and range of technical N_2O mitigation potential from nutrient management.

Enhanced Efficiency Fertilizers

Akiyama et al. (2010) performed a global meta-analysis on the impact of enhanced efficiency fertilizers (EEFs) on soil N_2O emissions. They included 113 data sets of field experiment data from 35 studies. Although not all studies were based in the United States, the meta-analysis showed the most comprehensive analysis on EEFs and did include some field studies from the United States. EEFs that showed N_2O mitigation potential included nitrogen inhibitors (-38% decrease [-44% to -31%]) and polymer-coated fertilizers (35% decrease [-58% to -14%]). A 36.5% average reduction from EEFs was then multiplied by annual N_2O soil emissions from synthetic fertilizers (EPA 2023) to get an average of a 22.9 MMT CO_2e/yr reduction. The process was then repeated for the upper and lower confidence interval (CI) range to estimate an 8.8–36.4 MMT CO_2e/yr potential mitigation.

Manure Management

Lowering Dietary Crude Protein

In a meta-analysis, Hou et al. (2015) examined different manure management strategies for lowering associated emissions. They found a 15% reduction of N_2O in solid-based manure systems from lowering the dietary crude protein in livestock. Niles and Wiltshire (2019) found that the percentage of livestock operations with solid-based manure systems in the United States is 19.7%. We multiplied these percentages with annual N_2O manure management GHG emissions in the United States as reported by EPA (2023) to get a 0.5 MMT CO_2e/yr potential mitigation.

Artificial Film Covering

In a meta-analysis, Hou et al. (2015) examined different manure management strategies for lowering associated GHGs. They found a 98% reduction of N_2O in external slurry-based manure systems when adding artificial film covering. Niles and Wiltshire (2019) found that the percentage of livestock operations with slurry-based manure systems in the United States is 23.0%. We then multiplied these percentages with annual N_2O manure management GHG emissions in the United States as reported by the EPA (2023) to get a 3.9 MMT CO_2e/yr potential mitigation.

Field Burning

No-Till/Leave Residue in Field

By switching management strategies from field burning agricultural residues to no-till, current GHGs associated with field burning would be eliminated. This would be equivalent to 0.2 MMT CO_2e/yr as reported by EPA (2023).

Bioenergy Production

By switching management strategies from field burning agricultural residues to using residues for bioenergy production, current GHGs associated with field burning would be eliminated. This would be equivalent to 0.2 MMT CO_2e/yr (EPA 2023)

CH_4

Enteric Fermentation

Feed Additives

In a meta-analysis, Honan et al. (2021) reviewed 209 papers to analyze the mitigation impact of feed additives on CH_4 enteric fermentation emissions. They found that a variety of feed additives led to a 3%–98% reduction in CH_4 enteric fermentation emissions. We then multiply these percentages by annual CH_4 enteric fermentation GHG emissions in the United States as reported by EPA (2023) to get a 10.3–191.0 MMT CO_2e/yr potential mitigation, or an average of 100.7 MMT CO_2e/yr.

Selective Breeding

In a review, Pickering et al. (2015) found a 25%–45% potential reduction in CH_4 enteric fermentation emissions with selective breeding based on limited studies available. Although the included studies were not performed in the United States, the breeding potential and results could be applied to U.S. livestock operations. We then multiplied percentages by annual CH_4 enteric fermentation GHG emissions in the United States as reported by EPA (2023) to get a 48.7–87.7 MMT CO_2e/yr potential mitigation, or an average of 68.2 MMT CO_2e/yr.

Manure Management

Anaerobic Digestion

EPA (2018) estimates a potential 2.2 million ton reduction of CH_4 emissions from adding manure anaerobic digester biogas recovery at large-scale swine and dairy cattle farms in the United States. We then multiplied the 2.2 million tons by the global warming potential of CH_4 (28) to get a 61.6 MMT CO_2e/yr mitigation potential of anaerobic digestors.

Acidification of External Slurry

In a meta-analysis, Hou et al. (2015) examined different manure management strategies for lowering associated GHGs. They found an 87% reduction of CH_4 in external slurry-based manure systems. Niles and Wiltshire (2019) found that the percentage of livestock operations with slurry-based manure systems in the U.S. is 23%. We then multiplied these percentages by annual CH_4 manure management GHG emissions in the United States as reported by EPA (2023) to get a 13.2 MMT CO_2 CO_2e/yr mitigation potential.

Rice Cultivation

Alternate Wetting and Drying

Runkle et al. (2019) performed a 3-year study across two rice fields in Lonoke County, Arkansas, and found a 64.5 ±2.5% reduction in CH_4 from implementing alternate wetting and drying (AWD) irrigation methods in rice cultivation. This study was included for its geographic relevance in the United States because all meta-analysis and other long-term studies took place outside of the United States. This small sample size introduces a large uncertainty in the estimate for other geographical locations and rice cultivation management strategies across the United States. To estimate CH_4 mitigation potential, we multiplied 64.5 ±2.5% by current CH_4 emissions from rice cultivation in the United States as estimated by EPA (2023) to get a 10.8 (10.4–11.2) MMT CO_2e/yr estimate from AWD.

Field Burning

No-Till/Leave Residue in Field

By switching management strategies from field burning agricultural residues to no-till, current CH_4 emissions associated with field burning would be eliminated. This would be equivalent to 0.5 MMT CO_2e/yr as reported by EPA (2023).

Bioenergy Production

By switching management strategies from field burning agricultural residues to using residues for bioenergy production, current CH_4 emissions associated with field burning would be eliminated. This would be equivalent to 0.5 MMT CO_2e/yr (EPA 2023).

CO_2

Land-Use Conversion to Croplands

Sustainable Bioenergy Production

Lemus and Lal (2007) found bioenergy production in degraded soils to sequester a range of 0.6 to 3.0 Mg C ha-1 yr-1. We then multiply this rate by the most current estimate of abandoned cropland hectares in the United States (9,542,580 ha) (USDA 2019a), the SOC to CO_2 eq. conversion factor (3.67), and MMT conversion factor to get a range of 21–105 MMT CO_2e/yr, or an average of 63.0 MMT CO_2e/yr.

Avoided Forest Conversion

EPA (2023) estimates soil, dead organic matter, and biomass carbon stock changes from forestland to cropland conversion to be 48.5 MMT CO_2e/yr in 2021. If these forest hectares were protected from cropland conversion, all 48.5 MMT CO_2e/yr of GHG emissions would be avoided. Note that these GHG emissions represent land use conversion to cropland over a 20 year period. These estimates represent the mitigation potential of long-term conversion avoidance.

Avoided Grassland Conversion

EPA (2023) estimates soil, dead organic matter, and biomass carbon stock changes from grassland to cropland conversion to be 9.8 MMT CO_2e/yr in 2021. If these grassland hectares were protected from cropland conversion, all 9.8 MMT CO_2e/yr of GHG emissions would be avoided. Note that these GHG emissions represent land use conversion to cropland over a 20 year period. These estimates represent the mitigation potential of long-term conversion avoidance.

Avoided Wetland Conversion

EPA (2023) estimates soil, dead organic matter, and biomass carbon stock changes from forestland to cropland conversion to be 0.7 MMT CO_2e/yr in 2021. If these wetland hectares were protected from cropland conversion, all 0.7 MMT CO_2e/yr of GHG emissions would be avoided. Note that these GHG emissions represent land use conversion to cropland over a 20 year period. These estimates represent the mitigation potential of long-term conversion avoidance.

Fuel Combustion

Electrification of Equipment

Northrup et al. (2021) estimates a 65%–90% reduction in farm machinery tailpipe emissions from electrification of farm machinery and equipment. We then multiply this reduction estimate by annual CO_2 emissions associated with agricultural fuel combustion in the United States as estimated by EPA (2023). This gave an estimate of 28.3 (23.7–32.9) MMT CO_2e/yr mitigation potential from electrification of farm equipment.

No-Till

USDA NRCS (2022) estimates an 8.3 MMT CO_2e/yr reduction if 100% of cropland adopted no-till. This estimate does not include farmland that already practices no-till.

Low-Carbon Biofuels

The IEA Technology Roadmap: Biofuels for Transport (2011) estimates that biofuels will provide 27% of transport fuel by 2050. We pair USDA data for farm energy expenditures with EIA (2023b, 2023c, 2023d) fuel price data to estimate on-farm energy consumption by fuel, including diesel, gasoline, and liquid petroleum gas (assumed to be primarily propane). Based on estimates for farm fuel consumption, 27% market share, and an estimated 75% reduction in lifecycle greenhouse gas emissions from second-generation biofuels (Jeswani et al. 2020), the total mitigation potential of biofuels is estimated at 6.69 MMT CO_2e/yr.

Precision Agriculture

Finger et al. (2019) estimates a 6%–25% reduction in fuel combustion with the adoption of precision agriculture. We then multiply this reduction estimate by annual CO_2 emissions associated with agricultural fuel combustion in the United States as estimated by EPA (2023). This gave an estimate of 5.7 (2.2–9.1) MMT CO_2e/yr mitigation potential from adopting precision agriculture.

On-Site Electricity Usage

Renewable Energy Production

Because on-site electricity GHGs are generally tied to the overall grid and renewable energy expansion, general transition estimates were used. We assumed an average 69.35% decrease in energy-related GHG in the United States based on slow- and fast-paced clean energy implementation scenarios (59.9%–94.1% range) by 2035 and 2050 (Shawhan et al. 2022). We then multiply these reduction estimates by annual CO_2 emissions associated with agricultural on-site electricity usage in the United States as estimated by EPA (2023). This gave an estimate of 24.2 (21.0–33.0) MMT CO_2e/yr mitigation potential from renewable energy production.

Urea Fertilization

Quantification of strategies for mitigating CO_2 emissions associated with urea fertilization was found to be a research gap within U.S.-based studies.

Liming

Precision Agriculture

Northrup et al. (2021) found a 25% reduction in lime use from the adoption of precision agriculture. We then multiply this reduction estimate by annual CO_2 emissions associated with liming in the United States as estimated by EPA (2023). This gave an estimate of 0.8 MMT CO_2e/yr mitigation potential from adopting precision agriculture for lime application.

Carbon Sequestration

Grazing Strategies

In a meta-analysis of 126 publications, Conant et al. (2017) found a 0.105 to 1 Mg C ha-1 yr-1 (avg: 0.47 Mg C ha-1 yr-1) sequestration potential of improved grazing management strategies. Many of the studies took place in the United States, especially in the midwestern region. We then multiply this carbon sequestration estimate by applicable grazing optimization hectares as estimated by Fagione et al. (2018) and by the SOC to CO_2 eq. (3.67) to get a 91.4 (20.4–194.5) MMT CO_2e/yr mitigation potential from improved grazing management strategies.

Diversified Crop Rotation

West and Post (2002) estimate a 80937 ±48562g C per acre/yr sequestration potential of diversified crop rotation in the United States. We then multiply this carbon sequestration estimate by acreage of corn, soybean, and wheat systems (USDA 2019a) in the United States to get potential carbon sequestration in applicable acres. We then multiply this carbon sequestration estimate by the percentage of these systems that have not adopted diversified crop rotation (Wang et al. 2021) and by the SOC to CO_2 eq. conversion factor (3.67) to get a 28.1 MMT CO_2e/yr mitigation potential.

Cover Crops

Fargione et al. (2018) estimate cover crops to offer a 103 MMT CO_2e/yr in carbon sequestration potential in the United States. They used a recent meta-analysis of data from 139 plots at 37 sites to estimate the benefit of integrating cover crops into the fallowing period of the five major crops in the United States (corn, soy, wheat, rice, and cotton).

Agroforestry

Roe et al. (2021) estimate nutrient management to mitigate 381.3 MMT CO_2e/yr in the United States. They use per hectare GHG mitigation reduction potential from Chapman et al. (2020) multiplied by applicable hectares in the United States (348,420,208 ha) to get the average and range of technical potential carbon sequestration from agroforestry practices.

Biochar

Roe et al. (2021) estimate biochar application to mitigate 327.3 MMT CO_2e/yr in the United States. They use per hectare GHG mitigation reduction potential from Griscom et al. (2017) multiplied by applicable hectares in the United States (95,371,478 ha) to get the average and range of technical potential carbon sequestration from agroforestry practices. With such a large CO_2 sequestration potential, we averaged the estimate with another source. Fargione et al. (2018) found biochar to offer a 95 MMT CO_2e/yr sequestration potential in the United States. We then found the mean of these two estimates to be 211.1 MMT CO_2e/yr.

No-Till

In a recent analysis, Sperow et al. (2016) estimate the carbon sequestration potential of no-till practices in the United States to be 35 Tg C yr-1. They use the IPCC county-specific factors to estimate changes in SOC in the United States for applicable acres. We then multiply this carbon sequestration estimate by the SOC to CO_2 eq. factor (3.67) to get a 128.5 MMT CO_2e/yr mitigation potential of no-till practices in the United States.