Ambitious Climate Mitigation Pathways for U.S. Agriculture and Forestry: Vision for 2030

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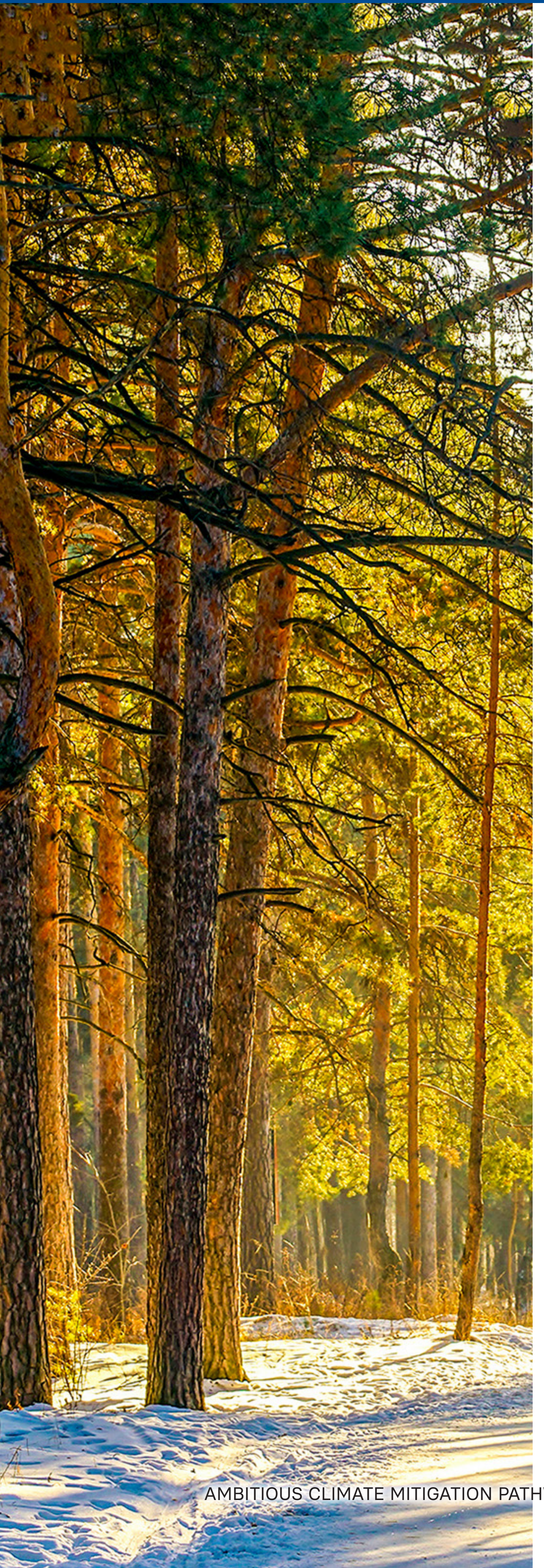

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Executive summary

The agriculture sector accounts for more than 10% of United States' greenhouse gas emissions and is the country's largest source of methane and nitrous oxide emissions. Forests account for the bulk of the U.S. terrestrial carbon sink and have the potential to capture more. Together, these two land-based sectors offer crucial opportunities to help the U.S. achieve economy-wide net-zero GHG emissions by 2050 and meet its Nationally Determined Contribution to the Paris Agreement.

This report charts an ambitious path forward to secure these opportunities. It establishes aggressive yet feasible net GHG emissions reduction targets for each sector, supported by published scientific studies, that can guide efforts to sharply reduce net GHG emissions from working lands in the U.S. by the year 2030. Agriculture's share of these net emission reduction targets represents a 23% decrease from the sector's total emissions in 2018; the forestry sector would increase GHG removals by 43% compared with its total in 2018.

The targets are based on current technical feasibility and assumptions about near-term innovation, and are built up from a set of aggressive and realistic net emission reduction targets for individual mitigation practices in the agriculture and forestry sectors. The technologies and practices specified could feasibly achieve these science-based targets through permanent GHG emission reductions and carefully managed removals, while providing additional environmental benefits such as better air, water and soil quality, and improved wildlife habitats. Variables including U.S. agricultural productivity, cropland acreage, human diet and cattle herd size were assumed to remain fairly stable in assessing the feasibility of meeting these targets by 2030.

The report includes an economic analysis of the identified technologies and practices whenever necessary data were available,[1] to highlight those that could most cost-effectively contribute to the targets. The available marginal abatement cost curves (MACCs) underpinning this analysis do not account for social or health costs of non-GHG emissions and other pollutants. The additional costs of addressing those impacts need to be studied and incorporated into future economic analyses.

This report's findings are presented at the national level, and it is important to recognize that agricultural and forestry practices, land conversion rates and GHG emissions differ at the farm, county, state and regional levels. As such, the potential for GHG emission reduction and removal also varies, and climate mitigation initiatives must be tailored to meet local needs and conditions to maximize benefits.

[1] Economic data were not available for three practices that were included in the emission reduction targets, and we could not analyze their marginal abatement costs: reduced on-farm use of fossil fuels, reduced on-farm use of electricity, and reduced demand for synthetic nitrogen fertilizer that can result in avoided emissions from manufacturing.

All public- and private-sector stakeholders interested in reducing GHG emissions from agriculture and forestry should prioritize and focus on enabling opportunities that have the greatest scientific certainty of permanent GHG reductions for the lowest cost, while investing in additional research and development oriented toward the most promising mitigation pathways.

Considering a synthesis of published expert assessments, the U.S. agriculture and forestry sectors could set an aggressive and achievable science-based target to reduce annual net GHG emissions by approximately 560 million metric tons of carbon dioxide equivalent (MMT CO_2e) by the year 2030, using 100-year global warming potentials (GWPs).[2]

- This science-based target is based on current technical feasibility and assumptions about near-term innovation. It is built up from a set of aggressive but realistic net emission reduction targets for individual mitigation practices in the agriculture and forestry sectors.
- The 560 MMT CO_2e reduction target includes 63 MMT CO_2e of methane from livestock and rice cultivation using a 100-year GWP (2.5 MMT of methane gas), which is equivalent to 181 MMT CO_2e using a 20-year GWP.
- Ceasing conversion of existing forest and grasslands to cropland avoids releasing stored soil and biomass carbon and accounts for 55 MMT of the 560 MMT target. This can be accomplished by increasing sustainable productivity on existing cropland and forestland, disincentivizing further conversion to cropland.
- Carbon sequestration in cultivated soils is not included in this report as an opportunity for carbon dioxide removals due to highly variable and impermanent net GHG benefits.

Putting the target into context:

- The 560 MMT CO_2e target for GHG emission reductions from agriculture and forestry is equivalent to avoiding the annual emissions of more than 120 million gasoline-powered cars or more than 150 coal-fired power plants.
- In 2005, the U.S. emitted roughly 6,600 MMT CO_2e total (White House 2021b); a net reduction of 560 MMT CO_2e by the agriculture and forestry sector would account for an 8.5% reduction from total U.S. 2005 levels, or about 17% of reductions necessary by 2030 to meet the U.S.' Nationally Determined Contribution to the United Nations Framework Convention on Climate Change as of 2021.[3]
- In 2018, the baseline year used for this report's analysis, the U.S. emitted roughly 5,900 MMT CO_2e total (EPA 2020); a reduction of 560 MMT CO_2e by the agriculture and forestry sectors would provide a 9.5% decrease from total 2018 levels.
- Although the largest share of U.S. GHG emissions comes from carbon dioxide, the agriculture sector accounts for the nation's largest share of methane and nitrous oxide emissions. Livestock emissions[4] of methane are agriculture's leading contributor to near-term climate warming, representing the greatest opportunity for immediate, irrevocable emissions reductions.

When the practices' annual mitigation potentials are analyzed at various prices of CO_2e, the best available MACC data show that the price of CO_2e would have to be at least \$27/metric ton[5] to meet the science-based net annual emissions target by 2030, if using 100-year GWPs.[6]

- When considering their ability to achieve rapid near-term climate benefits, improved manure management and enteric methane reducing solutions are good investments for emissions reduction. The use of a 100-year GWP for methane masks this potential.
- At a price of \$10/metric ton of CO_2e, improved forest management (70 MMT CO_2e) and avoided land conversion — both forests (32 MMT CO_2e) and grassland (22 MMT CO_2e) — remove or avoid the most

[2] For consistency with the Inventory of U.S. Greenhouse Gas Emissions and Sinks, CO_2 equivalents used in this report are based on 100-year GWPs (or GWP-100) from the Intergovernmental Panel on Climate Change's Fourth Assessment report, unless indicated otherwise. GWP is a measure of the relative influence of a unit (e.g., 1 kg) of a GHG on global temperature within a given time horizon, which can be a 100-year or 20-year period (EPA 2020). Expressing non-CO_2 GHGs as CO_2e involves weighting gases by their GWP, in comparison to that of CO_2.

[3] The Nationally Determined Contribution aims to reach 50 percent of 2005-level emissions by 2030; the percentage figure calculated here is based on the difference between 2005 levels and that target, but the total emissions reductions required to reach the target level will depend on actual emissions in the intervening years.

[4] Livestock emissions include those from manure and enteric fermentation. They do not include nitrous oxide or CO_2 emissions from grazing land or animal feed production.

[5] Pricing is based on 2020 USD.

[6] The economic studies reviewed for this analysis used 100-year GWPs; the carbon market is also standardized on 100-year GWPs. The economic findings in this report are thus based on 100-year GWPs. However, the use of 100-year GWPs fails to capture the significant near-term climate benefits of reducing methane emissions — a potent greenhouse gas with a short atmospheric lifetime. For this reason, the report provides additional detail on methane emissions and reduction potential.

emissions compared to other pathways for which economic data are available, and therefore represent the most impactful investment at that price point.

- The two agricultural mitigation categories with the largest opportunities for emissions reduction or removal at \$25/metric ton of CO_2e (GWP-100) are agroforestry (32 MMT CO_2e) and improved manure management (13 MMT CO_2e). Overall, agricultural mitigation practices are a more expensive method of emissions reduction and removal than forestry and avoided land conversion practices, although improved cropland nitrogen management reduces nitrous oxide emissions by 9 and 11 MMT CO_2e at \$10 and \$25/metric ton of CO_2e, respectively.
- Enteric methane emission reduction solutions do not provide more than 10 MMT CO_2e of mitigation until \$75/metric ton of CO_2e, and improved rice production stays below 3 MMT CO_2e even at \$100/metric ton of CO_2e.
- At a price of \$25/metric ton of CO_2e (GWP-100), the combined total emissions reduction across all practices would be 536 MMT CO_2e annually, with improved forest management (197 MMT CO_2e), reforestation (184 MMT CO_2e), avoided land conversion — grassland at 50 MMT CO_2e and forests at 32 MMT CO_2e — and agroforestry (32 MMT CO_2e) providing the most emissions reduction or removal for the investment.
- Most practices' mitigation potentials respond more slowly to increased prices after about \$50/metric ton of CO_2e, after which additional climate measures from working lands and elsewhere will be needed to drive impact. Price increases over time are an expected outcome of increasing demand for climate solutions.
- Available research suggests that the forest sector has the strongest potential to increase long-term carbon storage for the lowest cost, at about 80 MMT CO_2e \$10/metric ton and 520 MMT CO_2e at \$50/metric ton, but more data are needed to reduce uncertainties. More specifically, improved forest management is believed to have the highest carbon benefits for the lower carbon cost, at about 70 MMT CO_2e at \$10/metric ton and 277 MMT CO_2e at \$40/metric ton.

The short atmospheric lifetime of methane provides a unique opportunity to reduce mid-century warming, with increased climate benefits if emission reductions are achieved as soon as possible.

- All the published economic studies used in this report's analysis were based on 100-year GWPs, and their findings cannot be readily translated to 20-year GWPs.
- Even so, the short-term climate benefits of reducing methane emissions are well established: Because any given amount of methane has a much higher warming impact in the near term than over a 100-year time horizon, early-action emission reductions likewise have an outsized near-term mitigation impact.
- Given their high short-term impacts, efforts to reduce methane emissions from livestock production should be prioritized immediately.

Equity and environmental justice issues in the agriculture and forestry sectors should be considered when developing GHG mitigation strategies.

- Structural discrimination in the agricultural sector has caused longstanding impacts to Black, Indigenous and other people of color, including reduced and restricted access to land ownership and other critical resources, barriers to recognitional and procedural equity and disproportionate harms to communities.
- Public- and private-sector plans and initiatives to reduce GHG emissions must be designed[7] to: address structural harms; to advance recognitional, procedural and distributional equity; and to advance environmental justice.
- Best practices include defining specific and measurable equity and environmental justice goals; addressing inequities in land access, ownership and ramifications for participation in GHG mitigation solutions; increasing equity in access to training and financial and technical assistance; investing in capacity-building in agriculture and forestry GHG mitigation solutions; increasing representation and inclusion in decision-making processes and leadership; and advancing environmental justice by addressing non-GHG pollutants associated with agriculture and forestry operations that negatively impact health and quality of life.

[7] Some climate mitigation practices in the agriculture and forestry sectors may be expensive relative to other options but may still be worth pursuing for environmental justice and equity benefits.

Introduction

In April 2021, President Biden announced the U.S.' new Nationally Determined Contribution under the Paris Climate Agreement to achieve a 50–52% reduction from 2005 levels in economy-wide net GHG pollution by 2030 (White House 2021a). This includes investment in clean power, electrification of transportation and buildings, industrial transformation, reductions in methane and other potent non-carbon dioxide climate pollutants, and reductions in net emissions from natural and working lands.

Net reductions in GHG emissions from cropland, livestock, and forestry systems are critical to this commitment and to the Paris Agreement goal of limiting climate warming to 1.5°C above preindustrial levels. They will also play a key role in achieving net zero emissions by 2050. Until now, however, the details of *how* the U.S. agriculture and forestry sectors can most effectively contribute to these goals have been unclear.

This report builds on previous analyses and published studies to present the first set of science-based GHG emissions reduction targets specifically for the U.S. agriculture and forestry sectors by 2030, identifying which climate mitigation practices and technologies can provide the greatest benefits at the least cost. The targets are built on an evidence-based foundation and supported by consideration of economic costs, where available, as well as existing momentum toward innovation. Efforts to achieve these targets can benefit agricultural and forestry producers, local and downstream communities and the larger economy.

Soil carbon sequestration on croplands, often proposed as an effective natural climate solution, is not included in this analysis due to concerns with quantification, the relationship between soil carbon and emissions of other GHG emissions, rates of change in relation to current carbon stocks, measurement cost-effectiveness, as well as reporting and verification, impermanence and accounting issues (Oldfield et al. 2021). These empirical data gaps generate a lack of confidence and high uncertainty when it comes to scientists' understanding of the capacity for improved agricultural management to generate meaningful and lasting reductions in atmospheric carbon through soil carbon sequestration. Although practices typically proposed for increasing soil carbon (e.g., conservation tillage, use of cover crops, sustainable crop rotations, rotational grazing) have been shown to result in other valuable environmental benefits such as improved soil moisture content and reduced erosion, soil compaction and chemical runoff, their soil carbon impacts are not considered in this report for the reasons stated above. The vast potential for agriculture and forestry to provide natural climate solutions even without this uncertain source of removals demonstrates the immediate value of pursuing quantifiable climate mitigation strategies.

The science-based targets outlined in this report are consistent with recent climate commitments and investments from the Biden Administration and the U.S. Department of Agriculture. In 2021 and 2022, USDA committed billions of dollars to investments in climate-smart solutions that reduce GHG emissions, including $1 billion to expand markets for climate-smart commodities and $800 million to build critical climate-smart infrastructure. The U.S. Methane Emissions Reduction Action Plan is also focused on expanding incentives and voluntary partnerships to reduce methane emissions from agriculture, such as using the Environmental Quality Incentives Program, the Conservation Stewardship Program and the Rural Energy for America Program to finance adoption of improved manure management techniques.

Current landscape

The U.S. agriculture sector is a major contributor to national GHG emissions, particularly methane and nitrous oxide. The U.S. forest sector plays an important role in removing carbon dioxide from the atmosphere and has the potential to increase its drawdown capacity further.[8] Together, agriculture and forestry provide many high-value opportunities[9] to reduce the nation's contribution to climate change in equitable and sustainable ways.

The *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, published annually by the U.S. Environmental Protection Agency, allocates emissions to sectors — including agriculture and forestry. These allocations, however, do not capture the full range of emissions attributable to agriculture such as upstream emissions from fertilizer manufacturing, on-farm electricity use, fossil fuel combustion by farm equipment and the conversion of other types of land to cropland (Hayek and Miller 2021). For this report, these additional sources are added to those allocated to the agriculture sector in the U.S. inventory, using data for the year 2018 from the 2020 *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. Conversion of forests to other land uses is one of the largest sources of CO_2 emissions globally; in this report the conversion of forests to cropland is allocated to agriculture sector emissions.

As shown in Figure 1, the agriculture sector accounted for more than 10% of U.S. GHG emissions in 2018, reaching emissions of approximately 738 MMT in carbon dioxide equivalent (CO_2e) terms (at GWP-100),[10] consisting of:

- 10.1 MMT of methane (253.4 MMT of CO_2e using a 100-year GWP, or 730 MMT of CO_2e using a 20-year GWP).
- 1.2 MMT of nitrous oxide (359.1 MMT of CO_2e).
- 125 MMT of carbon dioxide (EPA 2020, with agriculture-related land-use change, electricity and fuel allocated to the agriculture sector).

These values represent to 39% of total U.S. methane emissions, 81% of total nitrous oxide emissions, and 3% of net total carbon dioxide emissions.

[8] Parts of the forest sector act as sources of GHG emissions in scenarios of intense wildfire, insect/disease mortality, and logging. Intervention offers the opportunity to avoid or decrease these emissions.

[9] The criteria for defining "high-value" practices are described in the Appendix to this report.

[10] Unless noted otherwise, CO_2e values in this section are based on GWP-100 and emissions factors in the Intergovernmental Panel on Climate Change Fourth Assessment Report (AR4, 2007), which the U.S. Greenhouse Gas Inventory uses for consistency with international inventory guidance.

In contrast with agriculture, which is a net emitter of GHGs, forests removed 774 MMT of carbon dioxide from the atmosphere in 2018, but deforestation (in this case, conversion of forests to settlements) and other GHGs reduced this to a net -692 MMT CO_2e. Forests thus accounted for 87% of the net GHG reduction by the non-agricultural portion of U.S. land use, land-use change and forestry (EPA 2020).

Largest categories of annual emissions

- **Livestock-related enteric fermentation**,[11] generates 7.1 MMT methane (177.6 MMT CO_2e at GWP-100 or 511.5 MMT CO_2e at GWP-20), accounting for 70% of agricultural methane emissions. Nearly all (97%) of these emissions come from cattle, splitting out to 72% from beef and 25% from dairy.
- **Manure** generates 2.5 MMT of methane (61.7 MMT CO_2e at GWP-100 or 177.7 MMT at GWP-20), accounting for 24% of methane emissions from the agriculture sector, as well as 0.065 MMT of nitrous oxide (19.4 MMT CO_2e), accounting for 5% of the agriculture sector's nitrous oxide emissions. Nearly half (47%) of these emissions come from dairy cattle, 30% come from swine, and 16% come from beef cattle; the remainder are from chickens and other livestock.
- **Nitrogen fertilizer and manure application**[12] to cropping systems and grazing land generates 94% of the agriculture sector's nitrous oxide emissions (1.1 MMT nitrous oxide or 338.2 MMT CO_2e) (EPA 2020).

Smaller categories of annual emissions

On-farm energy use (e.g., mobile and non-mobile fuel combustion) comprises 6% of agriculture sector emissions (79.7 MMT CO_2e), consisting of 39.7 MMT from electricity, 39.4 MMT from fossil fuel combustion, and 0.6 MMT for mobile combustion. **Manufacturing of synthetic fertilizers** accounts for a total of 2% (23.7 MMT CO_2e) of agriculture sector emissions. Specifically, the production of ammonia emits 13.5 MMT CO_2e, production of nitric acid emits 9.3 MMT CO_2e, and production of phosphoric acid emits 0.9 MMT CO_2e (EPA 2020).

Annual Land Use, Land-use Change and Forestry (LULUCF) net emissions

In 2018, **LULUCF** collectively resulted in net GHG emission reductions of 773.5 MMT CO_2e. This includes:

- Net removal of 799.6 MMT CO_2 in above- and below-ground carbon stock.[13]
- 15.2 MMT CO_2e of methane emissions (0.610 MMT of methane), mainly from forest and grassland fires, along with emissions from coastal wetlands.
- 10.9 MMT CO_2e of nitrous oxide emissions (0.037 MMT of nitrous oxide), mainly from forest and grassland fires along with emissions from soils (EPA 2020).

Annual emissions by land use type

- **Croplands:** Although the GHG inventory models indicate that existing cropland serves as a minor carbon sink, this effect is offset by the much greater annual GHG emissions (55.3 MMT CO_2) due to cropland expansion from other land use types such as forests, grasslands and wetlands; more than 1 million acres are converted to cropland annually[14] (Lark et al. 2020).
- **Forests:** These remove an estimated net 754.5 MMT CO_2 through both existing forests (forest land remaining forest land) and conversion of other land use types to forest (e.g., through reforestation) annually. Most of this total GHG flux comes from carbon stock accumulation in above- and below-ground biomass, although increased carbon stock in harvested wood products also accounts for 98.8 MMT CO_2. The conversion of forests to settlements (i.e., development into urban areas) results in 62.9 MMT CO_2 emissions annually.

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[11] Enteric fermentation is a process that occurs in the digestive systems of ruminant animals, releasing methane.

[12] Nitrogen application includes synthetic fertilizer, manure deposited on grasslands, and managed manure and organic amendments, such as daily spread manure and commercial organic fertilizers.

[13] This value is based on the net combination of CO_2 emissions and removals from all land use types, including land staying in the same category (e.g., cropland remaining cropland, grassland remaining grassland) and land use changing to another land use type (e.g., grassland converted to cropland, forested land converted to urban settlements) (EPA 2020).

[14] Although approximately 1 million acres of land are converted to cropland annually, the total number of acres under cropland production has decreased over the past 20 years. This discrepancy is due to 1) different methods of accounting for acreage, 2) different methods of accounting for double cropping (growing two different crops in a single year, such as soybeans and winter wheat), 3) acreage taken out of production through the Conservation Reserve Program (a USDA program under which producers are paid to avoid farming at-risk or fragile land), and 4) the rate of cropland abandonment.

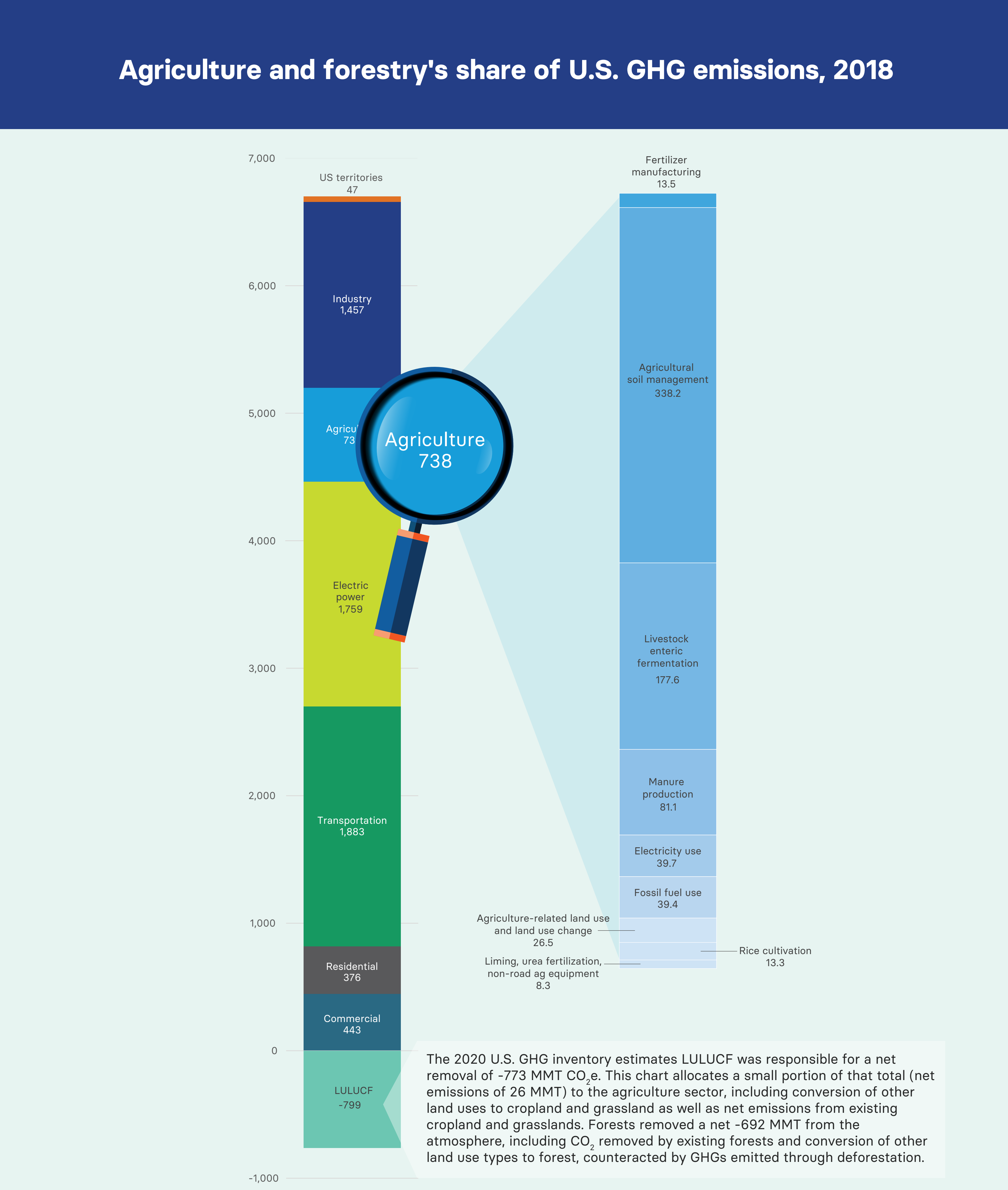


Figure 1. Agriculture and forestry's share of U.S. GHG emissions, 2018. Source: EPA 2020.

- **Grasslands:** Despite emissions from existing grasslands due to losses in soil carbon, grasslands result in net removal of 13.4 MMT CO_2 annually from conversion of other, higher-GHG-emitting land use types to grassland.
- **Wetlands:** Conversion of other land use types to wetlands similarly yields a small increase in carbon storage; overall, however, existing wetlands are net GHG emitters annually (4.4 MMT CO_2e).

Importance of reducing methane and nitrous oxide emissions

Although the largest share of U.S. GHG emissions is from carbon dioxide, the agriculture sector's pronounced methane and nitrous oxide emissions provide important opportunities to reduce climate impacts. This is due both to their high GWPs compared to carbon dioxide[15] and to the near-term benefits of reducing emissions of methane, with its shorter lifetime in the atmosphere.

Based on the latest science, a pound of methane traps almost 30 times more heat compared with a pound of CO_2 over a 100-year timeframe; that is, its 100-year GWP is nearly 30. But over a shorter horizon of 20 years, a pound of methane traps around 80 times more heat. Nitrous oxide is an even more powerful GHG than methane and has a much longer lifetime in the atmosphere (about 111 years compared with just 12 years for methane); its 100-year and 20-year GWPs are both about 270.

Even though CO_2 has a longer-lasting effect, methane sets the pace for warming in the near term. Figure 2 shows how the warming impact of methane is dramatically larger relative to other gases when using 20-year GWPs compared with 100-year GWPs. As with the rest of this report, this figure uses an older set of GWPs for consistency with the U.S. EPA GHG inventory.[16]

At least 25% of today's global warming is driven by methane from human actions. Methane emissions

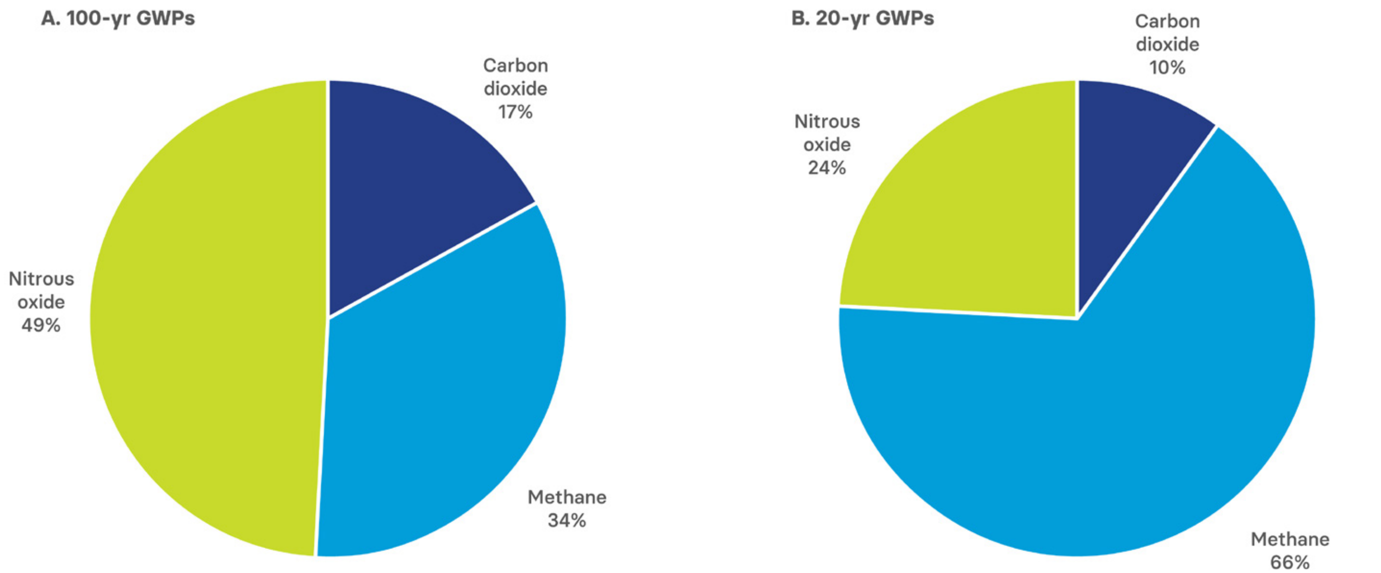


Figure 2. U.S. agriculture sector GHG emissions in 2018, allocated to the three major GHGs and contrasted with 100-year and 20-year GWPs. Estimates use GWPs from the IPCC Fourth Assessment Report. Data based on allocations of agriculture-associated fuel, electricity, land-use change, and fertilizer manufacturing emissions to the agriculture sector, using data from EPA's 2020 Inventory of GHG Emissions and Sinks.

[15] GWP reflects the relative influence of a unit (e.g., 1 kg) of a GHG on global temperature within a given time horizon, which can be a 100-year or 20-year period (USEPA, 2021). Expressing non-CO_2 GHGs as CO_2e involves weighting gases by their GWP, in comparison to that of CO_2.

[16] In comparison to the older (Fourth Assessment Report) GWPs here, both 100-year and 20-year GWPs of methane have been since revised to higher values in the IPCC's Fifth Assessment Report (IPCC 2013) and Sixth Assessment Report (IPCC 2021). As a result, methane has a larger impact relative to carbon dioxide than shown here: by about 8% in the long term (100-yr GWP) and about 11% in the short term (20-yr GWP), both even somewhat larger for fossil fuel methane.

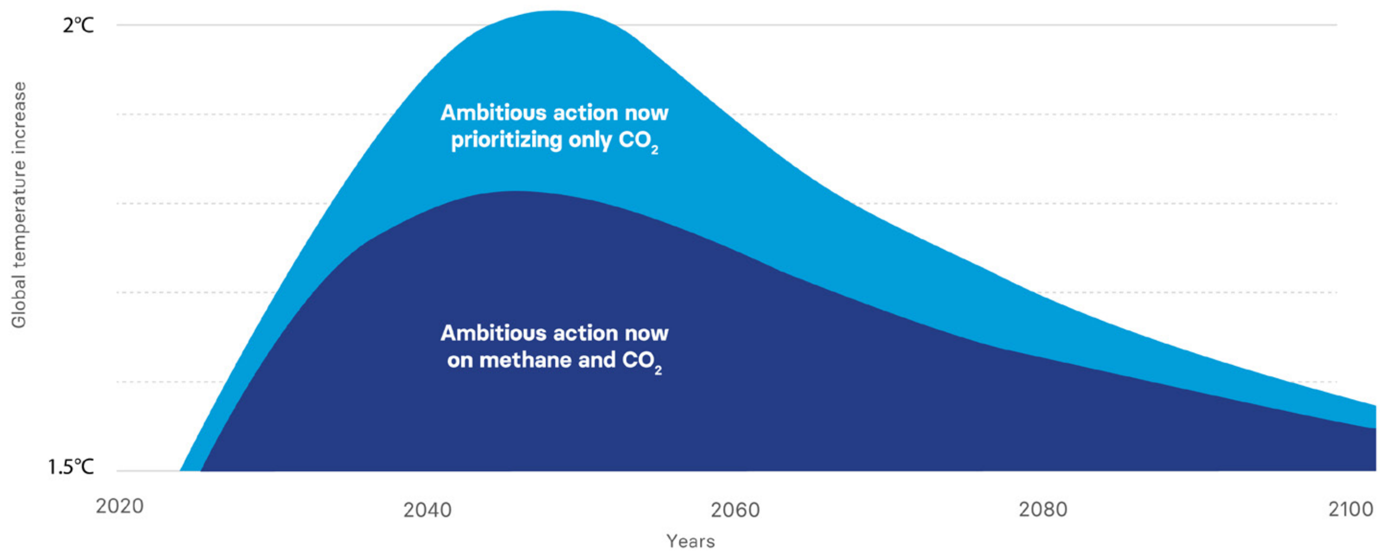


Figure 3. Early action on methane matters. Data from T. Sun et al. (2021).

from human activities have greatly increased since preindustrial times. They not only have caused the concentration of methane in the atmosphere to increase more than two and a half times, but also generated tropospheric ozone and stratospheric water vapor. All of these have contributed to more than one-quarter of today's warming. Reducing methane emissions provides immediate benefits in terms of reduced warming.

Enteric fermentation from livestock is the largest source of methane emissions in the U.S., accounting for 28% of the nation's total methane emissions in 2018 (EPA 2020); manure accounted for 8.8% and rice cultivation 2.3%. Reducing agricultural methane emissions can play a powerful role in meeting U.S. commitments under the Paris Agreement and is a critical part of avoiding the worst consequences of climate change (Anderson 2022). There is a growing literature describing the many long-term benefits of methane mitigation, as well as the importance of early action (Hu et al. 2013; Zickfeld, Solomon, and Gilford 2017; Ocko et al. 2021; T. Sun, Ocko, and Hamburg 2022; K. Sun et al. 2021).

Equity and environmental justice issues

Many equity and environmental justice issues intersect with GHG mitigation opportunities in the agriculture, forestry and land use sectors. This report includes brief descriptions of equity and environmental considerations in the Climate Mitigation Opportunity and Economic Analysis section.

Structural discrimination has caused longstanding impacts to Black people, Indigenous people and other people of color (BIPOC) in the agricultural and forestry sectors. These impacts include differences among producers and communities with respect to access to land and financial capital, capacity to implement mitigation options or alternatives, decision-making representation and exposure to pollutants and odors that impact human health and quality of life.

Issues of environmental justice — that impoverished communities of color bear the brunt of environmental degradation and have less access to clean air and water — are pertinent to agricultural and forestry operations that can create negative downstream (e.g., water pollution) and downwind impacts (e.g., air pollution), affecting local communities and beyond (EPA 2021a; 2019; Tessum et al. 2021).

Terms such as "equity," "environmental justice" and "disadvantaged" have multiple definitions. Those on the following page are EDF's definitions, and are used in this report. Some related and similar terms, such as the USDA's definition of Socially Disadvantaged Farmers or Ranchers (Congressional Research Service 2021) and the definition of Disadvantaged Communities used in the Climate and Economic Justice Screening Tool (CEQ 2022), are relevant to this discussion and may have specific implications for policy or program evaluation.

What are equity and environmental justice?

Equity is achieving fairness and balance in access to environmental resources (e.g., green space, safe neighborhoods, healthy homes, healthy fisheries), in bearing environmental burdens (e.g., pollution in air, water, and on land), and in participating in environmental decision making. Today, some populations—often ethnic minority communities, Indigenous persons, people of color, and low-income communities—have less access to resources and experience more burdens than others due to factors such as systemic racism, poverty and lack of access to political power. Equitable policies do not distribute resources equally or relieve burdens equally: they seek to address the imbalance (also known as the "disproportional burden") that groups experience.

Recognitional equity: Conditions in which impacted communities and marginalized groups and their culture, values, rights and perspectives are acknowledged, respected and represented.

Procedural equity: Conditions in which rule and decision-making processes are inclusive and enable the fair and effective participation of all relevant actors, impacted communities, and marginalized groups

Distributional equity: Conditions in which outcomes (both benefits and burdens) of conservation, communication, strategy, policy and management are distributed fairly.

Environmental justice is remedying environmental harms that have been purposefully or incidentally imposed on specific communities and preventing similar injustices from happening in the future.

Emissions reduction targets for the agriculture and forestry sectors: Vision for 2030

Based on our synthesis of published expert assessments, the U.S. agriculture and forest sectors can feasibly set science-based targets to reduce net GHG emissions by approximately 560 MMT of carbon dioxide equivalent (CO_2e) per year by 2030 (at GWP-100). This total includes a 2.5 MMT reduction in methane emissions, equating to 63 MMT of CO_2e at GWP-100 or 181 MMT CO_2e at GWP-20, the greater short-term impact owing to methane's shorter lifespan in the atmosphere and stronger near-term contribution to warming.

Agriculture's share of these reductions represents a 23% decrease from total agriculture sector emissions in 2018; the forestry sector would achieve a 43% increase compared with its total removals in 2018. The combined net reduction in GHG emissions from the two sectors would be equivalent to avoiding the annual emissions of more than 120 million gasoline-powered passenger vehicles or more than 150 coal-fired power plants.[17] For additional context, 560 MMT CO_2e exceeds the entire emissions in 2018 from the U.S. commercial sector (443 MMT CO_2e) or the residential sector (376 MMT CO_2e). Note that for agriculture to continue to provide needed food from crops and livestock, some GHG emissions are unavoidable, and thus the proportional reduction from agriculture may be less than that from other sectors. The combined land-based sector provides a significant portion of the overall mitigation needed by 2030 to meet the U.S.' National Determined Contribution under the Paris Climate Agreement to achieve a 50–52% reduction from 2005 levels in economy-wide net GHG pollution by 2030.

The overall target is based on current technical feasibility and assumptions about near-term innovation and is not constrained by the price of carbon or spending.[18] It is built up from a set of aggressive and realistic net emission reduction targets for individual mitigation practices in the agriculture and forestry sectors. The following variables were assumed to

[17] U.S. EPA Greenhouse Gas Equivalencies Calculator, https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

[18] Cost-effectiveness is evaluated in the next section of this report, which then identifies an optimal mix of technologies and practices for achieving the targets.

remain stable in assessing the feasibility of meeting these targets by 2030: cattle herd size; human diet; agricultural productivity; and cropland acreage (i.e., acreage will not need to be reduced by more than approximately 5% to achieve the agroforestry target).

The breakdown of these targets by gas is summarized in Table 1, followed by more detailed descriptions. Table 2 then summarizes the science-based targets for individual practices. The Subsector Detail section provides additional documentation outlining the rationale and development of the targets.

Carbon dioxide emission reduction, avoidance and removals target

The total annual CO_2 emission reduction and avoidance target for the agriculture and forestry subsectors by 2030 is 135 MMT.

- The bulk (55 MMT) of avoided emissions in the year 2030 would be achieved by immediately halting all U.S. land-use conversion of forests, grasslands and wetlands to cropland.
- Another 63 MMT of avoided emissions would be achieved by immediately halting all U.S. conversion of forests to settlements.
- The remaining 17 MMT would be contributed through:
    - Reduced CO_2 emissions from upstream fertilizer manufacturing and distribution, enabled through improved cropland nutrient management to reduce demand for fertilizer.
    - Improved electricity efficiency in the agriculture sector.
    - Reduced use of fossil fuels by cutting some field equipment operations such as tillage and by beginning to electrify the agricultural fleet.

In addition to CO_2 reductions and avoidance from the agriculture and forestry subsectors, the science-based target includes estimated near-term annual removals and avoided emissions within the agriculture and forestry sectors of 330 MMT of CO_2 via reforestation, improved forest management and agroforestry:

- Reforestation would remove an estimated 150 MMT of CO_2.
- Improved management of existing forests, which includes fire mitigation, plantations and disease and pest management, would remove and avoid a combined total of about 100 MMT of CO_2.
- Agroforestry would remove an estimated 80 MMT of CO_2 through the installation of wind breaks, riparian buffers and other tree-based agricultural management.

While significant in volume, these latter estimates are subject to several important uncertainties, as discussed in the Limitations and Uncertainties section of the Appendix.

Methane emissions reduction target

The total annual emission reduction target for methane by 2030 is 2.5 MMT, which equates to 63 MMT of CO_2e using 100-year GWPs from the IPCC's Fourth Assessment Report or 181 MMT of CO_2e using 20-year GWPs.

Table 1. Feasible and realistically achievable emission reduction and removal targets for agriculture and forestry sectors by 2030.

Gas	MMT of gas	MMT CO_2e, GWP-100	MMT CO_2e, GWP-20	Percent change from 2018
Emissions reductions				
Carbon dioxide	135	135	135	72% reduction
Methane	2.5	63	181	25% reduction
Nitrous oxide	0.1	32	31	9% reduction
Carbon dioxide removals				
Forests	250	250	250	32% increase in removal capacity
Agroforestry	80	80	80	N/A*

*The U.S. GHG Inventory does not provide estimates for CO_2 removals specifically from agroforestry.

- More than half (34 MMT of CO_2e) of this amount would be reduced methane emissions from ruminant enteric fermentation through adoption of currently available technology and future innovation, including methane-inhibiting feed additives and animal drugs, and improved genetics and health. This reduction is equivalent to 19% of enteric methane emissions in 2018.
- The other 29 MMT CO_2e would come from reducing emissions related to manure management (e.g., covering liquid manure storage pits and lagoons to capture and destroy the methane or adopting lower methane emission systems such as solid/liquid separation), along with a small contribution from rice management.

Nitrous oxide emissions reduction target

The total annual emission reduction potential for nitrous oxide by 2030 is estimated to be 32 MMT of CO_2e, using 100-year GWPs from the IPCC's Fourth Assessment Report.

- Most of this reduction (27 MMT CO_2e) would come from improving nitrogen management on cropland.
- The remaining 8 MMT would come from improving livestock manure management and using nitrification inhibitors on grazing land.

Table 2. Net emission reduction targets for specific GHG mitigation practices in the agriculture and forestry sectors.

Greenhouse gas	Mitigation opportunity	MMT CO_2e	MMT methane
Carbon dioxide emission reductions	*Reduced demand for fertilizer (ammonia production)*	*6.9*	–
	Reduced on-farm fossil fuel combustion	*6.9*	–
	Reduced on-farm electricity use	*2.8*	–
	Avoided conversion of forest, grassland, and wetland to cropland	*55*	–
	Avoided conversion of forests to settlements	*63*	
	Total	**135**	**–**
Methane emission reductions	*Reduced enteric methane emissions*	*34*	*1.4*
	Reduced manure methane	*25*	*1*
	Reduced rice methane	*4*	*0.16*
	Total	**63**	**2.5**
Nitrous oxide emission reductions	*Reduced soil nitrogen management nitrous oxide (fertilizer etc.)*	*27*	–
	Reduced manure management nitrous oxide	*4.8*	–
	Total	**32**	**–**
Carbon dioxide removals and avoided emissions	*Reforestation*	*150*	–
	Improved forest management	*100*	–
	Agroforestry	*80*	–
	Total	330	–
GRAND TOTAL		**560**	**2.5**

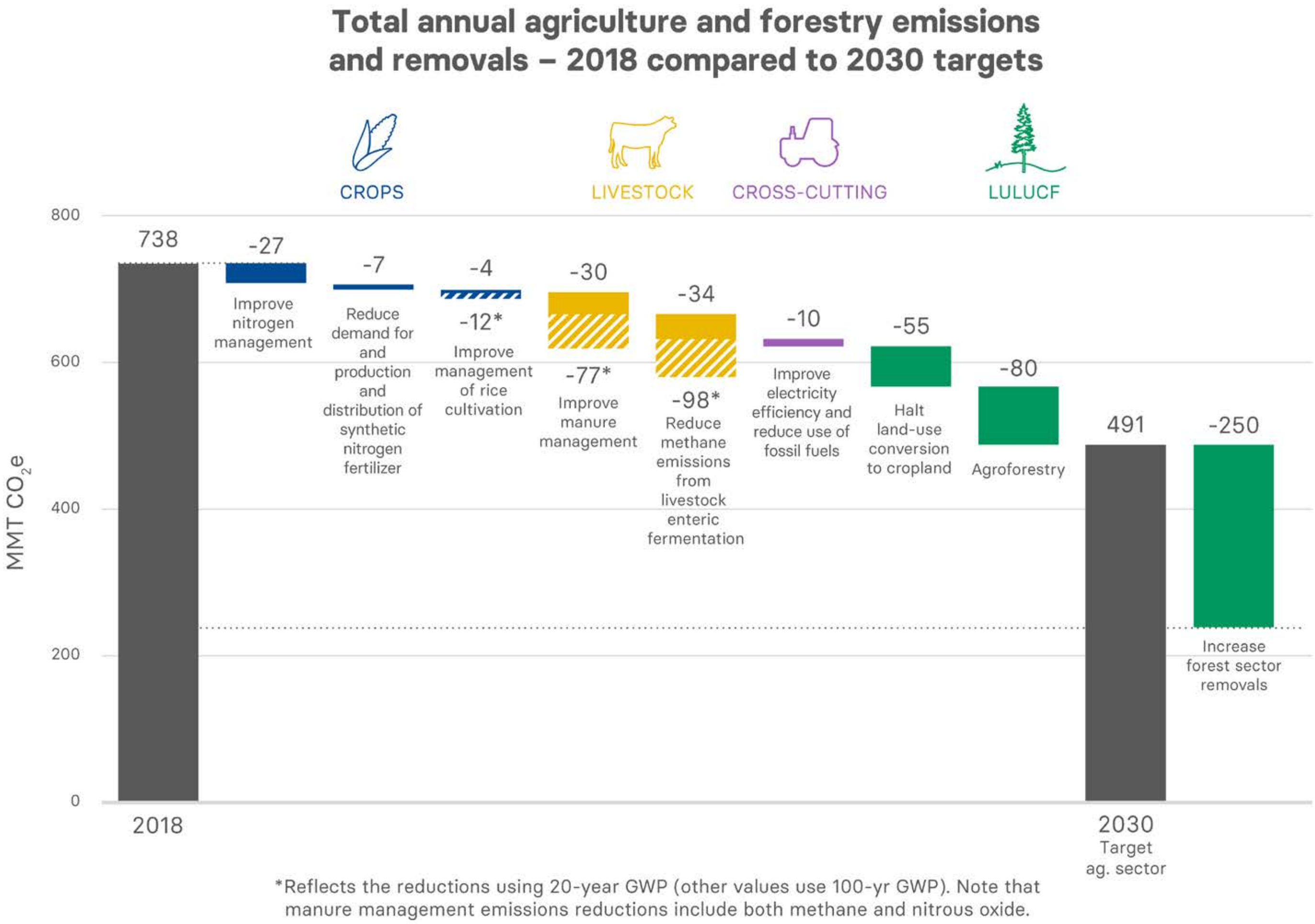


Figure 4. Annual GHG reductions and removals realistically achievable by the U.S. agriculture and forestry sectors by 2030.

Covered Manure Lagoon Anaerobic Digester on a Hog Operation

Climate mitigation economic analysis: Overview

The previous section presents science-based targets for feasible GHG emission reductions and removals by 2030 in the agriculture and forestry sectors; this section attempts to identify — to the extent possible, given available data — the practices and actions identified that could provide the largest GHG emission reductions or removals at lowest cost.

To assess the overall GHG reduction potential and costs of specific practices or actions, the analysis conducted for this section used MACCs published by U.S. government agencies or in the scientific literature. MACCs are a commonly used tool to identify the lowest-cost opportunities for GHG mitigation or removals. They combine estimated costs for implementing different levels of practice adoption with the anticipated GHG reduction potential at those levels.

To identify high-value opportunities that provide the greatest permanent emissions reduction or long-term removal benefit at carbon values below $100/ton of CO_2e (i.e., metric ton or 1,000 kg),[19] a value chosen as an upper bound beyond which prices were unlikely to rise during the period of analysis, the authors compiled MACC data from published studies[20] on the practices in for which economic data were available.

Although the authors attempted to find published MACC data for all of the practices that contributed to the science-based targets described in this report, data were available for only a subset of practices (see Figure 5). Overall, the MACC analysis faced challenges due to the relatively small number of published MACCs on agricultural and forestry practices in the U.S. (many of which are based on the same underlying data sources), the lack of MACC data for some key practices that could contribute to GHG mitigation targets, and the general challenges associated with building MACCs (e.g., determining representative costs of implementing practices and actions and estimating GHG reductions or removal amounts associated with a given practice or action). The Appendix to this report

[19] Although carbon market prices are standardized to units of CO_2e, this may at times be incorrectly worded as “tons of carbon.” One metric ton of carbon (C) is equal to 3.67 metric tons of CO_2e.

[20] See the Appendix for a full list of the studies evaluated for each practice and a detailed description of the analytical approach used for the analysis.

Narrowing down the GHG mitigation practices analyzed in this report

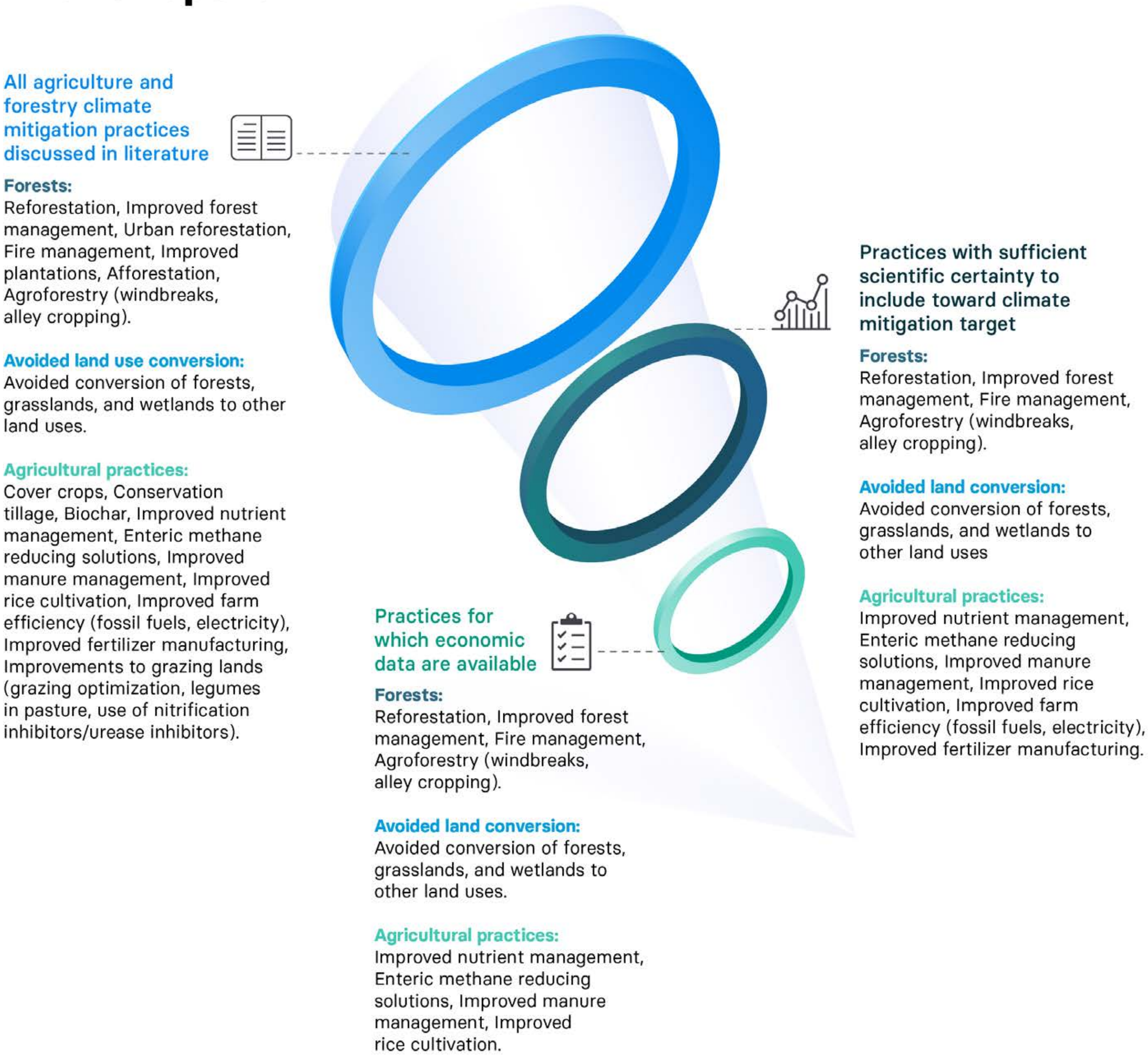


Figure 5. GHG mitigation practices considered in this report.

provides a discussion of limitations and uncertainties constraining the analysis, a list of the studies used to develop the MACCs and a description of the MACC analysis methodology.

The available MACCs that underpin this analysis do not account for social or health costs of non-GHG emissions and other pollutants, and additional costs to address those impacts should be studied and incorporated into future economic analyses. Additionally, some of the mitigation practices identified may be cost-prohibitive to lower-income and smaller producers, absent additional support (e.g., grants or technical assistance).

The price of carbon in U.S. regulatory markets in late 2021 and early 2022 ranged from ~$3–33/ metric ton[21] (RGGI 2022; CARB 2022). The Biden and Obama administrations recognized a social cost of

[21] Carbon price range is based on current costs of allowances under the U.S compliance carbon markets (California's Western Climate Initiative and the Regional Greenhouse Gas Initiative) as of May 2022.

carbon (a measure, in dollars, of how much damage results from emitting 1 metric ton of carbon dioxide) of $51 (Interagency Working Group on Social Cost of Greenhouse Gases 2021), applying that price for public sector cost-benefit evaluations.

The price of carbon on the voluntary and regulatory market is projected to rise over the next 10 years to approximately $100/metric ton (Trove Research 2021; Bloomberg NEF 2022; S&P Global 2018; Ecosystem Marketplace 2021). Because of this price variation and the different costs of mitigation practices at given levels of practice change, an economic analysis comparing interventions can help stakeholders understand where to direct limited financial resources to achieve the most climate mitigation.

Figure 6 shows the emissions reductions achievable for each practice at a range of carbon prices from $10 to $100, which helps to identify the practices that can deliver the most emission reductions for the lowest cost through a variety of policy solutions.[22] The height of each bar represents the total emission reductions from combined practices at that carbon price. The bar on the far right shows the maximum potential (also called the technical potential) for each of the practices that could occur where price is not a constraint. Note that for two practices — improved on-farm fossil fuel use and improved upstream nitrogen production — the only available data were for technical maximum emissions reduction, i.e., the potential emissions reduction resulting from complete adoption of the practice. For these practices, and for other technical maximum estimates from the literature, the technical potential was added to the calculated overall MACC curve above the price of $100/metric ton CO_2e.

Figure 6 shows that at $10/metric ton CO_2e, approximately 170 MMT CO_2e can be reduced or removed annually, of which 78% (132 MMT CO_2e) comes from improved natural forest management (68 MMT CO_2e), avoided forest conversion to cropland (32 MMT CO_2e), avoided grassland conversion to cropland (22 MMT CO_2e) and improved manure management (10 MMT CO_2e). Stated otherwise, if stakeholders want to invest $10/metric ton CO_2e on carbon markets, these practices will result in the largest removals or emissions reductions/avoidance for the price. Within those practices, stakeholders can further prioritize if they want their efforts to go toward increased removals (e.g., improved forest management), decreased loss or conversion of natural lands (e.g., avoided forest and grassland conversion), or maximum short-term impact (e.g., reducing methane from manure management).

This type of analysis can be conducted at different prices to determine which practice results in the largest reductions or removal at a given price, as well as the type of emissions reduction (e.g., CO_2 or methane) or removal in which the stakeholder wants to invest. Given the nature of the MACC curves used in this analysis, which are based on limited datasets and regionally specific GHG removal or reductions data and prices, the same practices may achieve different levels of mitigation per dollar at each price point. Practices such as improved natural forest management, forest fire management and improved plantation management have been grouped into a larger improved forest management category to increase the robustness of the model.

- At $25/metric ton of carbon, 535 MMT CO_2e can be reduced or removed, of which 88% (470 MMT CO_2e) comes from improved forest management (204 MMT CO_2e), reforestation (184 MMT CO_2e), avoided grassland conversion (50 MMT CO_2e) and avoided forestland conversion (32 MMT CO_2e).
- At $50/metric ton of carbon, 763 MMT CO_2e can be reduced or removed, of which 70% (687 MMT CO_2e) comes from improved forest management (271 MMT CO_2e), reforestation (249 MMT CO_2e), avoided grassland conversion to cropland (97 MMT CO_2e) and agroforestry (70 MMT CO_2e).
- Above $50/metric ton of carbon, the mitigation or sequestration potential flattens out and the amount of sequestration per dollar invested does not increase significantly. This indicates that options to reduce GHG emissions or increase removals in the agriculture and forestry sector will be most cost-effective overall at prices of $50/metric ton of carbon or less. Conversely, paying more than $50/metric ton of carbon in these sectors does not dramatically decrease emissions or increase removals.

As shown in the chart, the cumulative reductions, avoidance and removals of all the practices surpass the science-based target for 2030 at $27/metric ton of carbon. Even at $20/metric ton of carbon, the combination of practices still achieves more than 400 MMT CO_2e in net mitigation. As noted above, the combined impact of the practices becomes

[22] Carbon prices throughout are stated in 2020 U.S. dollars.

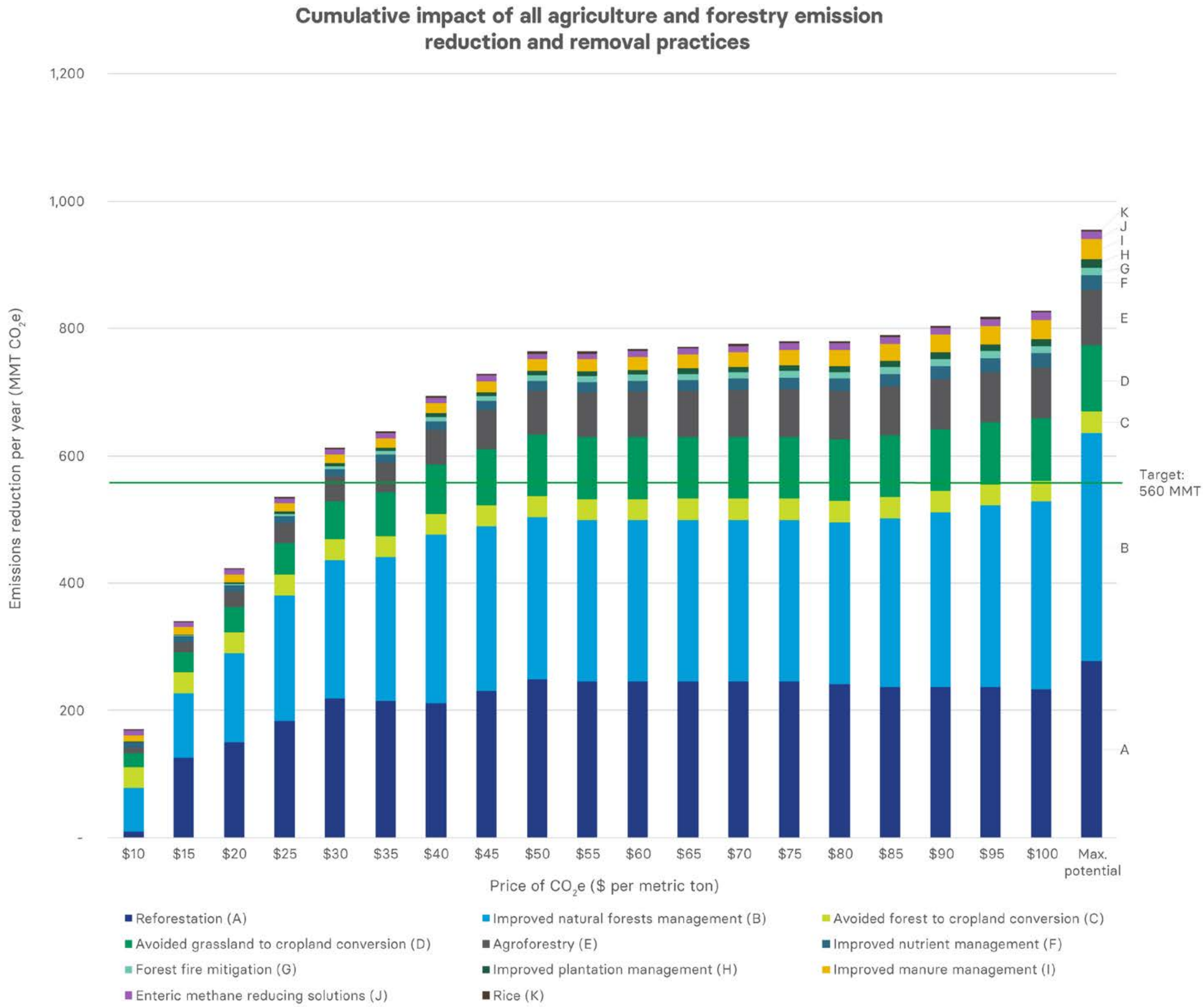


Figure 6. Cumulative impact of all agriculture and forestry emission reduction and removal practices for which economic data were available. The science-based feasible and ambitious target is shown for comparison.

Note: Values above use 100-year GWP for methane and nitrous oxide. Practices that primarily reduce methane, such as manure management and avoided enteric fermentation, have a much larger impact when using 20- or 50-year GWPs because methane has a short lifetime in the atmosphere. At a 100-year GWP, the mitigation potential of strategies to reduce methane may be undervalued compared to their short-term positive impacts.

**MACC data for enteric methane reducing solutions were developed before the newer feed additives became a potential option, and thus they include optimized grazing intensity, grazing legumes, improved feed conversion and better feed and animal management but not enteric fermentation inhibiting products. As a result, the potential mitigation at different prices is likely to change (i.e., increase) in future assessments.*

less sensitive to price starting at $50/metric ton, where subsequent price increases have little effect, until impact starts to climb slowly again after $80/metric ton.

Figure 7 and Figure 8 split out the practices by sector (agriculture and land use/forestry).

Another way to analyze emissions reductions per practice is to rank individual practices according to their GHG mitigation potential at different prices, as shown in Table 3. This can be useful in prioritizing investment in practices at current vs. future prices. Note that at $25/metric ton, even though only three

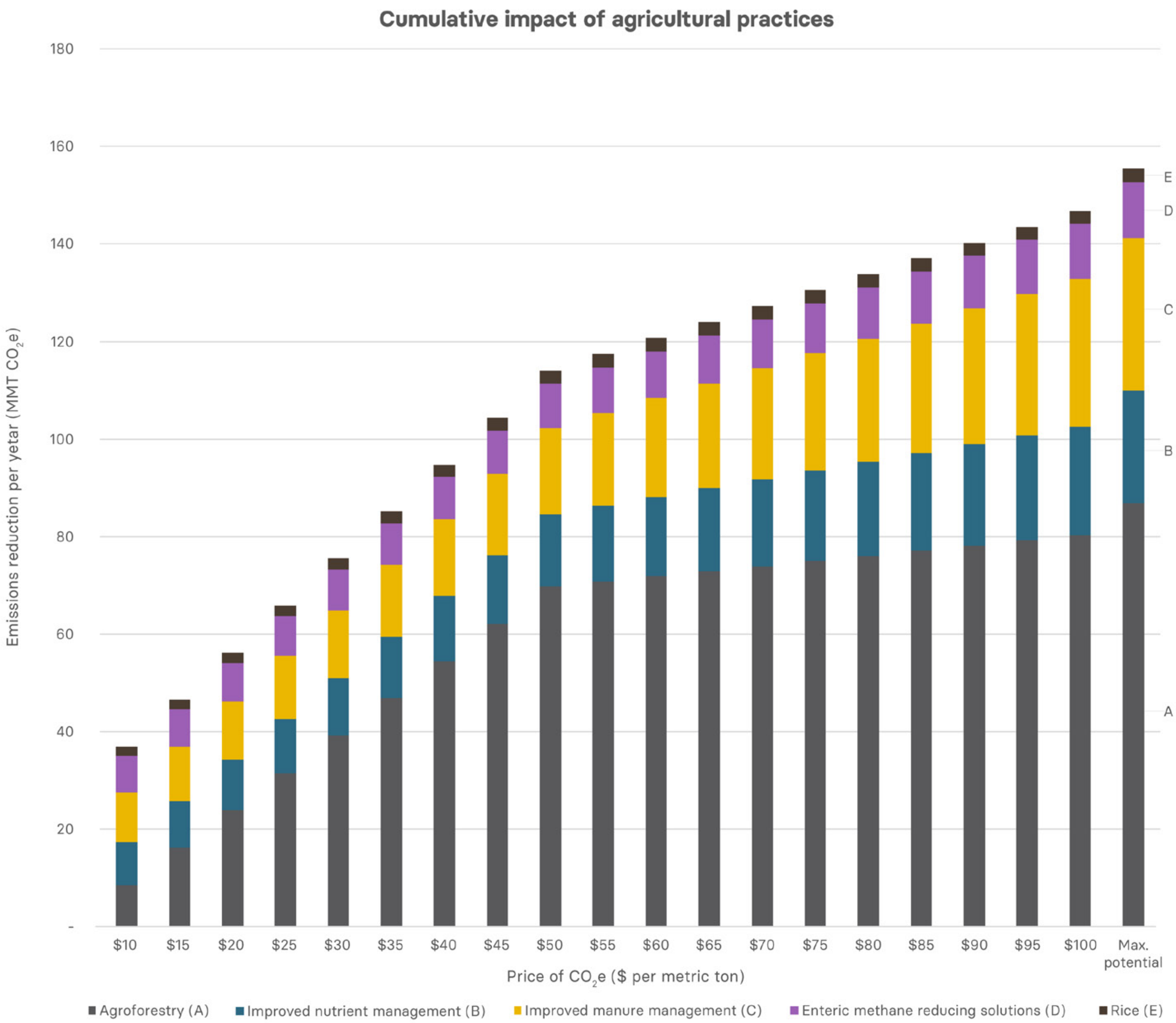


Figure 7. Cumulative impact of agricultural practices for which economic data were available.

practices meet their individual targets, the cumulative impact of all practices combined comes close to meeting the total 560 MMT CO_2e science-based target for 2030.

Practices may move up and down in ranking due to their price schedule on the MACC, where different levels of adoption of that practice and the resulting mitigation potential become available at different carbon prices. Some practices have relatively low transition costs, so lower carbon prices can encourage greater levels of adoption compared with practices that have higher transition costs. For the more expensive practices, adoption may not be unlocked until carbon prices are high enough to help offset more of those costs.

Many practices plateau — i.e., their mitigation potential increases more slowly or stagnates — when no additional adoption is unlocked for an increase in price. For instance, most of these practices' mitigation potentials respond more slowly to increased prices after about $50/metric ton of CO_2e, after which point additional climate measures from working lands and elsewhere will be needed to drive impact. In this case, producers who were encouraged by the financial incentive to transition have already done so, leaving those producers who have hesitations and concerns

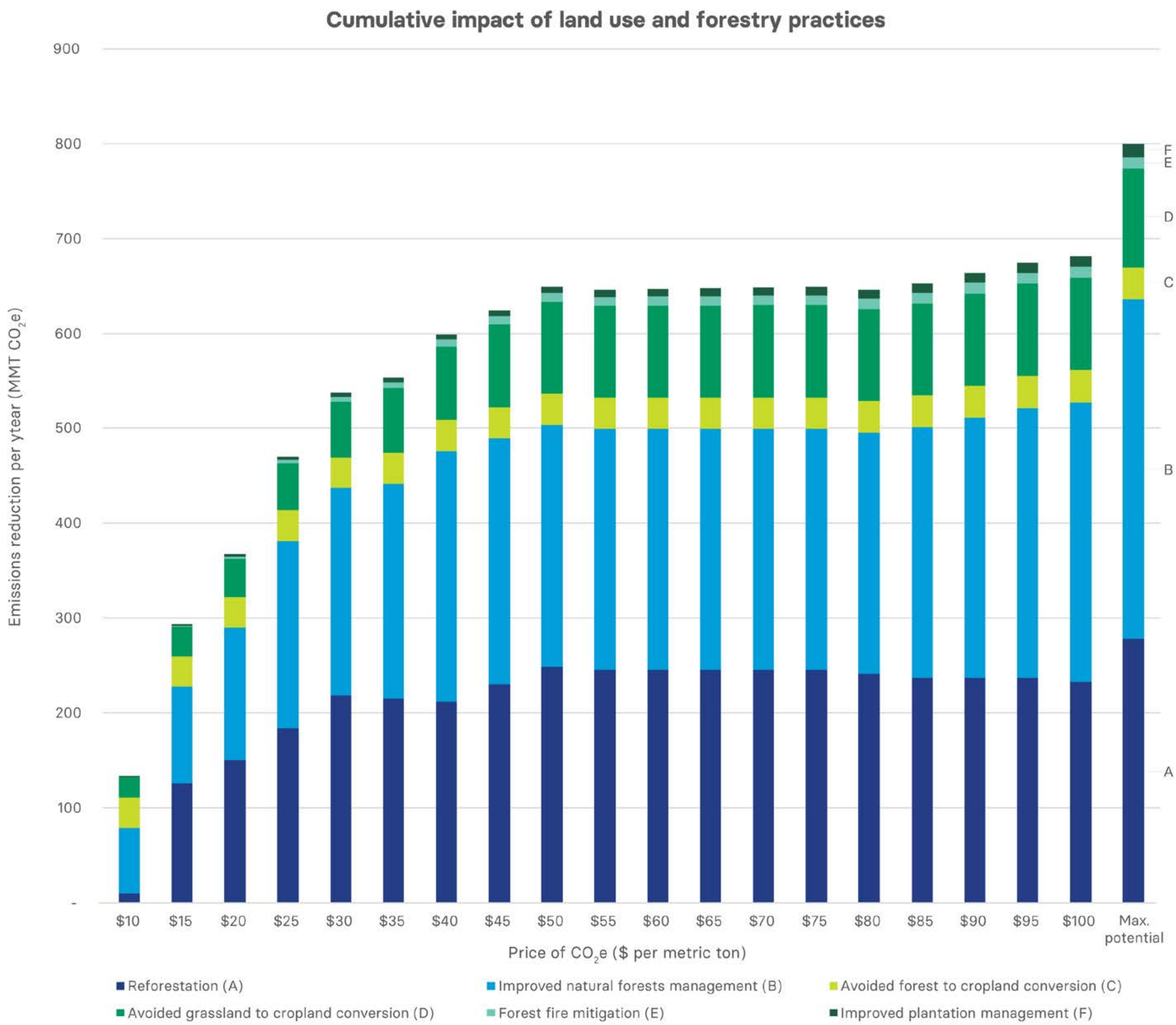


Figure 8. Cumulative impact of land use and forestry practices for which economic data were available.

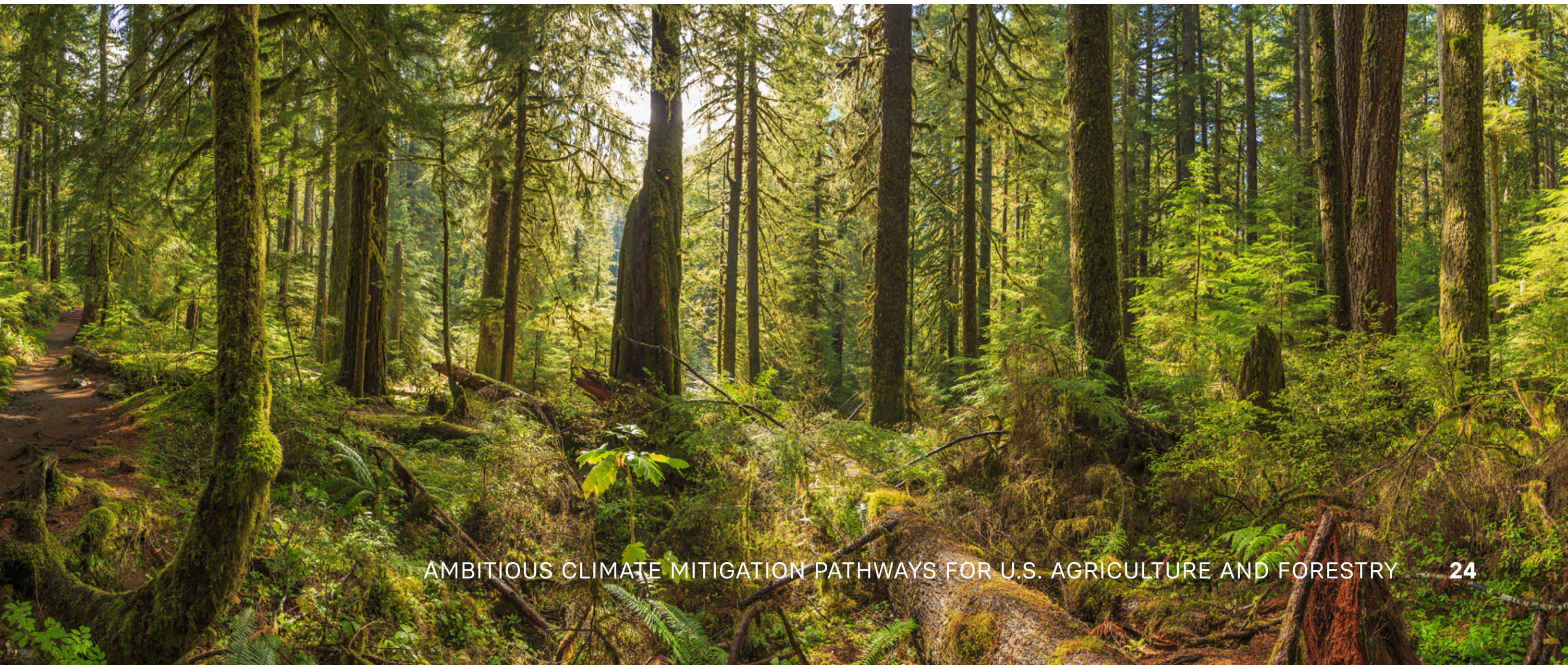
that are not alleviated by financial incentives. For all these reasons, some practices shift to higher relative rankings in Table 3 at different carbon prices. The cost of practice adoption should include the costs of changing systems to remove barriers to adoption, such as improving market options, having tree seedlings available, and promoting community collaboration.

The adoption of climate mitigation practices depends on a complex mix of interacting factors, financial incentives being only one of them. Despite the potential financial and environmental benefits of many GHG-reducing practices in the agriculture and forestry sectors, it has been challenging to increase the scale and rate at which practices are adopted by producers. Factors such as land/farm characteristics, awareness of practices and producer characteristics such as knowledge and attitude, perceived impact on yield, previous experience, risk tolerance and environmental consciousness are sometimes correlated with adoption at the individual producer level (Ranjan et al. 2019; T. Liu, Bruins, and Heberling 2018; Niles and Wiltshire 2019; Searchinger et al. 2021).

Adoption of practices also occurs within a socio-ecological context that varies across time and space. Examples of contextual factors that influence adoption are supply chain pressures, local soil and environmental conditions, equipment availability, farming norms and farmer social networks (Prokopy et al. 2019). Even though some factors are correlated with adoption, 35 years of research has shown that individual factors are not powerful or consistent predictors of practice adoption (Prokopy et al. 2019). Researchers recommend that scientists and practitioners focus more on the social and systemic factors that make up the context in which conservation adoption behavior takes place and how those factors interact with individual producer decision-making to shape behavior. Addressing these systemic factors across larger geographic and temporal scales in conjunction with financial incentives is the most promising approach to affecting adoption behavior for climate mitigation practices.

Table 3. Individual practices ranked in descending order from 1–9 by annual mitigation potential (MMT CO_2e), where 1 is the highest potential, at four carbon prices ($10, $25, $50, $100). Green text indicates that a practice meets its science-based target mitigation level at that price; black text indicates that it does not.

	$10	$25	$50	$100
1	Improved forest management: 70	Improved forest management: 204	Improved forest management: 271	Improved forest management: 317
2	Avoided forest conversion: 32	Reforestation: 184	Reforestation: 249	Reforestation: 233
3	Avoided grassland conversion: 22	Avoided grassland conversion: 50	Avoided grassland conversion: 97	Avoided grassland conversion: 97
4	Improved manure management: 10	Avoided forest conversion: 32	Agroforestry: 70	Agroforestry: 80
5	Reforestation: 10	Agroforestry: 32	Avoided forest conversion: 33	Avoided forest conversion: 34
6	Improved nutrient management: 9	Improved manure management: 13	Improved manure management: 18	Improved manure management: 30
7	Agroforestry: 9	Improved nutrient management: 11	Improved nutrient management: 15	Improved nutrient management: 22
8	Enteric methane reducing solutions: 7	Enteric methane reducing solutions: 8	Enteric methane reducing solutions: 9	Enteric methane reducing solutions: 11
9	Improved rice production: 2	Improved rice production: 2	Improved rice production: 3	Improved rice production: 3



Biogas Drying Unit Adjacent to a Covered Lagoon

Climate mitigation opportunity and economic analysis: Subsector detail

The sections below provide a detailed overview of the five major emission and removal categories: 1) livestock, 2) cropland, 3) agroforestry, 4) land-use conversion and 5) forestry, including economic data when available. This includes a brief background on each of the emission categories, a summary of the available MACC data, and a discussion of regional differences in both emission sources and mitigation potential. Additional details on the MACC data, including limitations, are provided in the Appendix.

These sections also include brief discussions of relevant equity and environmental justice needs that should be considered in developing mitigation responses.

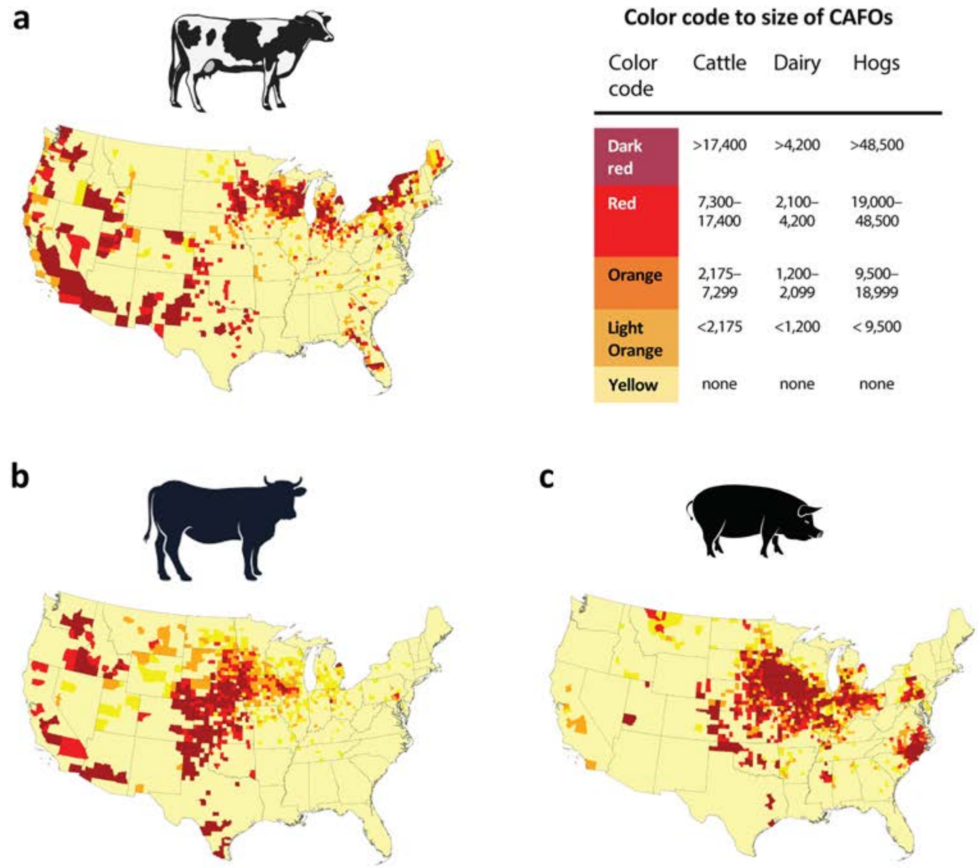
Livestock

In 2021, U.S. farmers produced meat and dairy products from a population of 101 million head of cattle — 87% of which were for beef,[23] the remaining 13% for dairy — 74.2 million pigs, 2.1 billion chickens,[24] and 104.3 million turkeys[25] (USDA NASS 2022a; USDA NASS 2021; 2019). Livestock are produced across the continental U.S., with regional variation by animal type. Beef production is concentrated in the Southern and Northern Plains regions as well as Missouri; dairy production is located primarily along the northern and western parts of the country, with California, Wisconsin, Idaho, Texas and New York the top-producing states; swine production occurs predominantly in the Upper Midwest (Iowa and Minnesota) and the Southeast (North Carolina)

[23] Beef cattle count includes beef cows that have calved, calf crop, cattle on feed, beef replacement heifers, and bulls and steers.

[24] Includes broiler chickens and laying hens. Total chicken population numbers are from the 2017 Census of Agriculture. While USDA publishes estimates of chicken populations excluding broilers annually, population estimates for broilers are published only in the Census of Agriculture.

[25] Note that USDA only surveys turkey operations during the Census of Agriculture. Turkey population numbers are from the 2017 Census of Agriculture.



Color code to size of CAFOs

Color code	Cattle	Dairy	Hogs
Dark red	>17,400	>4,200	>48,500
Red	7,300–17,400	2,100–4,200	19,000–48,500
Orange	2,175–7,299	1,200–2,099	9,500–18,999
Light Orange	<2,175	<1,200	< 9,500
Yellow	none	none	none

Figure 9. Maps of CAFOs for (a) dairy cattle, (b) beef cattle, and (c) hogs in 2017 in the contiguous United States (Glibert 2020) Modified; figures are originally from Food and Water Watch (2020).

(USDA NASS 2022a; Montefiore et al. 2022). See Figure 9 for details.

Due to economies of scale, the overall trend in livestock production in the U.S. has been away from smaller farms and toward larger farms called Concentrated Animal Feeding Operations (CAFOs) (USDA ERS 2020). Large CAFOs are defined as an operation in which over 1,000 “animal units” are confined for more than 45 days a year, equating to about 700 dairy cows, 1,000 meat cows, 2,500 pigs or 125,000 chickens (USDA NRCS n.d.). Smaller CAFOs also exist with other defining characteristics. CAFOs are associated with productivity benefits such as reduced cost per animal and faster speed to maturity, which can reduce the GHG emissions intensity and land use of livestock per unit of production (FAO 2020).

However, the higher concentration of animals in one place also tends to generate negative impacts including greater methane emission levels from liquid manure storage (cattle and swine), air and noise pollution and waste runoff (Glibert, 2020). The resulting environmental justice impacts on adjacent and downstream communities have been challenging in many regions. For this reason, the design and implementation of climate mitigation measures must be carried out in consultation with locally impacted communities.

The two major GHG emissions sources associated with livestock production are methane from enteric fermentation[26] (mostly from cattle) and methane and nitrous oxide emissions from manure management. Manure quantity (the amount produced per animal) and composition (ratio and amount of nitrogen, carbon and phosphate) vary by livestock type, which affect GHG emissions. Enteric fermentation is associated with ruminant digestion and is therefore primarily associated with cattle in the U.S. Enteric fermentation generates the largest quantity of emissions associated with livestock production (see the Current Landscape

[26] Enteric fermentation is the production of methane by animals as they digest food. Due to their unique stomachs, ruminant animals (e.g., cows, sheep, and goats) are able to digest grass and other plants but are the major emitters of methane in the process.

section for details). While poultry and minor livestock categories also result in GHG emissions, this section focuses on emissions from manure management of beef, dairy and swine production and enteric fermentation emissions from beef and dairy cows.

Enteric methane emissions

In 2018, enteric fermentation contributed 177.6 MMT CO_2e, making it the largest source of anthropogenic methane emissions in the U.S. (EPA 2020), with 72% from beef and 24% from dairy animals (EPA 2020). Opportunities for reducing enteric fermentation generally overlap with population maps of beef and dairy cows. (See Figure 9).[27]

Mitigation opportunities

Several viable strategies are available for reducing emissions from enteric fermentation, including optimizing feed digestibility, improving herd health and reproduction, selectively breeding for cattle with lower levels of enteric methane production, and using rumen modifiers such as feed additives and animal drugs (de Haas et al. 2021; CARB 2021; Dong, Li, and Diao 2019; Searchinger et al. 2021). Emissions intensity can also be reduced by increasing production efficiency, i.e., producing more meat and milk per animal or per unit of feed (Searchinger et al. 2021). Increasing production efficiency is particularly critical since enteric methane emissions are directly related to quantity of feed consumed (Searchinger et al. 2021).

Technologies and practices that reduce methane emissions from enteric fermentation are applicable to most dairy and beef operations. The greatest opportunities for emissions reductions are in regions with many CAFOs, such as dairies in California and Wisconsin and beef feedlots in Texas and the Great Plains (Kansas, Nebraska and Colorado). Significant opportunities also exist to mitigate emissions from grazing cattle, particularly in regions with large amounts of grazing land such as the Mountain West and Southern Plains (USDA NRCS n.d.).

To develop the science-based target for enteric methane reducing solutions, we used peer-reviewed evidence and system-level understanding of dairy and beef production in the U.S., estimating that it will

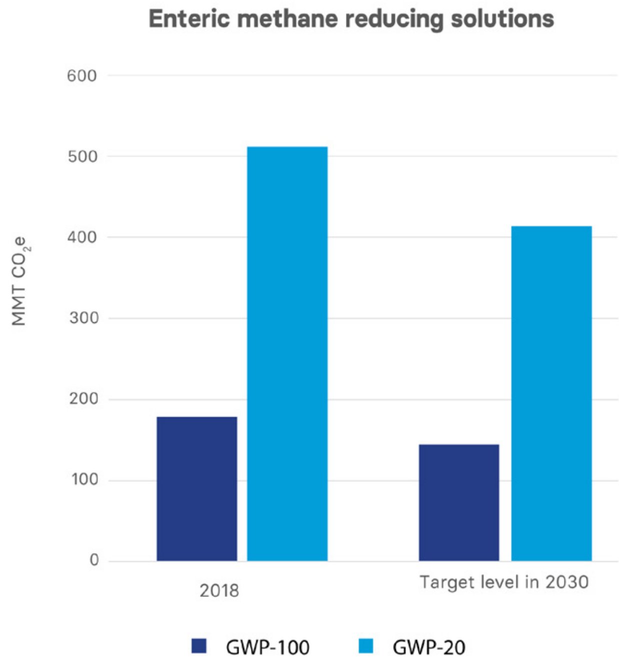


Figure 10. U.S. enteric methane emissions for 2018 compared with projected 2030 emissions after achieving the science-based target annual reduction of 30 MMT CO_2e (or 86 MMT CO_2e using a 20-year GWP) through enteric methane reducing solutions.

be economically and practically feasible to reduce cattle enteric emissions by 10%–20% from the 2018 baseline. In 2018, as noted above, the U.S. livestock enteric emissions (177.6 MMT CO_2e100/yr) came mostly from beef and dairy, which comprised 128.1 MMT and 43.6 MMT, respectively (EPA 2020).[28] Life-cycle assessment research suggests that 84% of beef enteric emissions occur during the cow-calf phase (from pregnant and nursing cows), with the rest (16%) during backgrounding and feedlot (Beauchemin et al. 2010). Beef cows are on range or pasture during large parts of the year, and feed additives are not yet practical for grazing animals — especially those widely dispersed on low producing rangeland. However, it could be possible to mix methane reducing compounds into feed during winter months when these animals are fed hay or silage.

We estimate that mature beef cows get 30% of their feed as harvested (cut, stored, and fed) forage (see next paragraph for details; possible range from 5% to more than 50%). We can then say feed additives could

[27] Note that this figure does not show populations of grazing cattle. Reducing enteric fermentation from grazing cattle is also critically important, as grazed cattle produce more methane emission per head compared to those with high-quality mixed-ration diets (e.g., dairies) or cattle finished in feedlots on grain diets, due to the lower digestibility of grass-based diets (Garnett et al. 2017).

[28] Note that these numbers are the national inventory values, using AR4 GWPs; for the purpose of this analysis they are not converted to AR5 or to Mg of methane.

be used for 84% x 30% of beef[29] and 80% of dairy. Dairy cattle in the U.S. and Canada are 93% stall-fed (Wolf, Asrar, and West 2017); this is reduced to 80% to account for calves, heifers, dry cows and some dairies that may not have access to feed additives. The most researched additive (3-NOP—not yet licensed for sale in the U.S.) reduces enteric emissions by 32% in dairy (Feng and Kebreab 2020, Fig. 2) and 22% in beef (Dijkstra et al. meta-analysis, quoted in Feng & Kebreab 2020). With this level of implementation, we could get 7% methane emission reduction in beef (9.0 MMT CO_2e) and 26% (11.2 MMT CO_2e) in dairy, for a total of 20.2 MMT CO_2e or 11% reductions. This rounds down to 10% reductions (6% from 2005) for our low estimate, which assumes that the availability of feed additives increases in the near term.

Note that backgrounding and feedlot have much lower methane emissions per unit of feed (about 50%), due to the higher digestibility of grain compared with grass and hay. Feed additives will therefore have less impact in these facilities. The EPA GHG inventory's detailed calculations (Annex 3.10 of the 2020 inventory) suggest that beef cow-calf operations are on non-grazing feed such as hay or silage for 5% to 15% of total intake — but inconsistencies in the data as presented provide low confidence in these numbers. Extension resources and producer magazines suggest that beef cows are fed hay (as opposed to grazing) for 6–9 months of the year in northern states such as North Dakota. Thus, without doing an in-depth exploration for each beef-producing state, we approximate that 30% of beef cattle (cow-calf) feed is in hay and other non-grazing format with potential for feed additive implementation.

We provide a high-range estimate of 20% (16% from 2005) enteric emission reductions for the possibility that feed additives could be offered to a larger portion of the cattle herd (Searchinger et al. 2019) or that feed additives could be combined with genetic improvement (breeding), feed processing or other diet manipulation, and improved herd productivity for greater impact (Ahmed et al. 2020; Herrero et al. 2016). Searchinger et al. (2019) estimated a 30% reduction in enteric emissions by providing feed additives to all ruminants in North America. This estimate seems high given the lower methane-mitigation efficacy for 3-NOP in beef animals compared to dairy (Dijkstra et al., quoted in Feng & Kebreab 2020) and considering that still we do not know how to make this work for grazing animals. Thus, we choose a conservative value of 20% reduction.

Ahmed et al. (2020) estimated that 1) improved genetics could be implemented for 45% of the global cattle herd, reducing enteric emissions by 11% (45% * 11% = 5%), 2) improved productivity such as reproductive health and other efficiency gains could reduce global enteric emissions by 8%, 3) feed additives could be used for 20% of the global cattle herd with 15% emission reductions (20% * 15% = 3%) and 4) feed-grain processing could be improved for 15% of global cattle, with 17% reductions (15% * 17% = 2.6%). If these are additive, the total enteric emission reductions would be 19%. Herrero et al. (2016) estimated that global enteric emissions could be reduced by around 10% with improvements in animal health, reduced mortality, better reproductive management and faster weight gain. They did not mention feed additives to reduce methanogenesis, which would then be added to this estimate.

Cost analysis

The cost of reducing methane emissions from livestock enteric fermentation at different prices of CO_2e depends on the technology used. A cost analysis across all technology types is shown in Figure 11.

- A carbon price of $10 per metric ton would result in a reduction of 7.47 MMT CO_2e.
- $50 per metric ton would result in a reduction of 9.15 MMT CO_2e.
- $100 per metric ton would result in a reduction of 11.26 MMT CO_2e.
- Using a 20-year GWP for methane instead of the default 100-year value would increase the cost-effectiveness of reducing methane from enteric fermentation: at $10/metric ton, for example, enteric fermentation technologies could avoid more than 26 MMT CO_2e using a 20-year GWP compared with 9.15 MMT CO_2e using a 100-year GWP.
- For context, an investment in air-source heat pumps for space-conditioning of buildings at $10 per metric ton of carbon would avoid 3.1 MMT CO_2e (EDF 2021).

Manure production

In 2018, manure was responsible for 61.7 MMT CO_2e of methane and 19.4 MMT CO_2e of nitrous oxide

[29]The remaining 16% of beef emissions (backgrounding and feedlot) provide little mitigation opportunity due to high digestibility of grain, which reduces emissions by about 50% already.

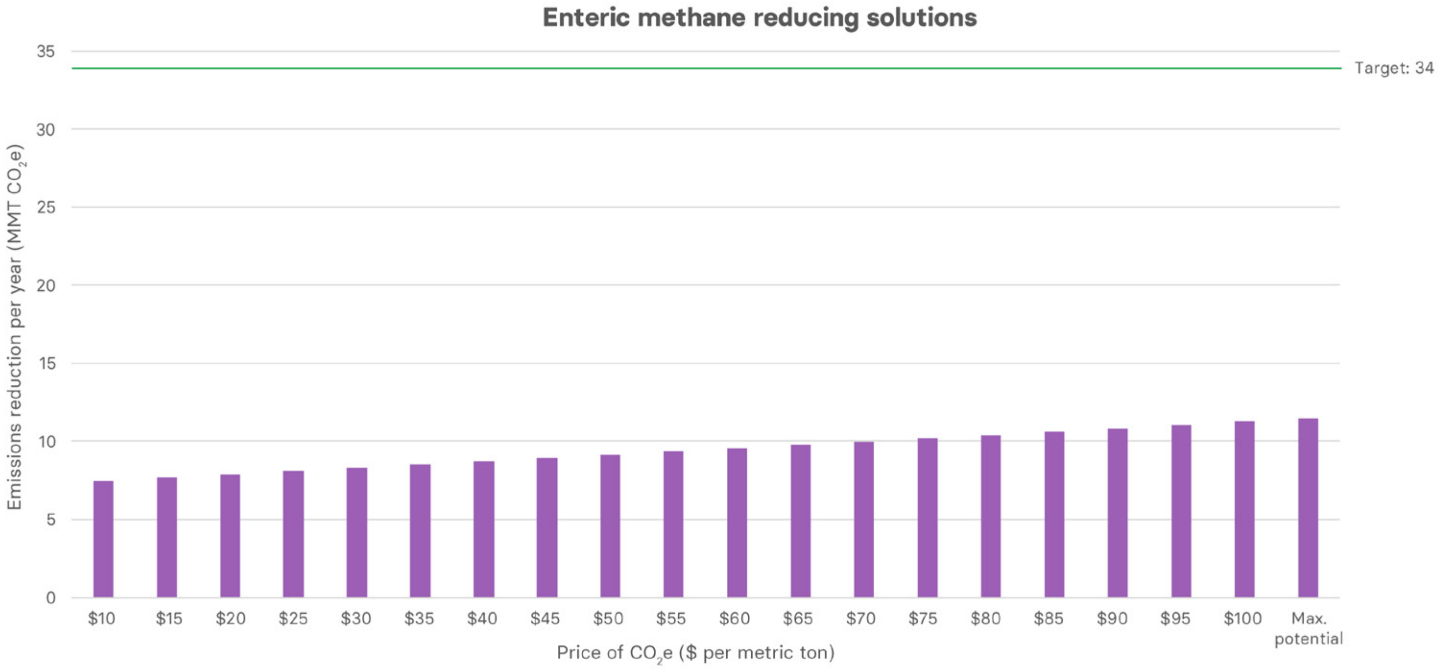


Figure 11. Anticipated net GHG mitigation possible from enteric methane reducing solutions at different carbon market prices, based on available economic cost data.

emissions, for a total of 81.1 MMT MMT CO_2e (EPA 2020).

Mitigation opportunities

Manure can be managed in different ways, each of which can affect both methane and nitrous oxide emissions rates. These practices include leaving it in the pasture, collecting the manure from corrals and barns and spreading it daily on cropland or storing the manure on farm for less frequent field application.

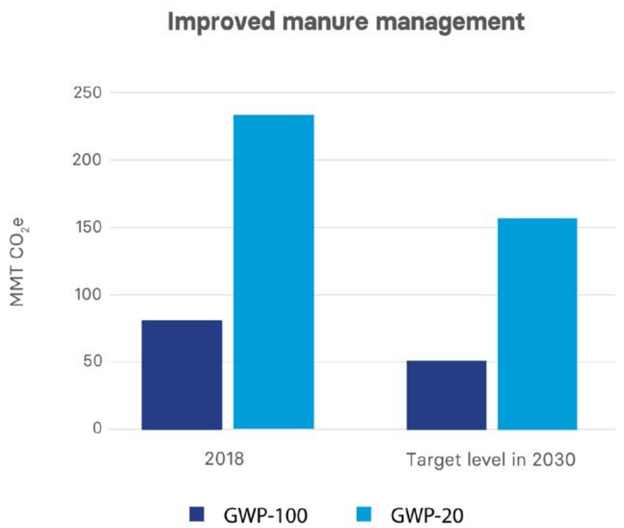


Figure 12. An estimated 29.8 MMT CO_2e could be avoided annually by 2030 (or 76 MMT CO_2e using a 20-year GWP) through improved manure management.

Storage capacity on farms has increased over the past decades in response to requirements to avoid losses of nutrients and pathogens to surrounding ecosystems. Greater storage volume also allows application timing to fit better with crop needs and weather. Manure (with or without added bedding and water) can be stored as a solid, as a liquid slurry in a tank or a deep pit, or collected and stored in an anaerobic lagoon. Dry systems such as solid storage are most common for beef and poultry operations, whereas wet systems such as anaerobic lagoons and liquid slurry operations are commonly used by dairy cattle and hog operations (Glibert 2020).

In addition to varying by animal type, the type of manure management system used depends on farm size and location. Smaller farms tend to rely on lower methane-emission, dry manure management strategies, such as storing it in stacks or piles for later spreading on fields or leaving it directly in pastures (EPA 2021b). In contrast, large operations such as dairy and swine CAFOs tend to rely on wet manure management systems such as wet flushing and scraping systems, which help move manure from barns to storage tanks and lagoons. Although wet management systems can help control large volumes of manure, they produce more GHG emissions than dry systems due to storage in anaerobic tanks and lagoons. Opportunities for manure management align well with locations of dairy, beef and swine populations and CAFOs (see Figure 9).

The majority of methane emissions from manure management across all animal types occurs in wet systems (Searchinger et al. 2021). For wet systems, addressing the way manure is stored after collection is critical to reducing emissions. Installing anaerobic digesters and methane recovery systems (e.g., covering open lagoons, thus enabling the capture of the methane produced), for example, can reduce emissions from wet manure. There has been an increase in manure methane emissions over the past 20 years because more farms are using larger storage pits/lagoons/ponds (EPA 2020). This allows farms to better manage nutrients and apply the manure to fields when the crops need the nutrients. However, it also means more anaerobic conditions, and because there is a lot of organic matter for the microbes to digest, the redox potential goes down, carbon substances are the only electron acceptor remaining, and methane is produced.

In addition to installing digesters, producers can use a variety of other management practices to reduce methane emissions from manure. These include removing manure from higher-temperature barns on a more frequent basis, separating solid from liquid manure and improving barn design systems to encourage livestock to depose urine and feces in different places. Microbial additives can also significantly decrease methane emissions from manure stored in wet form (Iowa State University Extension n.d.). Regions with high concentrations of dairy and swine CAFOs that rely on liquid manure management techniques, such as California, the Upper Midwest and the Southeast, are key geographies for improved manure management. Adoption of these management techniques will likely depend on the level of financial support from government and other stakeholders in each region, given the high cost to adopt more advanced techniques such as anaerobic digestors. The State of California, for example, supports farmers' financial transition to improved manure management through the Alternative Manure Management Program.

Manure management is an area where particular attention to environmental justice is necessary. Technologies and manure management methods that reduce methane emissions may have some benefits to local communities, but they rarely address the full spectrum of community impacts of livestock production. For example, odor and water quality issues remain, and communities may also have concerns about the siting of new infrastructure. It is essential that manure methane solutions also address local impacts to communities and incorporate transparent and inclusive decision-making to avoid prioritizing GHG mitigation over the needs of farms' neighbors.

Based on recent syntheses, we estimate that it will be economically feasible (approximately <$100/metric ton CO_2e) to reduce current livestock manure methane emission rates in the U.S. by 30%–50% (Pape et al. 2016; Ahmed et al. 2020; Fargione et al. 2018). The first two studies, one U.S.-focused (Pape et al. 2016) and the other global (Ahmed et al. 2020), arrive at their estimates using quite different methodologies, so their similarity is striking.

Pape et al. (2016) estimated that ~50% of manure methane in the U.S. could be captured by covering the existing liquid storage on the largest dairy (>300 head) and swine (>825 finished hogs) facilities, which are the most economically feasible for covering. The 2020 McKinsey report (Ahmed et al. 2020) came up with a similar reduction potential estimate for global manure methane emissions. While they call the practice "expand use of anaerobic manure digestion," it is primarily cover and capture of dairy and hog manure storage, with some other digestor types (e.g., plug flow, complete mix). They estimate a 79% methane reduction with 60% implementation, for an overall 47.4% emission reduction.

Note that Fargione et al. (2018) cite Pape et al. (2016) for their estimate of 24 MMT CO_2e (50% reduction from the baseline year used). While the first two studies are reports, Fargione et al. (2018) is a highly cited peer-reviewed publication and was broadly used for the NASEM (2019) report led by Pacala and others on negative emission technologies. One other estimate of manure methane emission reductions was lower (Herrero et al. 2016; only 12% reduction of global manure methane), but with very little explanation. Since the detailed explanation from the higher estimates made sense (and assumptions could be tested), we use those for the high range (50% from 2018). The low range (30% reduction from 2018) allows for slower implementation rates and continued transition to more liquid manure storage that may or may not be covered.

The science-based target of 30 MMT CO_2e includes 25 MMT CO_2e of methane and 4.8 MMT CO_2e of nitrous oxide.

Cost analysis

Improved manure management is a cost-effective strategy to mitigate GHG emissions:

- From the economic information available, a carbon price of $10 per metric ton is expected to result in 10.2 MMT CO_2e emission reduction for manure management, while prices of $50 and $100 per metric ton would result in reductions of 17.6 MMT CO_2e and 30.3 MMT CO_2e, respectively (Figure 13).
- If near-term impact is prioritized, using a 20-year GWP for methane instead of the default 100-year value would increase the cost-effectiveness of manure management. For example, at $25/metric ton, improved manure management could avoid more than 37 MMT CO_2e using a 20-year GWP compared with 13 MMT CO_2e using a 100-year GWP.
- To put these methane emission reductions into the context of options for net CO_2 emission reductions, an investment in biomass-powered electricity at $100/metric ton would avoid 13.7 MMT CO_2e (EDF 2021).

Figure 13. Anticipated net GHG mitigation possible from improved manure management at different carbon market prices, based on available economic cost data.

Cropland

In 2021, approximately 315 million acres of row crops were planted across the U.S., 76% of which consisted of four major crops: corn (93 million acres), soybeans (87 million acres), wheat (46 million acres) and cotton (14 million acres) (USDA NASS 2020). Figure 14 shows the percentage of land area used as cropland by county in 2012: the darker the color, the higher the proportion of cropland in a county. As shown in the map, the Corn Belt has the largest proportion of land area dedicated to crop production in the country.

Aside from net soil carbon changes, the two major GHG-producing categories associated with row crop production are 1) production and use of crop nutrients and pesticides (i.e., making and applying synthetic and organic fertilizers and pesticides), and 2) fuel and electricity use. Emissions from both categories vary by local ecosystem and environment, the specific crop grown and the production method used. The application of nitrogen fertilizer and manure results in the largest quantity of emissions associated with row crop production, in the form of nitrous oxide.

Fertilizer manufacturing

Agricultural fertilizers used in row crop farming can be energy-intensive to make. Manufacturing synthetic fertilizers accounts for 2% (23.7 MMT CO_2e) of agriculture-related emissions, with the vast majority (97%) from production of nitrogen (N) fertilizer (EPA 2020).

Mitigation opportunities

Options for reducing the GHG intensity of N fertilizer manufacturing include using renewable energy as an energy source during manufacturing and producing N fertilizers with “green” ammonia as a base (e.g., produced from N_2 via cryogenic distillation and H_2 via low-temperature electrolysis) instead of conventionally produced ammonia (e.g., produced from natural gas via steam reformation and synthesis via the Haber-Bosch process). Producing N fertilizers from green ammonia using renewable energy can reduce GHG emissions by 91% compared with conventionally produced ammonia (Kwon et al. 2021; X. Liu, Elgowainy, and Wang 2020). In addition, lower overall N application rates (less demand resulting in reduced N manufacturing) could lower emissions (Kwon et al. 2021; Fargione et al. 2018).

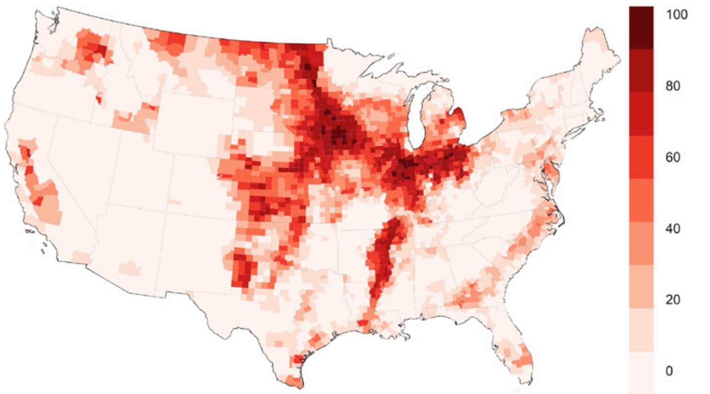


Figure 14. Percentage of cropland by county in 2012 (Spangler, Burchfield, and Schumacher 2020).

Cost analysis

Due to a lack of cost data related to improvements in the fertilizer manufacturing process, no cost analysis was conducted for this mitigation measure.

Nitrogen management

Nitrogen (N) is an essential input in crop production, the largest quantity as synthetic fertilizer, with approximately half that amount of N also added to agricultural land as manure (Falcone, 2021). Other N sources include legume crops — which capture or fix N from the atmosphere via symbiosis with rhizobium bacteria — atmospheric deposition and irrigation water. In 2021 more than 12 MMT of synthetic N fertilizer was applied to row crops in the U.S., with corn having both the highest proportion of its production area fertilized

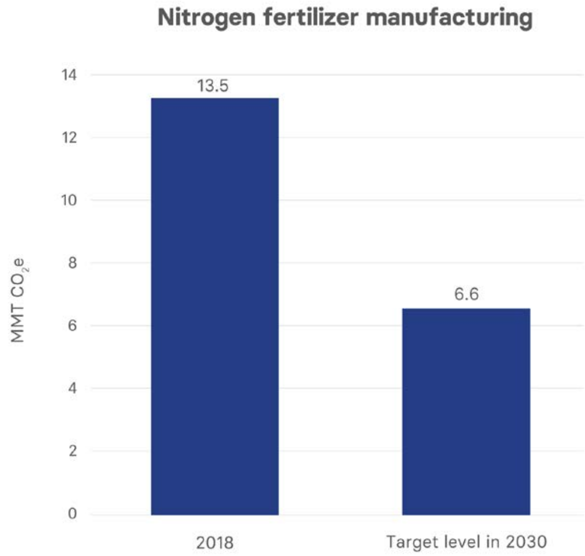


Figure 15. An estimated 10.6 MMT CO_2e could be avoided annually by 2030 from improved fertilizer manufacturing.

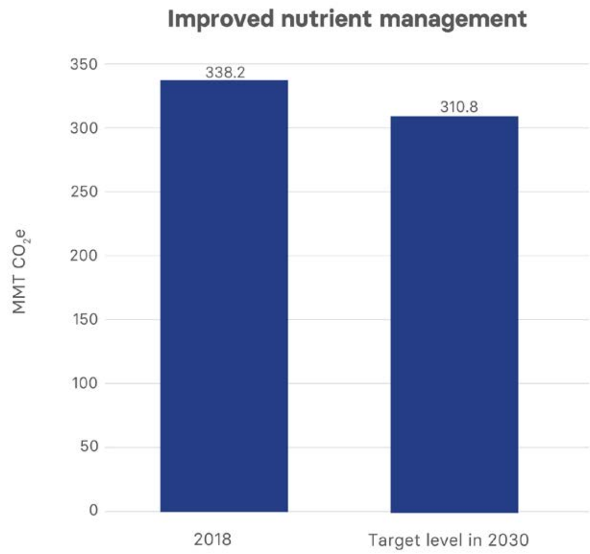


Figure 16. An estimated 27.4 MMT CO_2e could be avoided annually by 2030 through improved nutrient management.

(98%) and the highest fertilizer application rate (149 pounds/acre) nationally, followed by cotton with 78% of acres fertilized at 94 pounds/acre, wheat with 88% of acres fertilized at 78 pounds/acre and soybeans with 29% of acres fertilized at 17 pounds/acre (USDA NASS 2022b; USDA ERS 2019a; Menegat, Ledo, and Tirado 2021).

Applied annually, usually only 40–70% of the N fertilizer applied is utilized by the crop, while the remaining N (i.e., N balance or "surplus N") is volatilized as nitrous oxide or ammonia, immobilized in the soil or leached as nitrate in water[30] depending on a complex interaction of factors (Johnson 2011). Soil-management nitrous oxide losses account for 46% of agriculture-related emissions (using 100-yr GWPs). Fields or field portions with high N balance also have correspondingly high rates of direct nitrous oxide cropland emissions and water nitrate leaching, both of which can negatively affect environmental and public health (Ward et al. 2005; Ewing and Runck 2015; Gomez Isaza, Cramp, and Franklin 2020). Indirect nitrous oxide emissions — converted from nitrate in drainage canals, streams and other water — account for about 15% of the total (EPA 2020).

Figure 17 shows the average N balance (i.e., the amount of added N not removed in the harvested crops) for eight major crops in the U.S., where grey indicates no surplus and red indicates the highest level of surplus. Unsurprisingly, corn production, which has both the largest number of acres grown and the highest average N application rates, also has the most regions with high N balance.

Mitigation opportunities

Row crops are grown with a variety of production practices based on type of crop, farmer needs and goals, equipment and labor availability, geographical differences and local weather and environmental conditions. Different production practices or combinations of production practices can result in different GHG emission rates and environmental impacts.

For example, intensive row crop farming,[31] which can include conventional tillage, fall or early spring fertilizer application and winter fallow (i.e., bare, unplanted soil) is associated with greater levels of soil disturbance, higher rates of nitrous oxide emissions and nitrate leaching and higher CO_2 emissions from fossil fuel use from tractor passes. Greater soil disturbance is associated with higher rates of erosion and losses of soil carbon. In contrast, row crops grown with conservation practices — such as reduced or no tillage, winter cover crops and more complex conservation rotations — may require lower N fertilization rates,

[30] Depending on the specific soil type, local conditions, crop grown, and production methods used, nitrogen added to the soil system can be modified into nine different states of oxidation (or forms of N), each of which is associated with different properties and different loss pathways (e.g., lost through erosion, volatilized into the air, leached into the water, or denitrified).

[31] Intensive row crop farming is defined as modern farming in which large scale monocultures of crops are grown using high levels of mechanization and agrichemicals, such as fertilizers and pesticides.

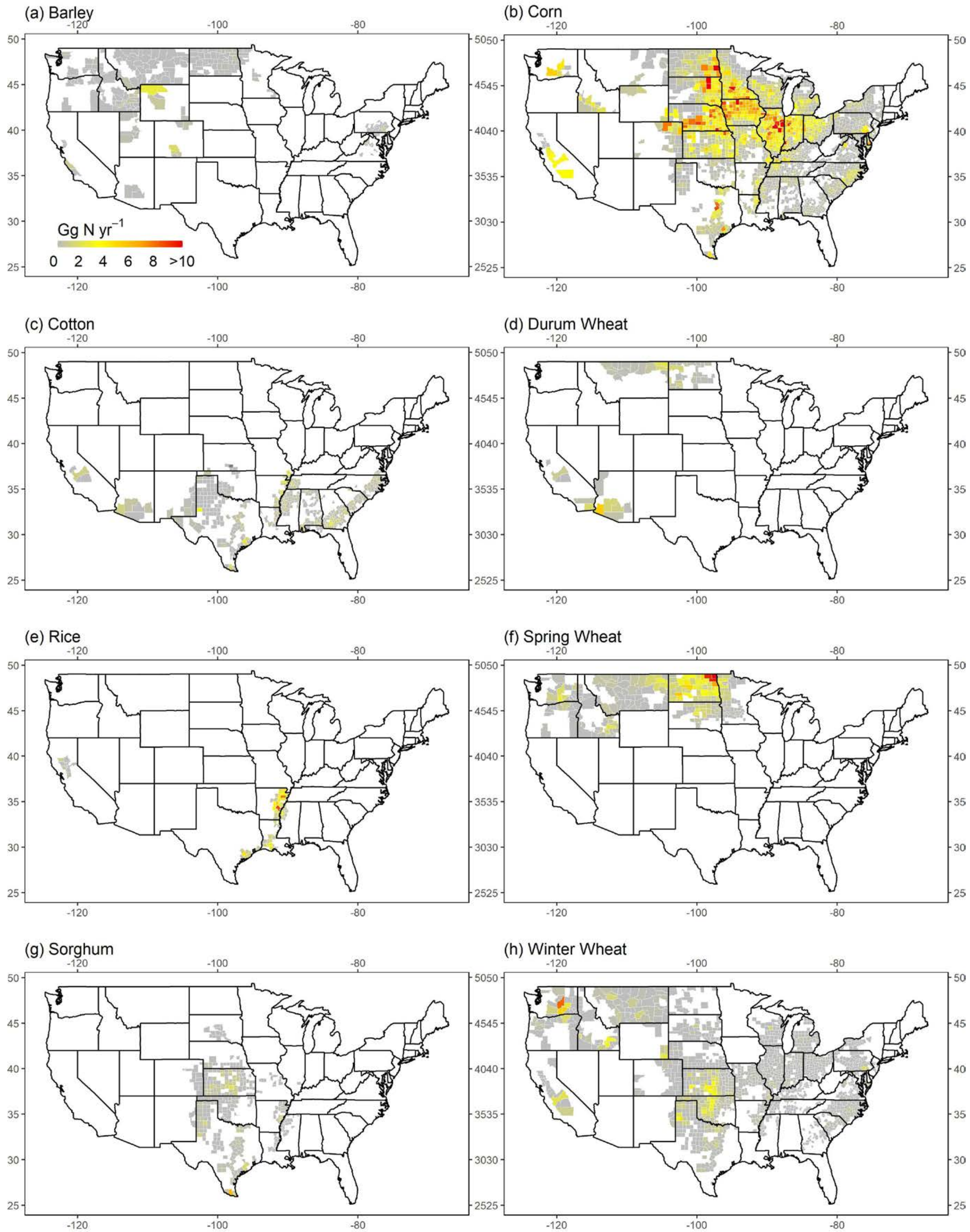


Figure 17. County level 2015-2019 average N surplus (units in gigagrams N/year) of the eight major crops grown in the United States (Zhang, Cao, and Lu 2021).

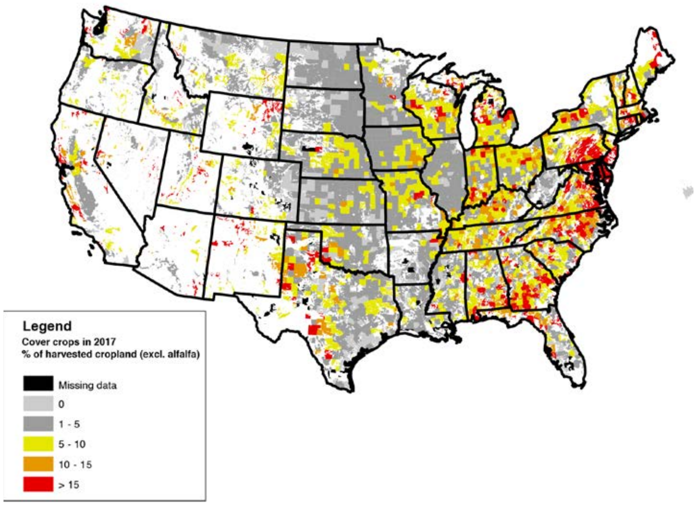


Figure 18. *Adoption of cover crops relative to harvested cropland, across counties in the contiguous United States in 2017* (Source: Wallander et al. 2021, modified).

reducing the surplus N and the risk of losses via nitrous oxide emissions and nitrate (NO_3) leaching. Such practices also reduce soil disturbance and associated erosion rates, while also lowering CO_2 emissions from fossil fuel use, among other environmental benefits (USDA NRCS 2017; 2016a; 2016b; 2016b; Thapa, Mirsky, and Tully 2018; Abdalla et al. 2019; USDA NRCS 2021; 2020). Reduced tillage and cover crops are discussed in more detail below. As shown in Figure 18, cover crops are not currently widely used in the U.S. except for concentrated areas in the East and small-scale exceptions elsewhere (University of Missouri 2022; USDA 2019). The many areas where cover crops are used only minimally (or not used at all) present GHG mitigation opportunities through increased use of cover cropping.

Most cropland has some potential to reduce nitrous oxide and nitrate losses by improving N management. This can involve using "4R" practices (i.e., the right fertilizer source, right application time, right rate and right application method). Enhanced-efficiency fertilizers contain inhibitors or are coated for slow release, and studies have measured reduced nitrous oxide emissions because more of the added N is available to the crop. Precision agriculture, such as the use of Variable Rate Technology (VRT) tractors, can also help producers reduce overall fertilizer rates and thus reduce high N balances and associated losses. Potential barriers to adoption of any of these practices include lack of information, risks (real and perceived), additional costs, regional applicability and small farm size, particularly when large equipment must be purchased such as VRT tractors.

Although economic data are available related to soil carbon storage potential for tillage and cover crops, no economic data are currently available for nitrous oxide emissions reductions associated with these practices. Uncertainty, reversibility, net GHG and monitoring challenges kept the soil carbon sequestration mitigation pathway out of the science-based target. Any nitrous oxide emission impact from these conservation practices is incorporated into overall "improved N management." For these reasons, we did not separately include these practices in the cost analysis below.

Peer-reviewed research syntheses and reports provide a wide range of possible nitrous oxide emission reductions (2%–50%) with improved N management on cropland (Fargione et al. 2018; Pape et al. 2016; Eagle and Olander 2012; Winiwarter et al. 2018; Ahmed et al. 2020). The science-based target (27 MMT CO_2e/year) falls somewhere in between. Other potential nitrous oxide emission reductions come from using nitrification inhibitors on grazing land and from improved manure management (Ahmed et al. 2020).

Cost analysis

Available abatement cost data suggest that reduced N_2O emissions of approximately 22 MMT CO_2e could be achieved at a carbon price of $100/metric ton CO_2e (Figure 19). The maximum amount of mitigation at any price (i.e., the "technical potential") at the national level from these sources is slightly higher. Values were obtained by taking an unweighted average of U.S.-specific nitrous oxide mitigation levels across a range of carbon prices from recent MACC publications (e.g., Pape et al. 2016; Fargione et al. 2018; Cook-Patton et al. 2021; Roe et al. 2021; Wade et al. 2022) to obtain an average emissions reduction per carbon price, then using a linear regression to create a best-fit line that could be used to get an estimated emissions reduction for all potential carbon prices. Estimates of technical potential (e.g., Eagle and Olander 2012; Winiwarter et al. 2018) were also included in the emission reduction potential at any carbon price over $100 USD.

Higher payment rates for carbon are expected to achieve greater N_2O emission reductions:

- At $10 per metric ton, the estimated annual emission reduction is 8.8 MMT CO_2e, at $50 it is 14.8 MMT CO_2e, and at $100 per metric ton it is 22.3 MMT CO_2e

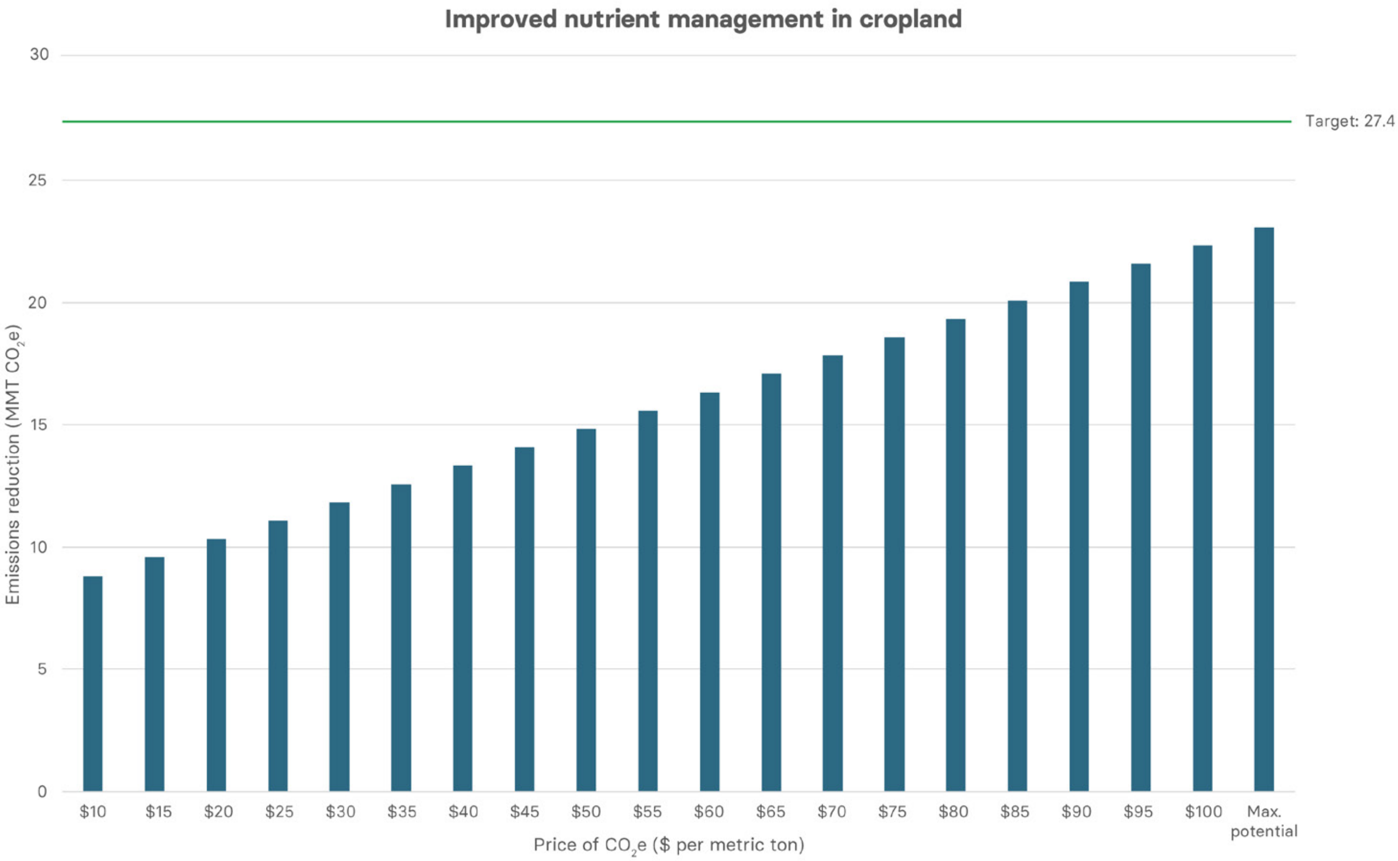


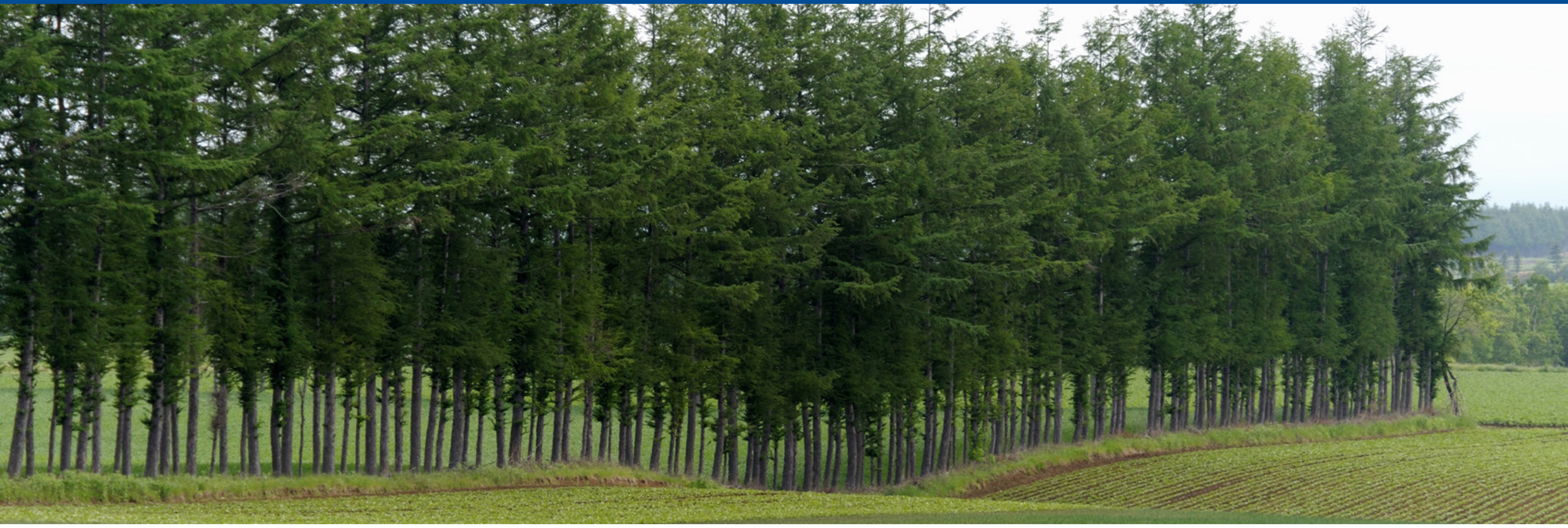
Figure 19. Anticipated net GHG mitigation possible from improved nutrient management in cropland at different carbon market prices, based on available economic cost data.

with a maximum technical emission reduction of 23.1 MMT CO_2e.

- For context, an investment in biomass-powered electricity at $100/metric ton would avoid emissions totaling 13.7 MMT CO_2e (EDF 2021).
- Note that actual costs in any specific location will vary depending on location and the specific practices used.

The available economic data generate economic potential (and maximum technical) estimates that are slightly lower than the science-based target in this report because different data sources are used for the two assessments. As described previously, the MACC analysis is based on five recently published MACC analyses, plus two papers with technical potentials for nutrient management emissions reductions. When comparing the maximum mitigation potential between sources, there was a distinct pattern of four data sources (Fargione et al. 2018; Cook-Patton et al. 2021; Eagle and Olander 2012; Winiwarter et al. 2018) with higher maximum CO_2e potential estimates (between 20 and 45 MMT CO_2e) and three data sources (Pape et al. 2016; Roe et al. 2021; Wade et al. 2022) with significantly lower maximum potential estimates (between 3.4 and 11 MMT CO_2e). Although both analyses use four references in common (Pape et al. 2016; Eagle and Olander 2012; Fargione et al. 2018; Winiwarter et al. 2018), the science-based target did not include the more recent publications with MACC analyses (e.g. Cook-Patton et al. 2021; Roe et al. 2021; Wade et al. 2022). The additional references used in the economic assessment included some much lower maximum potentials that effectively pulled down the average. This result illustrates the high level of uncertainty associated with developing both the maximum technical mitigation potentials and the costs to achieve them. It is likely that future targets and MACC assessments will become more aligned as additional data are collected and models continue to improve.

Although the aggregated MACC shows a national-level cost for implementing nutrient management practices, the amount of implementation possible (i.e., potential adoption rate) and costs of implementation (i.e., adoption cost) can vary by region or county depending



on multiple factors including ease of implementation, regional cost differences, baseline of sustainable practice adoption, local GHG emission rates and other factors.

Agroforestry

Large-scale crop and livestock systems in the U.S. tend to favor a specialized approach, in which areas for crops are separate from other types of vegetation and grazing livestock have a wide-open pasture or range in which to roam. Traditional agricultural practices, and those still used by some Indigenous communities around the world today, use tree cover and perennial crops to improve the productivity and sustainability of cropland. Many "modern" U.S. producers are beginning to incorporate similar techniques. Alley cropping, riparian buffers, silvopasture and tree-based windbreaks (all described briefly below) can improve the health of crops and soil without significant additional labor for producers, with the added benefit of sequestering carbon above and below ground.

Alley cropping involves planting rows of trees and shrubs on either side of a narrow area used for crop production. This serves to protect the crop and soil from wind, decrease soil and nutrient erosion due to runoff, and in some cases provide secondary tree crops such as fruit and nuts.

Riparian buffers are made up of a combination of trees, shrubs and other perennial plants alongside streams, lakes and wetlands, intended to filter nutrients, pesticides and animal waste from agricultural runoff as well as reduce erosion and sediment in runoff. They also provide habitat and food for aquatic and terrestrial species and protect downstream communities from pollution and flood damage.

Silvopasture is the practice of intentionally integrating trees and grazing livestock on the same land to provide land-health benefits as well as moisture and temperature management for the livestock. Trees for silvopasture can improve soil quality, provide a windscreen, or — in the case of fruit and nut trees — provide a secondary crop.

Windbreaks are trees and shrubs planted in a line to slow the wind, improving conditions for soils, crops, livestock, wildlife and nearby communities.

Mitigation opportunities

Sources used to develop the science-based target and the MACC analysis investigated the benefit of agroforestry for GHG removal and the extent to which setting a carbon price at different levels would encourage farmers to use agroforestry techniques on their land. Up to 10% of U.S. cropland could be modified to include alley cropping, and 5% could be allocated to windbreaks (Fargione et al. 2018). Other sources estimate that up to 20% of cropland could cost-effectively be allocated to include agroforestry practices, not all of which displace existing agricultural systems (Roe et al. 2021).

To be conservative and to avoid market-shock leakage of emissions and negative food-production implications, the science-based target of 80 MMT CO_2e includes agroforestry practices installed on the equivalent of no more than 10% of U.S. cropland area, which includes pasture land and could include marginal lands that are already set aside in the Conservation Reserve Program or are abandoned cropland. This value is based on the average emissions reduction estimates from combined agroforestry practices in the Fargione et al. 2018 and Roe et al. 2021 studies, and intersects with the $100 value in Figure 20.

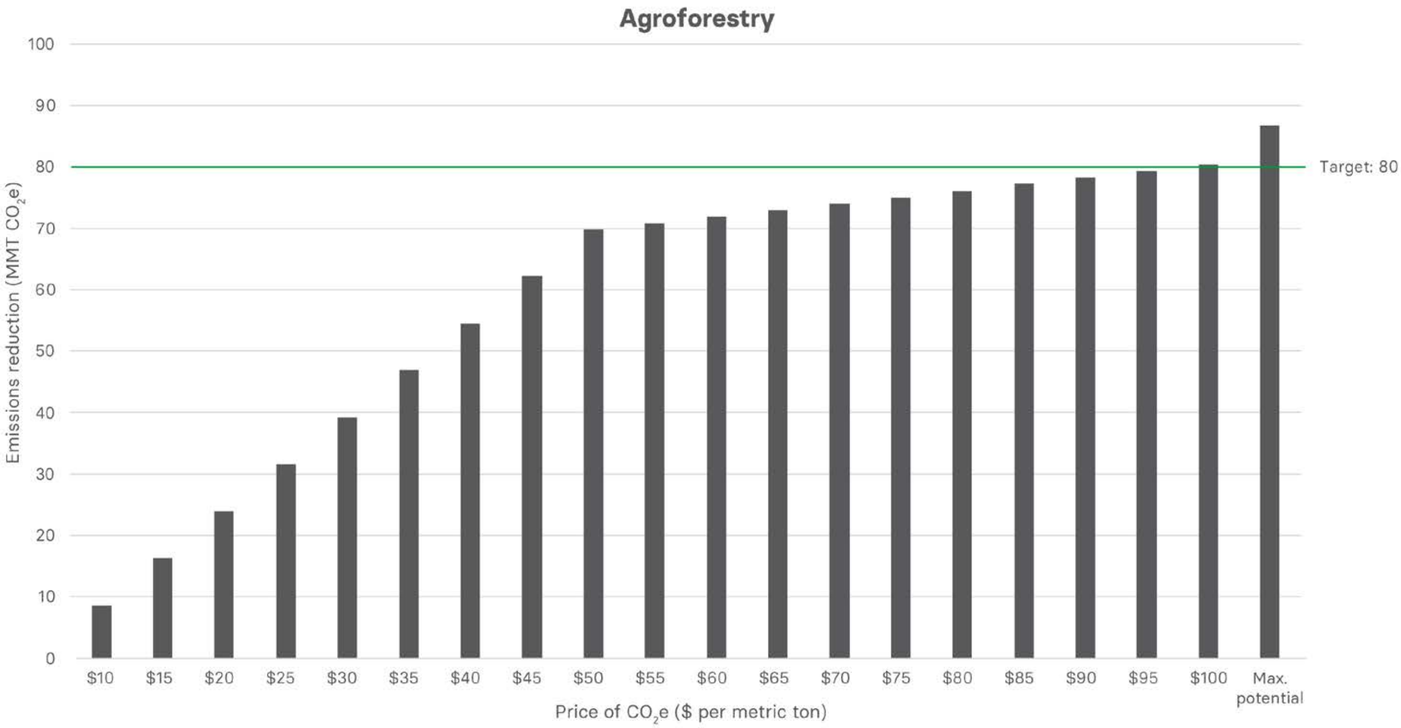


Figure 20. Anticipated net GHG mitigation possible from agroforestry at different carbon market prices, based on available economic cost data.

Cost analysis

Agroforestry tends to have higher start-up costs as the trees are incorporated into agricultural systems; however, once those trees grow and take root, they can absorb more CO_2 from the atmosphere. Our analysis shows that the rate of agroforestry implementation is highly related to carbon price up to $50 per MMT CO_2e, where mitigation potential grows more slowly:

- Combining all agroforestry types, a carbon price of $10 per metric ton would result in a reduction of 8.6 MMT CO_2e.
- $50 and $100 per metric ton would result in a reduction of 69.8 and 80.3 MMT CO_2e, respectively.
- For context, an investment in new hydroelectricity at $100 per metric ton would avoid 54.9 MMT CO_2e.
- Overall, agroforestry practices have a maximum potential to remove 86.8 MMT CO_2e from the atmosphere annually.

Land-use conversion

Land-use change occurs for a variety of reasons, including commodity price changes, human population growth, trends in consumption and dietary choices, changes in yield, livestock intensification, as well as the impact of agricultural and natural resource policies, urban pressure and environmental factors (e.g., climate change, forest fires or droughts). All of these can prompt private landowners to change land use to maximize their economic returns (USDA ERS 2019b; Gurgel, Reilly, and Blanc 2021). Specific drivers for conversion to and abandonment of cropland include commodity market prices and weather shocks, with particular impact for marginal land with low water capacity in rainfed regions (Chen and Khanna 2021).

Although overall cropland acreage has decreased since the 1980s, conversion to cropland still occurs, with approximately 90% of conversion coming from grassland (Auch et al. 2022; Lark et al. 2020).[32] As shown in Figure 22, the highest rates of cropland expansion occurred in the eastern side of North and South Dakota (also called the Prairie Pothole Region), in southern Iowa and northern Missouri (also called the Dissected Till Plains) and High Plains border areas between Kansas, Oklahoma and Texas (Lark et al. 2020).

Although there remains scientific debate about exact emission levels, conversion from forested land, grasslands or wetlands to croplands generates CO_2 emissions as land goes from higher to lower carbon density; the largest difference results from forestland

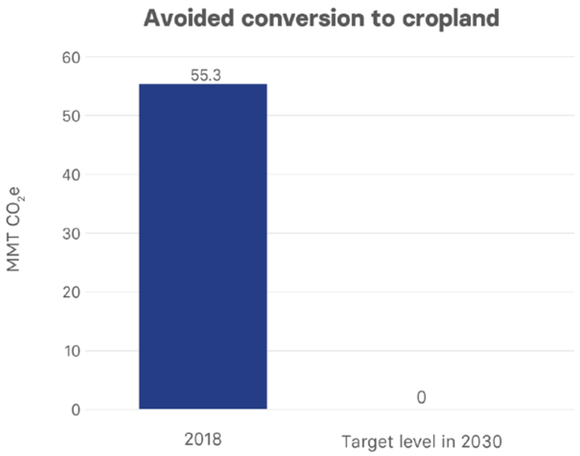


Figure 21. By halting all conversion to cropland immediately, 55.3 MMT of CO_2 emissions could be avoided annually by 2030.

conversions (Spawn, Lark, and Gibbs 2019; Lark et al, 2020). In addition to emitting CO_2 from soil C and biomass loss, conversion to cropland can also cause erosion, reduce air and water quality, and generate other negative ecosystem impacts such as loss of local habitats. Cropland expansion can also have negative environmental justice impacts by introducing new sources of environmental pollutants, such as agricultural fertilizers, pesticides and herbicides, to nearby communities.

In 2018, conversion to cropland resulted in emissions of 55.3 MMT CO_2e, with 8.5 MMT CO_2e from grassland conversion, 48.7 MMT CO_2e from forestland conversion and 0.6 MMT CO_2e from wetland conversion

[32] As noted earlier, although approximately 1 million acres of land are converted to cropland annually, the total number of acres under cropland production has decreased over the past 20 years. This discrepancy is due to 1) different methods of accounting for acreage, 2) different methods of accounting for double cropping (growing two different crops in a single year, such as soybeans and winter wheat), 3) acreage taken out of production through the Conservation Reserve Program, and 4) the rate of cropland abandonment.

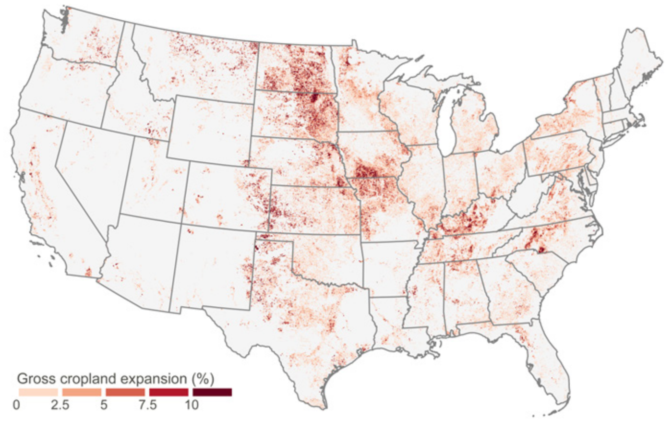


Figure 22. Gross cropland expansion in the contiguous United States from 2008-2016 (Lark et al. 2020).

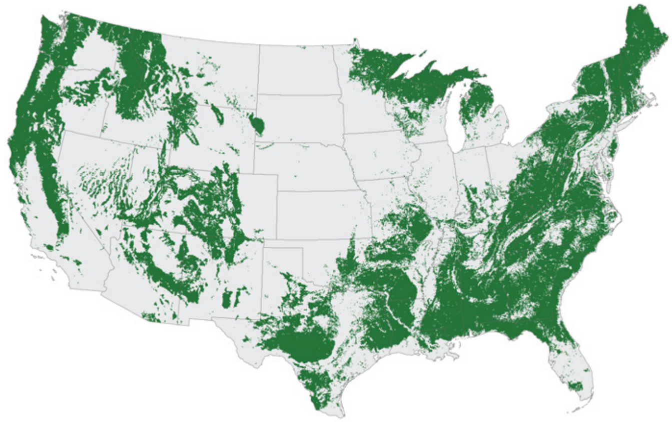


Figure 23. Forested land in the contiguous United States in 2018 (Domke et al. 2020).

(EPA 2020).[33] The science-based target assumes that this conversion could be halted to avoid all these emissions. Although reducing conversion of land uses with high carbon density to those with lower carbon density is important, only grassland and forestry conversion are presented in the cost analysis due to data limitations. These two pathways make up most of the mitigation potential.

Conversion of Forestland to Cropland and Other Land-Use Types

As described in more detail in the forestry section, there are currently approximately 750–800 million acres of forested land in the U.S.. The highest concentrations of forest land occur in the North, Southeast, the Northwest and Alaska (see Figure 23) (Domke et al. 2020; USDA 2017). Forests are particularly carbon-dense ecosystems, and many forests in the U.S. serve as strong carbon sinks.

Between 1985 and 2016, approximately 11 million acres of forestland were converted to other land use types in the continental U.S., most of which occurred in the Southeast, including Louisiana, Mississippi, Alabama, Georgia, Florida, South Carolina and North Carolina (Auch et al. 2022). Net forest loss in the U.S. in recent decades has been driven primarily by conversion from forest to developed land (i.e., settlements) (Sleeter et al. 2018). This process is expected to drive deforestation at an increasing rate in the near future in regions such as the Southeast (Wear and Greis 2013), posing a threat to forests that serve as strong carbon sinks. Indeed, the conversion of forest to developed land is estimated to have eliminated a carbon sink of 25 MMT of carbon per year between 1973 and 2010 in the contiguous U.S. (Sleeter et al. 2018). The loss of forest biomass upon forestland conversion to settlements emitted 63 MMT CO_2e in 2018 (EPA 2020). Catastrophic wildfire in the West and unstainable timber harvest (i.e., harvested land that is not reforested) are also important drivers (Sleeter et al. 2018).

Although other land use conversions may be greater current and future threats to forest carbon in the contiguous U.S., the impact of forest-to-cropland conversion should be considered as well. Between 2008 and 2016, most of the conversion occurred in states east of the Mississippi, with the highest conversion rate occurring in Southeastern states (see Figure 24) (Lark et al. 2020).

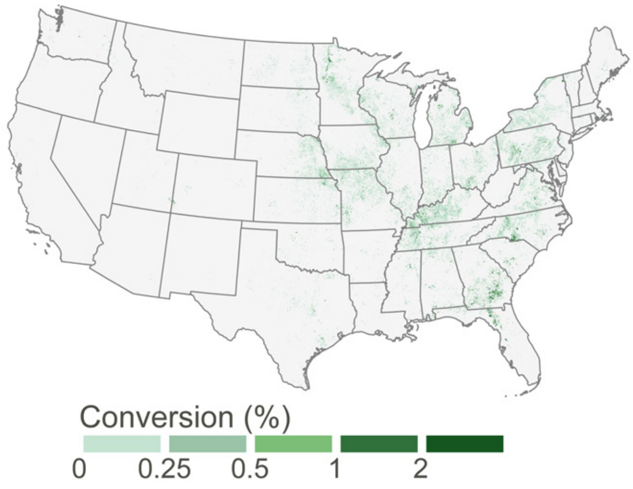


Figure 24. Conversion of forested land to cropland, 2008–2016, in the contiguous United States (Lark et al. 2020).

[33] Note that total annual emissions from forest, wetland, and grassland conversion to cropland are higher (57.8 MMT CO_2e) than the net estimated emissions from all land-use conversion to cropland (53.3 MMT CO_2e). This is due to "negative emissions" (e.g., carbon sequestration) when settlements and other lands are converted to cropland.

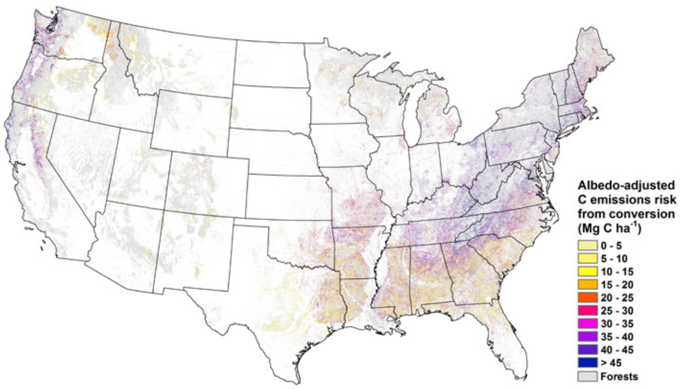


Figure 25. Potential carbon emissions from areas at high risk of forest conversion (Fargione et al. 2018). Figure and dataset developed by C.A. Williams and H. Gu (2017).

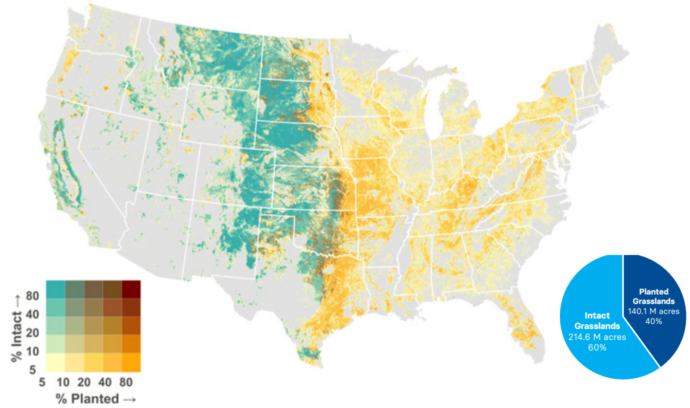


Figure 26. Acres of potentially intact or planted grasslands in 2017 (Lark 2020).

In regions with high land-conversion pressures (see Figure 25), it is especially crucial to implement the natural climate solutions (NCS) mitigation hierarchy proposed by Cook-Patton et al. (2021), which directs strategies to focus first on protecting, then managing and finally restoring forest landscapes. Avoiding the conversion of forests prevents the large amounts of carbon already stored in these existing forests from being released into the atmosphere and maintains their ability to continue sequestering carbon. Keeping forest ecosystems intact also protects habitat for biodiversity, maintains water provisioning and supports human health (Cook-Patton et al., 2021).

An important consideration is that avoided forest conversion is susceptible to leakage — the displacement of deforestation activities from one area to another — which can negate overall climate and/or biodiversity benefits. Efforts to minimize leakage include improving agricultural practices to reverse land degradation and prevent the clearing of forests for new agricultural lands, or jurisdictional approaches to forest carbon management, such as the LEAF or REDD+ models used in the tropics (Cook-Patton et al. 2021; Schwartzman et al. 2021).

Conversion of grassland to cropland

Grasslands, also called prairies, rangelands or pastures, are composed of grasses, legumes, forbs and other vegetation. In 2017, there were approximately 355 million acres of grassland in the contiguous U.S., of which 60%, or 215 million acres, were considered intact or original (Lark 2020).[34] Although grasslands historically covered a majority of the U.S., the current range of intact grassland runs down the middle of the country from North Dakota to Texas, west of the Mississippi, whereas planted grasslands cover most states east of the Mississippi (see Figure 26).

Approximately 720,000 acres of grasslands were converted to cropland in 2016, with the largest conversion rates in North and South Dakota followed by Kentucky, Iowa and Missouri (Lark et al, 2020). See Figure 27 for 2008–2016 conversion rates.

Conversion of wetlands to cropland

Wetlands are defined as transition lands between terrestrial and aquatic systems where the water table is either at or near the surface, or the land is covered with water (EPA 2020). Five types of habitats are considered

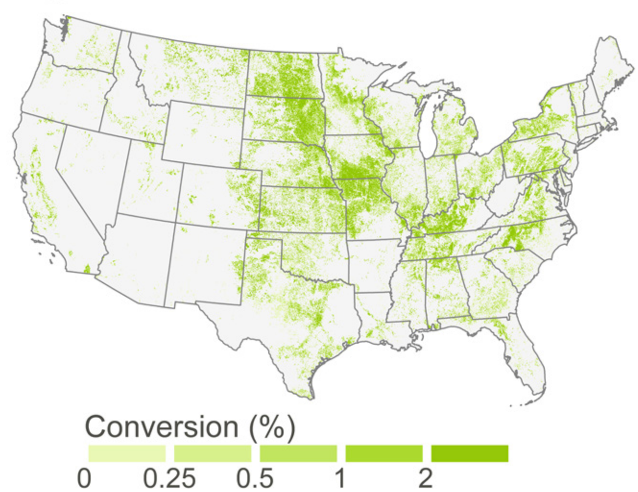


Figure 27. Conversion of grasslands to cropland between 2008 and 2016 (Lark 2020).

[34] Potentially intact grasslands were defined as those that had not been planted, plowed, or otherwise improved for the last 25 years according to data from the USGS National Land Cover Database and the USDA Cropland Data Layer.

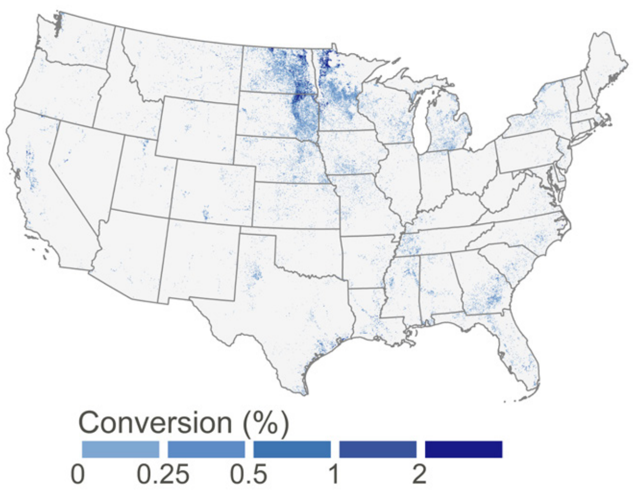


Figure 28. Conversion of wetland to cropland, 2008–2016, in the contiguous United States (Lark et al. 2020).

wetlands, including marine (ocean), lacustrine (lake), riverine (river), estuarine (saltwater marsh) and palustrine (freshwater marsh) (USDA 2020).

Wetlands provide critical habitat (e.g., for migratory birds) and ecosystem services, such as nutrient filtration and — particularly in the case of inland freshwater wetlands — carbon storage (Nahlik and Fennessy 2016). Present to some extent in every state, non-federal wetlands covered approximately 160 million acres in 2017 (USDA 2020).

Approximately 80,000 acres of wetlands were converted to cropland in 2016, with the largest conversion rates in North and South Dakota (Lark et al. 2020). See Figure 28 for details on wetland to cropland conversion from 2008–2016. Although existing wetlands are net GHG emitters (EPA 2020, estimates for 2018), cropland expansion into wetlands is concerning due to the considerable amount of carbon stored by wetlands and the other ecosystem services wetlands provide. For example, recent wetland conversions in the Prairie Pothole Region may have cascading negative impacts on wetland ecosystems and biodiversity such as increased food scarcity for waterfowl, flood risks and sediment pollution of water (Wright and Wimberly 2013; Gleason et al. 2011; Gleason and Euliss 1998). Due to lack of data, no cost analysis could be conducted for reducing CO_2e emissions from wetland conversion to cropland.

Mitigation opportunities

A review of the literature suggests that it will be possible to eliminate all U.S. land-use conversion to cropland (from forest, wetland and grassland) by 2030, avoiding the annual emissions of 55.3 MMT CO_2e (EPA 2020). Avoiding conversions of forests to settlements (development) could avoid another 63 MMT CO_2e. Although the EPA inventory assumes soil C measured to 30 cm, much greater values of potential avoided emissions reported in the literature assume soil C to 100 cm depth (Fargione et al. 2018). The science-based targets here, however, do not exceed inventory-reported emissions.

Co-benefits of halting such land-use conversion include improved soil, air and water quality and reduced impacts on ecosystems. Barriers include lost income from not converting land, opportunity costs, and lack of awareness of the importance and long-term value of preserving native lands.

The states or regions with the largest opportunities to end cropland expansion are the same regions where the majority of cropland currently exists (See Figure 22 for details). For example, states with over 500,000 acres of cropland expansion in 2008–2016 (from largest to smallest) included South and North Dakota, Texas, Missouri, Kansas, Iowa and Nebraska (Lark et al. 2020). However, while these states had the highest rates of cropland expansion, net conversion to cropland occurred to some extent in all 50 states. Every state thus has opportunities to stop further cropland expansion.

Cost analysis

Although the U.S. GHG inventory tracks emissions from avoided land conversion from one land classification to another, economic data on reducing land-use conversion are limited to broader categories. For this reason, the target for avoided conversion to cropland is assessed against MACCs examining avoided conversion of forest or grassland to any other land classification.

As shown in Figure 29, the CO_2e emission reductions for avoided forest conversion are relatively carbon price-independent. In contrast, avoided grassland conversion responds positively to carbon prices up to $50 per metric ton before leveling out. For example:

- At $10 per metric ton, the estimated annual emission reduction is 31.9 MMT CO_2e for avoided forest conversion (occurring mainly in the South and Pacific Northwest regions) and 21.7 MMT CO_2e for avoided grassland conversion.

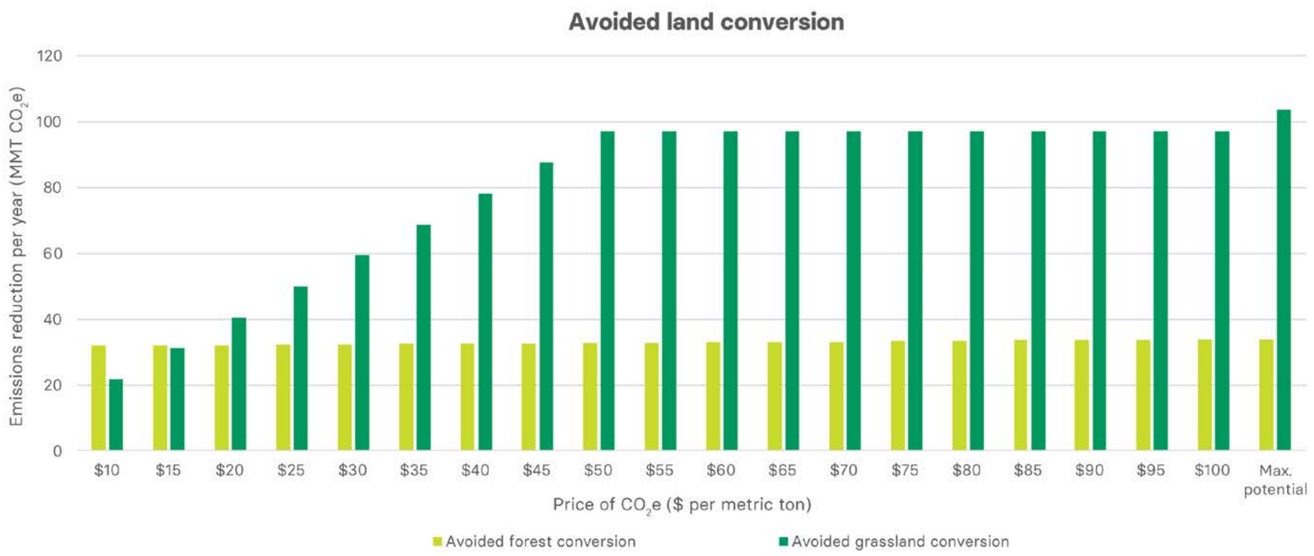


Figure 29. Anticipated net GHG mitigation possible from avoided land conversion at different carbon market prices, based on available economic cost data.

- At $50 per metric ton, the reduction is 32.73 MMT CO_2e for avoided forest conversion and 96.9 MMT CO_2e for avoided grassland conversion.
- At $100 per metric ton, the reduction is 33.76 MMT CO_2e with a maximum technical emission reduction of 33.9 MMT CO_2e for avoided forest conversion, and 96.9 MMT CO_2e with a maximum technical emission reduction of 103.7 MMT CO_2e for avoided grassland conversion.
- Combined, at $10 per metric ton the estimated annual emission reduction is 53.7 MMT CO_2e, at $50 per metric ton it is 129.7 MMT CO_2e, and at $100 per metric ton it is 130.7 MMT CO_2e with a maximum technical emission reduction of 137.6 MMT CO_2e.
- For context, an investment in offshore wind power at $100 per metric ton would avoid 79.8 MMT CO_2e (EDF 2021).

Figure 30 shows the combined impact of these two practices for a total potential emissions reduction from avoided land use change, with the combined height of the bars showing the maximum emissions reduction from avoided land use change possible at that carbon price. Note that actual costs in any specific location will vary depending on local land costs, yield potential and commodity or wood prices.

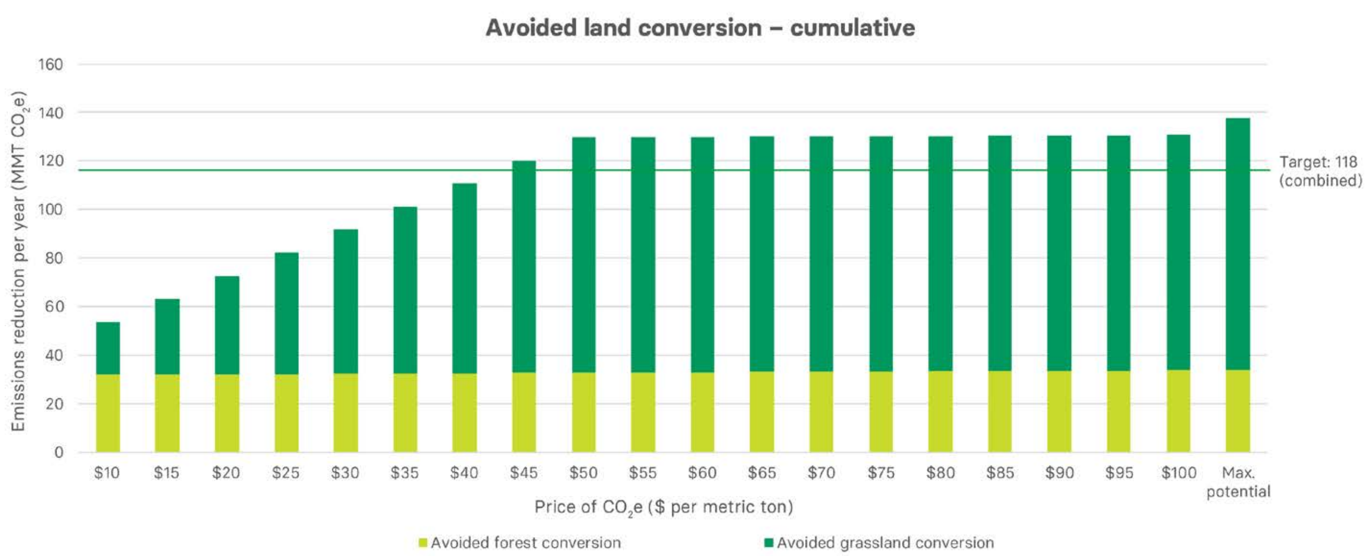
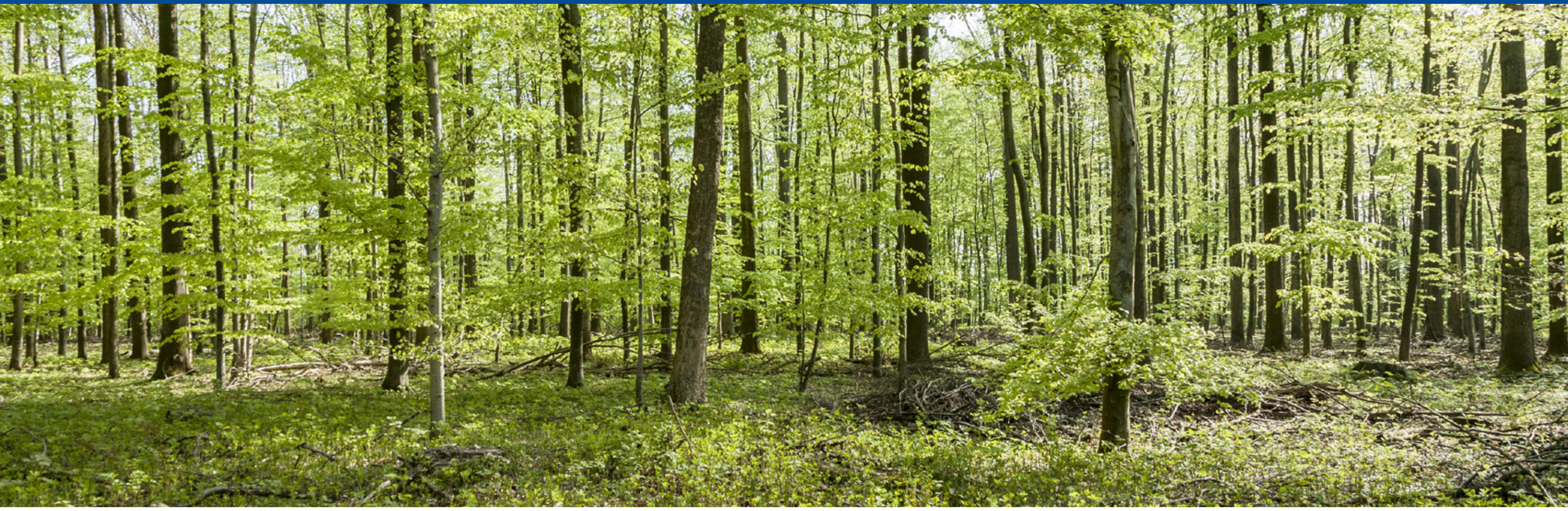


Figure 30. Anticipated cumulative net GHG mitigation possible from avoided land conversion of forest and grassland to all other land uses, at different carbon market prices, based on available economic cost data.



Forests

Forests are one of Earth's most vital resources. They play a crucial role in sequestering and storing atmospheric carbon, and offer important opportunities to reduce net GHG emissions. There are currently about 700–800 million acres of forested land in the U.S. with the highest concentration of forest land in the North and Southeast, the Northwest and Alaska (see Figure 23) (USDA 2017; The World Bank 2022).

In the contiguous U.S., forests and forest products store an estimated 61 billion metric tons of carbon (the equivalent of 220 billion metric tons of CO_2), and the forest carbon sink is estimated to absorb CO_2 at a rate equivalent to 13% of U.S. fossil fuel CO_2 emissions, based on inventories of forest carbon and fossil fuel emissions (Congressional Research Service 2022). It follows, then, that protection and stewardship of forest ecosystems in the U.S. may play an important role in reducing net CO_2 emissions.

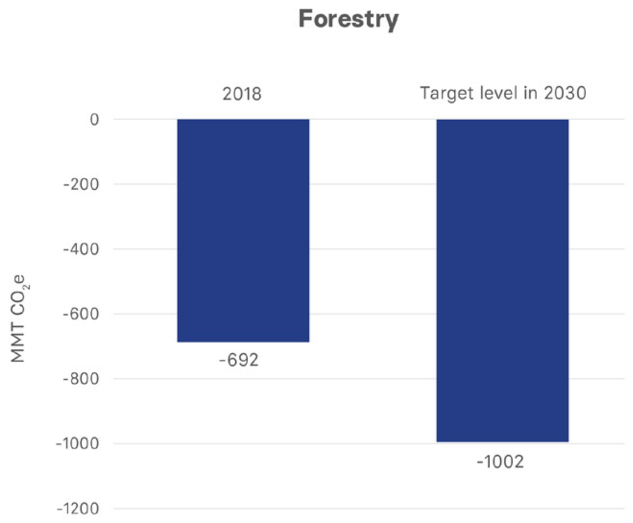


Figure 31. Net drawdown of GHGs from forestry could be increased by 310 MMT CO_2e by 2030.

However, challenges exist for the maintenance and enhancement of this strong carbon pool and sink. Many forest ecosystems are at risk of converting from net sinks to net sources of CO_2. In Canadian boreal forests, changing disturbance regimes have already contributed to a shift from sink to source, and rapidly changing climate conditions and disturbance regimes in the western U.S. put the forests in this region at risk of such a shift in the near future (Anderegg et al. 2022; Hicke et al. 2013; Giles-Hansen and Wei 2022). Furthermore, deforestation causes losses of current forest carbon stocks and future carbon sink potential. We must assess how to expand the forest sink where possible, increase resilience of threatened forest carbon, minimize losses of forest carbon from human activity and determine which regions may be unable to continue to sequester or store substantial carbon pools.

Forests can provide many other benefits beyond carbon sequestration. Depending on local and regional factors, ecosystem services offered by forests may include protection of soil from erosion, protection from floods, regulation of regional hydrology, plus provision of local cooling and biodiversity habitat. Other benefits include cultural significance, an improved quality of life for local communities, and provision of lumber and other forest products.

In short, opportunities exist for limiting long-term forest emissions and enhancing the forest carbon sink, with ample co-benefits. These strategies must be tailored for the specific threats or opportunities facing forests in a particular region, with considerations for local ecology, the economy and cultural factors.

Declining forest carbon sink

Forests in the U.S. have served as a net sink for many decades, but the rate of growth is declining and some forested regions — particularly in the western U.S. —

have shifted from sink to source of GHG emissions. In these regions, increased emissions are being driven by a variety of dynamics including fragmentation, unsustainable timber harvest rates, catastrophic wildfires, invasive species, native insects and pathogen outbreaks. From 1985–2017, the annual area burned at high severity has increased by an estimated factor of eight, with stand-replacing fires (those that cause mass mortality of trees) becoming more common (Parks and Abatzoglou 2020). These lines of evidence suggest a decrease in carbon sequestration capacity and a potential shift from carbon sink to carbon source in affected ecosystems.

For a discussion of deforestation and land use conversion on forest carbon stocks, please see the Land Use Conversion section above.

Mitigation opportunities

For this report, we use estimates of the CO_2 removal potential of reforestation and improved forest management published in *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (NASEM 2019). The NASEM value for reforestation includes afforestation, but since it does not separate the two we assume that afforestation contributes a minimal amount. Since other above-ground reforestation carbon storage estimates in the published literature are much greater (and all estimates have significant levels of uncertainty), the NASEM estimate serves as an appropriately conservative value.

The three main components of forest management for climate resilience and/or increased carbon storage potential include avoided forest conversion; improved forest management methods to improve forest resilience, mitigate forest fires, and increase carbon storage when feasible; and reforestation. Here, we discuss the dynamic biophysical potential, cost abatement estimates, barriers to adoption and other considerations of these forest management measures. However, the realizable climate mitigation potential of these strategies is not analogous to the biophysical climate mitigation potentials described in some sections of this report, as there are many limiting factors to implementation. The true realizable potential depends on the mechanisms developed to implement forestry practices at scale.

Avoided Forest Conversion. Forestland use conversion to cropland and urban development (i.e., settlements) is covered in the Land Use Conversion section above.

Improved Forest Management (IFM). Experts working with the National Academy of Sciences estimate that the mitigation potential of IFM ranges from 30 to 1,600 MMT CO_2 per year for the U.S. (NASEM 2019), which in this case includes the following practices:

- Accelerating regeneration in areas that have had major disturbances.
- Thinning or using controlled burns on forest understories in forests that are at risk for severe drought stress, severe fire or insect outbreaks.
- Increasing forest density in forests that are not at immediate risk for severe drought stress, severe fire or insect outbreaks, and that currently support a density of trees substantially less than what could be supported based upon the site's ecology and climate.
- Extending harvest rotations to grow larger trees and sustain carbon removal.
- Maintaining healthy forests by treating areas affected by insects and diseases or preventing conditions that foster outbreaks.
- Other silvicultural treatments that promote healthier and more resilient forests compared with untreated conditions.

There are tradeoffs across different species compositions, disturbance regimes and other variables that affect the efficacy of IFM, and often every forest stand will have different and unique IFM needs. In addition, if timber harvest is stopped or reduced to allow a forest to accrue more carbon, harvest may increase in nearby forests to meet the continuing demand for timber in a process known as leakage, thus offsetting the net carbon benefit. In short, ecological and economic factors must be considered. Experts estimate that the near-term annual mitigation potential of IFM for the U.S. is 100 MMT CO_2 (NASEM 2019).

Forest fire mitigation. Fire management goals include the restoration of more frequent, low-intensity, understory fires in fire-prone forests to avoid high-severity, stand-replacing fires. Typical fire management interventions include reducing density of trees and fuels in forests using methods such as thinning and prescribed burns, which have traditionally been used by Indigenous communities in western North America. This pathway urgently requires more attention and research, as climate and fire dynamics are quickly changing. Existing research estimates that reestablishing frequent, low-intensity fire regimes in fire-prone forest ecosystems could sequester 18 MMT CO_2e per year (Fargione et al., 2018). The climate benefit from fire mitigation is predicated on avoiding catastrophic wildfire and is calculated by comparing baseline fire emissions to actual emissions. However, this comparison is difficult as the forest sector does not yet have reliable estimates of wildfire emissions and forecasting baseline forest loss from wildfires is extremely difficult in a rapidly changing climate.

Fire mitigation strategies face many challenges that may diminish or negate their climate impact. Fuel treatments such as thinning and prescribed burns must be strategically placed on the landscape to deliver high climate benefits and act as "speed-bumps" to reduce wildfire intensity and severity (Tubbesing et al. 2019). However, for these fire mitigation activities to be effective, they must happen at a very large scale, which is limited by their expensive, repetitive and labor-intensive nature. Landscapes often need initial thinning treatments followed by consistent prescribed burns to maintain fire-adapted conditions in the long term (Collins et al. 2017).

Limited workforce and infrastructure availability, such as locally available contractors, small wood processing facilities and/or biomass-based power plants, near the areas being treated can limit treatment size, frequency and location. Steep or rocky topography and limited road networks can prevent access to places in the landscape where thinning or prescribed burns are most needed, especially in the case of thinning when large machinery is required (North, Brough, et al. 2015; Collins et al. 2010). When inadequately conducted, thinning activities through residual logging slash, desiccation of understory fuels and increased surface wind flow without accompanying surface fuel reduction can promote high-severity surface fires and increase the risks of high-severity crown fires (Prichard et al. 2021).

The cost of these treatments can be reduced by the sale of merchantable timber harvested during operations, but much of the thinning materials coming from fire-suppressed forests such as those in the West would be small-diameter trees that are not necessarily merchantable (North, Collins, and Stephens 2012). Bioenergy or biochar can be produced from these wood products, but more research is needed to assess the climate impact and market potential of these uses. Fire treatments may also have complex effects, both desirable and undesirable, on local ecology. Controlled burns aid in seed germination in many forests and encourage biodiversity and the growth of native plant species; they are a component of traditional Indigenous land stewardship in some cultures and regions, particularly in the western U.S. (Kimmerer and Lake 2001; Knapp, Estes, and Skinner 2009). However, these landscape treatments can be invasive to local ecosystems in the short term, especially in environments with a long history of fire suppression, and result in conflicts between reducing fire and protecting/conserving other resources such as wildlife habitats.

Some people advocate that fire suppression activities have created desirable conditions such as multi-storied or closed canopy stands for certain animal species. For example, controversies around the impact of prescribed burns on spotted owl populations and habitat quality limit the intensity of fuel treatments and the size of those treatments in California (Spies et al. 2006; North, Stephens, et al. 2015; Collins et al. 2010). Fuel treatments are also not permitted or are extremely limited in designated buffer zones for sensitive species and riparian areas, while the latter are often characterized by high fuel loads and high fuel continuity (both vertical and horizontal) and may benefit from thinning in some cases (Dwire et al. 2016). Such treatment might affect wildlife habitats negatively in the very short term, but has proved to be beneficial to them in the longer term by increasing the resilience and resistance of forests in which they are found (North, Stephens, et al. 2015; Collins et al. 2010; Stephens et al. 2012).

Feasibility and regulatory land-management constraints, such as permitting issues and temporal limitations, can also limit fire management interventions. Prescribed burns require specific environmental conditions and seasons, and can be conducted only when regional air quality districts have approved burn plans and designated the days during which burns can be conducted (Collins et al. 2010). Coordinating these plans can restrict an already limited "burn window." Fuel treatment projects also need to satisfy NEPA planning process requirements, which could require multiple years to complete for landscape-scale fuel treatment projects. Land managers also have limited time and resources to dedicate to this administrative work (Collins et al. 2010). Community buy-in for the increased use of managed wildfires and prescribed burns as restoration treatments can also be limited due to the perception of risk, as some controlled fires have escaped human control in the past in more fire-prone forests (North, Collins, and Stephens 2012). Finally, carbon emissions associated with thinning and prescribed burns must also be considered and accounted for. Direct emissions from prescribed burns can be very high due to high fuel loads in fire-suppressed areas (Collins et al. 2017). There is a substantial tradeoff between keeping high unstable carbon stocks on the ground versus reducing carbon stocks in the short term to promote stability in the long term (North, Stephens, et al. 2015; Collins et al. 2017).

Other IFM practices. An extension of harvest rotation in forests that supply timber may be effective at increasing the carbon stored in live trees and wood products, depending on the age at which stands are currently harvested and on projected tree growth, which in turn depends on the ecology and climatology of the forest. This technique involves increasing the age at which trees or stands of trees are harvested from the economically optimum age to the biologically optimum age (i.e., the age that maximizes the average tree growth per year or mean annual increment) (Fargione et al. 2018). Harvesting timber at this biological optimum maximizes the timber harvest in the long term, but economic factors often incentivize a shorter rotation length — leading to both decreased landscape carbon storage and a smaller average timber harvest in the long term (Carroll et al. 2012; Fargione et al. 2018; Foley 2009).

An extension of rotation length to the biological optimum maximizes the combined carbon storage in live tree biomass and timber products. In the long and sustained term, this has the potential to increase the average landscape carbon sequestration while maintaining or increasing yield to minimize leakage. However, despite the long-term optimization of timber yields, the implementation of this method over large areas without careful planning would delay harvests in the shorter term, potentially triggering leakage that may offset short-term carbon benefits. The biophysical mitigation potential of these strategies also varies widely by region and forest type. For example, in the case of timber harvest rotation length extensions, forests such as coastal Pacific Northwest Douglas fir or hemlock forests are prime candidates because of their ability to maintain high growth rates beyond the age at which many of these forests are harvested and to sustain high levels of biomass carbon storage. This provides a large increase in live biomass carbon sequestration with rotation length extension, without a large long-term decrease in timber volume (Foley 2009; Law and Waring 2015).

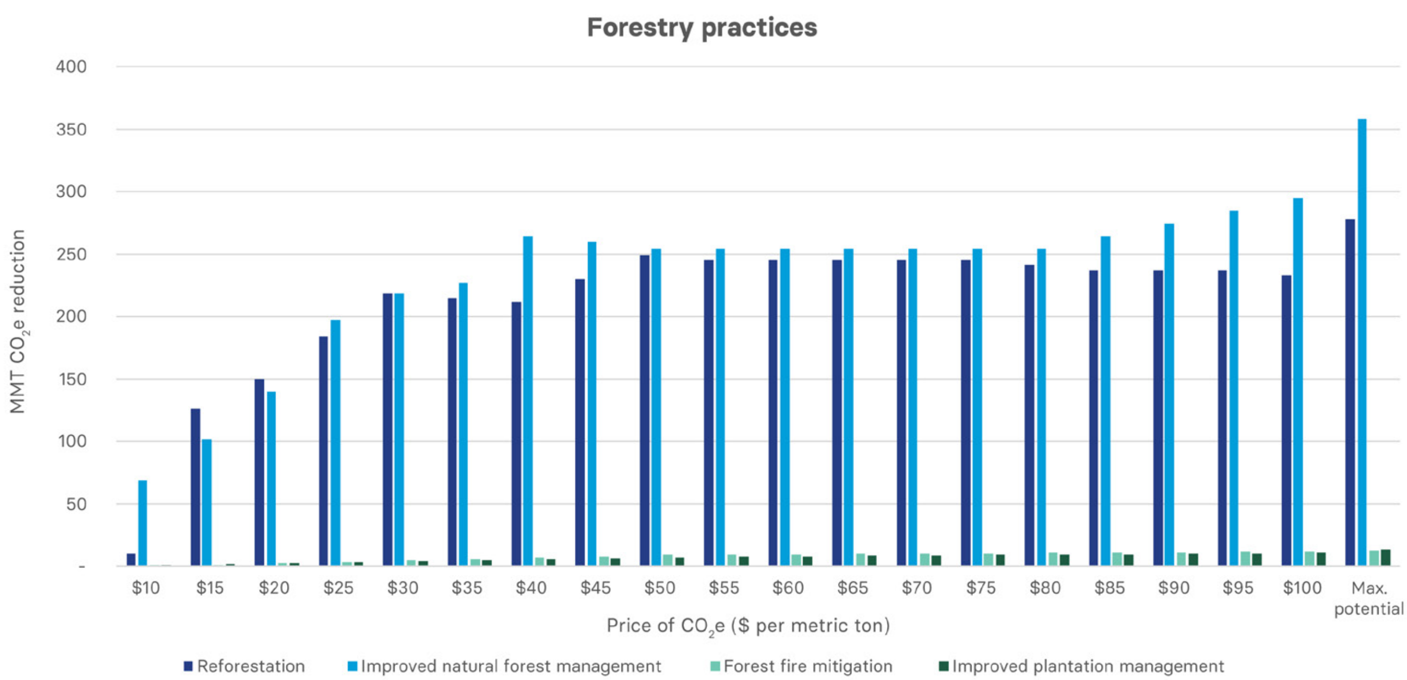


Figure 32. Anticipated net GHG mitigation possible from forestry practices at different carbon market prices, based on available economic cost data.

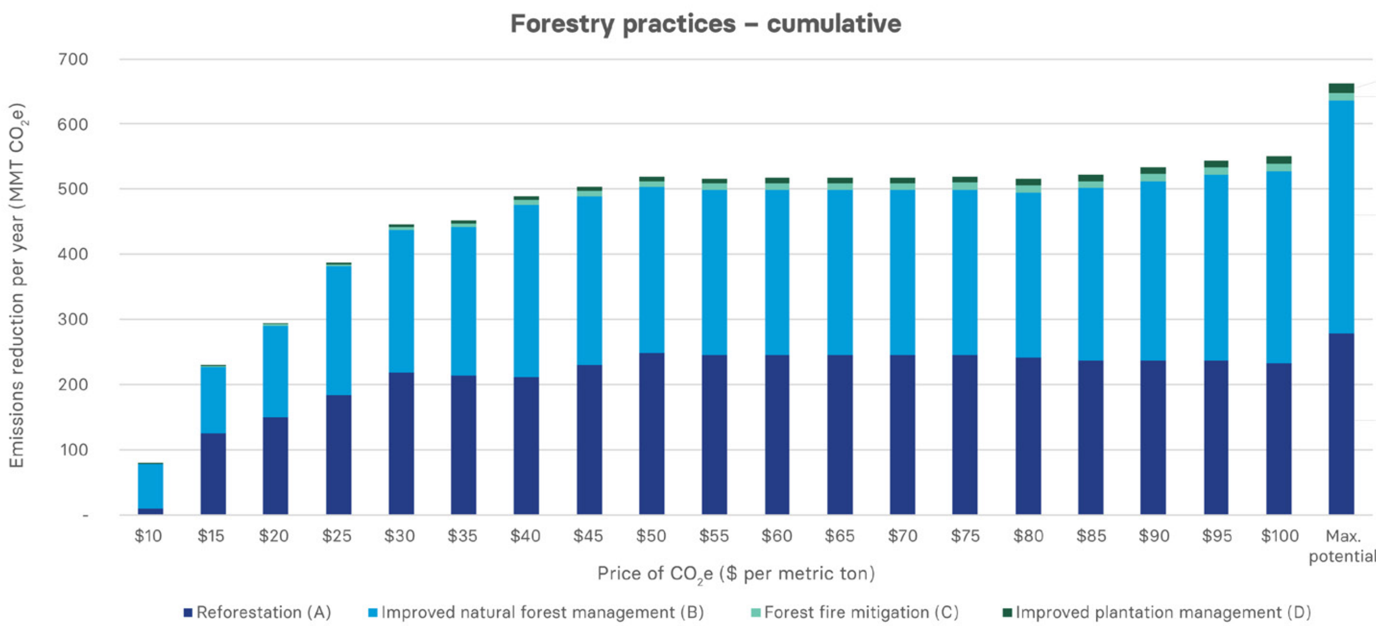


Figure 33. Anticipated cumulative net GHG mitigation possible from forestry practices at different carbon market prices, based on available economic cost data.

In other forests, carbon stocks may be increased by increasing the number of trees per unit area. According to the World Resources Institute, increasing tree density in eastern forests that the U.S. Forest Service considers less than fully stocked provides an opportunity to sequester around 220 MMT CO_2 per year by 2050 (Mulligan et al. 2020). A similar opportunity may exist on private lands in the eastern U.S. where private lands have not been sufficiently reforested after harvest, but data are lacking.

However, limits to tree growth and forest density — well as threats to forest carbon permanence and ecosystem resilience — must also be considered, and management in this context may encounter tradeoffs between short-term carbon density versus long-term sustainable carbon storage depending on the region and ecology. As discussed in the Forest Fire Mitigation section, reducing forest stocking may help to boost tree growth and decrease mortality from severe drought, disease, insect outbreaks and fire, thereby increasing long-term carbon sequestration even while immediately decreasing carbon stocks (Restaino et al. 2019).

The cost of some IFM practices may be higher because of the large area that must be treated to achieve results, and forest management would need to involve a much larger percentage of forest landowners than in any incentive program to date (NASEM 2019). Such practices might also be hard to implement in remote areas due to barriers similar to those described in the fire management subsection above (Gauthier et al. 2015).

Reforestation. Reforestation is estimated to have the largest biophysical maximum mitigation potential (307 MMT CO_2 per year) of all national climate solutions in the contiguous U.S. (Fargione et al. 2018). This estimate includes limited reforestation of agricultural and pasturelands to safeguard food production. Some studies estimate the mitigation potential increases to 381 MMT per year if all pastures in historically forested areas are reforested (Fargione et al. 2018), while others estimate that reforestation in the contiguous U.S. has the potential to sequester a more conservative 314 MMT per year (Cook-Patton et al. 2020). This potential is greatest in the Northeast (35%) and South Central (31%), with five states (Tennessee, Kentucky, Pennsylvania, Virginia and Arkansas) containing 26% of total mitigation potential, mainly in pasturelands (Cook-Patton et al. 2020). There is potential for reforestation of intensely burned regions in the West, but the landscape must be cleared of residual fuel from previous fires and reforested at much lower densities. In addition, reforested landscapes should be highly heterogeneous, both in terms of composition and structure, to increase their resilience and resistance to future disturbances and changing disturbance regimes. More research is necessary to determine the path forward for forests in this region. The biophysical potential of reforestation in boreal forests is not readily available in the literature (Bradshaw and Warkentin 2015).

These estimates reveal the biophysical/economic potential for reforestation in the U.S., but the realizable potential is much smaller. Experts have estimated the annual near-term reforestation mitigation potential in the U.S. at 150 MMT CO_2 (NASEM, 2019). This estimate takes into account availability of land and potential secondary impacts of reforestation activities such as changes in surface albedo (NASEM, 2019).

There is a bottleneck effect of resources available for reforestation, such as limited seed and seedling availability, workforce limitations and pre- and post-planning practices, that challenge the realization of biophysical reforestation potential in the U.S. (Fargione et al. 2021). Land competition is another threat to reforestation implementation and permanence. While some reforestation estimates include safeguards to pasturelands, others do not, and reforestation of pastureland could create higher food prices, and/or deforestation elsewhere (leakage), resulting in limited or neutral net climate benefits (Fargione et al. 2018; Cook-Patton et al. 2020).

Regardless of the limitations, reforestation of these areas would need to include millions of private landowners, many of whom may be unwilling to reforest their land for a variety of reasons. With these factors in mind, it is necessary to additionally filter the identified biophysical potential to include additional social and land competition filters to more realistically estimate the realizable reforestation potential in the U.S.. EDF is working on a study to help accomplish this.

Although reforestation typically increases carbon sequestration, net climate benefits may not occur in high-latitude boreal forests where the positive climate forcing induced by decreases in albedo can offset the negative forcing expected from carbon sequestration through reforestation (Betts 2000; Bright et al. 2015; Sjølie, Latta, and Solberg 2013). More research is needed to understand the climate forcing impact of albedo before employing boreal forest reforestation as a natural climate solution on a broad scale (Sjølie, Latta, and Solberg 2013).

Cost analysis

Reforestation and improved natural forest management respond positively to carbon prices up to $50 per metric ton and $40 per metric ton respectively. However, the mitigation potential of reforestation activities steadily decreases at higher prices for carbon (from $50 to $100 per metric ton). Conversely, at higher carbon prices (from $80 to $100 per metric ton) improved natural forest management's mitigation potential rises again:

- At $10 per metric ton, the estimated annual emission reduction is 10 MMT CO_2e for reforestation conversion and 68.9 MMT CO_2e for improved natural forest management.
- At $50 per metric ton it is 249.1 MMT CO_2e for reforestation, and at $40 per metric ton it is 264.5 MMT CO_2 for improved natural forest management.
- At $100 per metric ton it is 232.9 MMT CO_2e with a maximum technical emission reduction of 278.1 MMT CO_2e for reforestation, and 294.7 MMT CO_2e with a maximum technical emission reduction of 357.9 MMT CO_2e for improved natural forest management.

Similarly, forest fire mitigation and improved plantation management respond positively to carbon prices up to $100 per metric ton.

- At $10 per metric ton, the estimated annual emission reduction is 0 MMT CO_2e for forest fire mitigation and 0.9 MMT CO_2e for improved plantation management.
- At $50 per metric ton it is 9.1 MMT CO_2e for forest fire mitigation, and 7.3 MMT CO_2e for improved plantation management; and
- At $100 per metric ton it is 11.8 MMT CO_2e with a maximum technical emission reduction of 12.4 MMT CO_2e for forest fire mitigation, and 10.9 MMT CO_2e with a maximum technical emission reduction of 13.6 MMT CO_2e for improved plantation management.

Reforestation and improved natural forest management activities realize 96% of the combined forestry practices maximum technical mitigation potential. Improved plantation management and forest fire mitigation achieve 2.1 and 1.9% of the combined forestry practices maximum technical mitigation potential, respectively.

Combined, at $10 per metric ton the estimated annual emission reduction is 79.8 MMT CO_2e, at $50 per metric ton it is 519.8 MMT CO_2e, and at $100 per metric ton it is 550.3 MMT CO_2e with a maximum technical emission reduction of 662 MMT CO_2e.

The MACC data currently available in the literature are useful, but not definitive. Additional analyses are needed to articulate where the right climate practices should be applied and determine durability. These mitigation measures must be carefully applied on the landscape due to implications for carbon flux, livelihoods and other considerations.

Bringing equity and justice into the climate vision

Climate mitigation opportunities in the agriculture and forestry sectors can and must be designed to deliver equitable and just outcomes. Structural discrimination in these sectors has caused a multitude of impacts to BIPOC and other marginalized populations. Examples include limited access to and security of land — particularly with respect to the more than 60% of Black-owned land that is estimated to be Heirs Property, i.e., property passed to family members by inheritance, usually without a will or without an estate planning strategy (Federation of Southern Cooperatives 2022) — as well as limited access to and security of financial (Food Solutions New England 2020) and supportive resources due to historical exclusion, neglect and mistreatment of minorities and socially disadvantaged farmers by USDA and other public and private institutions (USDA 1997). The limited BIPOC representation and leadership in food systems (Union of Concerned Scientists and Heal Food Alliance 2020) also puts producers in BIPOC communities at a disadvantage.

These are examples of barriers and pain points that must be addressed when designing equitable climate mitigation strategies. Standard market-based or policy solutions need to be adapted accordingly. For example, producers who operate on a small scale, are in rural areas, have lower income, are members of BIPOC communities and/or are socially disadvantaged in other systemic and historical ways face challenges that make it difficult for them to qualify for and receive financial resources essential for continued production and the transition to climate mitigating practices, such as farm loans and supply chain initiatives. Larger or wealthier producers often have more access to agribusiness, technology and markets as well as risk mitigation products such as crop insurance and other government assistance.

Because of these barriers, resource-related inequities may also hamper socially disadvantaged producers' access to programs and incentives designed to encourage GHG mitigation practices. In turn, limited participation can hinder adoption at scales necessary to achieve essential GHG mitigation targets. (Murray 2015).

At the same time, many small farms and BIPOC producers have already embraced climate-smart practices for a variety of reasons, including cultural traditions, the need to mitigate risk through diversified production and income sources and pursuit of niche market opportunities. As climate solutions are developed and promulgated, they should consider both the barriers to participation by small and BIPOC producers, as well as the unique contributions that these producers can make.

In addition to the access and resource issues, small, rural, low-income and BIPOC communities often have inadequate opportunities to participate in the design and execution of policy decisions that affect them. Given this track record, these communities are less likely to trust institutions or experts providing technical and financial information, which may also affect their willingness to engage with that information or advice (Lemos, Kirchhoff, and Ramprasad 2012). This can result in persistent inadequate representation and missed opportunities if producers lack trust in institutions and are hesitant to engage in decision-making processes that may affect them. It is incumbent that these groups and communities are proactively engaged and that trust is built over time to provide for their full and equal participation in developing climate solutions.

Finally, GHG mitigating solutions could exacerbate environmental justice issues if they are not designed in a holistic way that is informed by consultations with local communities to address their concerns. Delivering justice requires a concerted effort from all stakeholders: government, business, investors, industry groups, civil society organizations and BIPOC and women's networks.

Conclusion: A call to action

This report identifies aggressive and realistic targets for reducing more than a half-billion metric tons of net GHG emissions from U.S. working lands by the year 2030 without relying on uncertain and impermanent opportunities such as soil carbon sequestration. It identifies a set of technologies and practices, with data on cost-effectiveness where available, that could achieve these targets while providing additional environmental and social benefits.

Supporting research, development and implementation of these practice should be a priority for all public and private sector stakeholders interested in reducing GHG emissions from the agriculture and forest sectors.

- USDA and EPA should review their grant programs and other support to producers and shift focus as needed toward encouraging practices and technologies with the highest value in terms of their mitigation potential and cost per metric ton of carbon reduced, avoided or removed.
- The conversion of forests, grasslands and wetlands to croplands and other uses is a major source of GHG emissions from the agriculture and forestry sectors. Federal, state and local governments, businesses, investors and industry groups should ensure that programs do not inadvertently incentivize conversion and should work to incentivize preservation of these critical carbon stocks and discourage conversion, with a goal of halting conversion entirely.
- Inequities and environmental justice issues are prevalent in the agriculture and forestry sectors. All stakeholders should integrate equity and environmental justice considerations into all financial and technical assistance programs for producers to ensure equal access to opportunities and eliminate negative impacts on communities downstream and downwind of working lands.

Congress, USDA, EPA and other agencies should step up overall funding and support for R&D on climate-smart agriculture and forestry. This includes research on the cost-effectiveness of climate-smart practices in agriculture and forestry to close the many gaps EDF encountered in conducting the analyses for this report. Research is also needed on mitigation potential of practices, and R&D funding should be stepped up for the development of new climate-smart technologies and practices — especially in areas such as enteric fermentation and manure management, which new analysis suggests are currently underfunded relative to their mitigation potential (Blaustein-Rejto, Dan, Jasmine Yu, and Emily Bass. Lab to Farm: Assessing Federal R&D Funding for Agricultural Climate Mitigation. The Breakthrough Institute, 2022).

Appendix

This Appendix provides additional background and technical detail on the analyses conducted for the report.

Agriculture sector emissions in 2018

EDF's analysis for this report is based on 2018 GHG emissions and carbon storage data as reported in the 2020 Inventory of U.S. Greenhouse Gas (GHG) Emissions and Sinks (EPA 2020). EDF's allocation of emissions to the agriculture sector differs from that reported in Inventory Table ES-6 (U.S. Greenhouse Gas Emissions Allocated to Economic Sectors) in that it includes emissions from agriculture-related land-use change, emissions from electricity used by the agriculture sector and emissions from fossil fuel combustion.

Table 4 provides a detailed breakdown of emissions by the U.S. agriculture sector using EDF's methodology. Values are reported in MMT carbon dioxide equivalent (CO_2e) using 100-year GWPs from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), for consistency with the U.S. inventory.

In contrast, Table ES-6 of EPA's 2020 Inventory of Greenhouse Gas Emissions and Sinks allocates 658.6 MMT CO_2e in 2018. Table ES-7, which includes

Table 4. U.S. agriculture sector GHG emissions in 2018, using EDF's allocations based on the U.S. EPA 2020 Inventory of U.S. Greenhouse Gas Emissions and Sinks. Sources in italics are related to agriculture but allocated in EPA's inventory to other sectors (energy, electricity, industry).

	Source	MMT CO_2e
Carbon dioxide	*Fertilizer manufacture (carbon dioxide emissions from ammonia production)*	*13.5*
	Herbicide and other chemicals manufacture	*N/A*
	Fossil fuel combustion	*39.4*
	Electricity-related (carbon dioxide)	*39.1*
	Cropland remaining cropland (changes in soil carbon)	*-16.6*
	Land converted to cropland (from wetland, forest, grassland)	*55.3*
	Grassland remaining grassland (changes in soil carbon)	*11.2*
	Land converted to grassland	*-24.6*
	Liming	3.1
	Urea fertilization	4.6
	Total	**125**
Methane	Enteric fermentation	177.6
	Manure management methane	61.7
	Rice	13.3
	Grassland remaining grassland (grassland fire)	*0.3*
	Field burning	0.4
	Non-road agricultural equipment	*0.1*
	Total	**253.4**

Table 4. U.S. agriculture sector GHG emissions in 2018, using EDF's allocations based on the U.S. EPA 2020 Inventory of U.S. Greenhouse Gas Emissions and Sinks. Sources in italics are related to agriculture but allocated in EPA's inventory to other sectors (energy, electricity, industry). (Continued)

	Source	MMT CO_2e
Nitrous oxide	Agricultural soil management	338.2
	Manure management nitrous oxide	19.4
	Grassland remaining grassland (grassland fire)	*0.3*
	Field burning	0.2
	Electricity-related nitrous oxide	*0.5*
	Non-road agricultural equipment	*0.5*
	Total	**359.1**
Sulfur Hexafluoride (SF6)	*Electricity-related sulfur hexafluoride emissions*	*0.1*
Grand Total		**737.6**

electricity-related emissions distributed to sectors, allocates 698.3 MMT CO_2e to the agriculture sector in 2018.

Net emissions from forestry and forest-related land use change in 2018

Table 5 summarizes net removals by forests as well as net emissions from conversion of forest land to other uses; note that EDF allocates emissions from the conversion of forests to cropland to the agriculture sector; those emissions are included in Table 4.

Economic analysis methods

To synthesize MACCs for each practice, we identified published sources that studied the impact of carbon pricing on mitigation in each practice, standardized the units and measurement systems across the sources, and constructed new MACCs by comparing the results of each paper with a basic statistical regression to define a best-fit curve. Our process included the following steps:

- Identifying applicable sources using a literature review.
- Extracting data and standardizing units.
- Designing regression to create best-fit curves based on distribution of data.

Identifying applicable sources using a literature review

Sources for the literature search were identified through:

- Existing knowledge of recent publications of U.S. specific, or global MACCs with U.S. specific data of agricultural and forestry practices.
- Google Scholar searches using combinations of the following search terms to find publications after 2015: "agricultural MACC" "United States" "forestry MACC" "GHG emissions" "economic analysis" "sustainable agriculture" "sustainable forestry".
- Forward (e.g., the "cited by" button on Google Scholar) and backward (e.g., looking at key references cited in the publication) searches of relevant published sources.

Table 5. Removals (in parentheses) and emissions from the U.S. forests sector in 2018, based on the U.S. EPA's 2020 Inventory of U.S. Greenhouse Gas Emissions and Sinks.

	Source	MMT CO_2
Carbon dioxide	Forest land remaining forest	(643.9)
	Land converted to forest land	(110.6)
	Conversion of forests to settlements	63
	Conversion of forests to grassland	15.9
		(675.6) total net flux

Once potential sources were identified, we read through each source ensuring that:

- The source had a definition of the mitigative practice that either matched or was analogous to those already decided on by EDF.
- The source had data on the projected emissions reduction or removal from implementation of the practice, either per acre or at maximum applicability U.S.-wide.
- If the source had economic data, connecting levels of mitigation with a range of carbon prices, including a maximum potential mitigation when carbon prices were greater than $100 per metric ton CO_2e reduced or removed, referred to as the "maximum potential."
- The data and results were specific to the U.S.
- The source and data were not collected and published before 2015.

After narrowing the collected sources down by the above requirements, we were left with the following list of sources to use for the creation of our MACCs. Table 6 provides a list of the studies we used to develop MACCs used in the analysis. The x's indicate the areas where MACC data were available from each study.

Details on the sources used for the MACC analysis are provided in Table 7, organized by subsector and mitigation category. Note that several of the studies relied on the same underlying datasets.

Table 6. Studies used to develop MACCs used in the analysis.

	Avoided land conversion	Efficiency improvement: fossil fuels	Efficiency improvement: fertilizer manufacturing	Manure management	Enteric fermentation	Agroforestry	Rice	Improved nitrogen fertilizer management	Forestry
Baker et al. (2017)									
Cook-Patton et al. (2020)									x
Cook-Patton et al. (2021)	x			x			x	x	x
Fargione et al. (2018)	x		x	x		x		x	x
Griscom et al. (2017)							x		x
Kwon et al. (2021)		x	x	x				x	
NASEM (2019)									x
Northrup et al. (2021)		x	x					x	
Pape et al. (2016)	x			x				x	
Proville et al. (2020)	x						x		
Roe et al. (2019)				x	x	x	x	x	x
Roe et al. (2021)				x	x		x	x	x
Sperow (2019)									
Sperow (2020)									
Van Winkle et al. (2017)	x								x
Wade et al. (2022)	x			x	x		x	x	x

Table 7. Underlying data sources used for MACC analysis, by subsector and mitigation category.

Subsector	Mitigation category	Sources for MACC data	Notes
Dairy, swine	Manure management	Cook-Patton et al. 2021 Pape et al. 2016 Roe et al. 2021 Fargione et al. 2018 Wade et al. 2022 (5 models)	Cook-Patton et al. 2021 used data first obtained by Fargione et al. 2018
Dairy	Enteric fermentation	Roe et al. 2021 Roe et al. 2019 Wade et al. 2022 (5 models)	
Crop	Improved nutrient management	Cook-Patton et al. 2021 Pape et al. 2016 Roe et al. 2021 Fargione et al. 2018 Wade et al. 2022 (5 models) Eagle and Olander 2012 Winiwater et al. 2018	All individual datasets
Crop	Rice	Cook-Patton et al. 2021 Fargione et al. 2018 Griscom et al. 2017 Roe et al. 2021 Roe et al. 2019	Cook-Patton et al. 2021 used data first obtained by Fargione et al. 2018
Crop	Improved farm management – fossil fuels	Kwon et al. 2021	
Crop	Improved upstream nitrogen production	Fargione et al. 2018 Kwon et al. 2021	
Crop	Agroforestry (alley cropping, windbreaks, riparian buffers, overall agroforestry)	Roe et al. 2021 Fargione et al. 2018	Created New Dataset Created New Dataset
Forestry	Reforestation	Cook-Patton et al. 2020 (Two models, 2025 and 2030) Fargione et al. 2018 Griscom et al. 2017 NAS 2019	Cook-Patton et al. 2021 used data first obtained by Fargione et al. 2018
Forestry	Improved forest fire management	Cook-Patton et al. 2021 Fargione et al. 2018	Cook-Patton et al. 2021 used data first obtained by Fargione et al. 2018
Forestry	Improved forest management	Baker et al. 2017 Cook-Patton et al. 2021 Fargione et al. 2018 Griscom et al. 2017 NAS 2019 Van Winkle et. al 2017	Cook-Patton et al. 2021 used data first obtained by Fargione et al. 2018
Forestry	Improved plantation management	Fargione et al 2018 Griscom et al. 2017 Cook-Patton et al. 2021	Cook-Patton et al. 2021 used data first obtained by Fargione et al. 2018
Land conversion	Avoided conversion of forest to cropland	Cook-Patton et al. 2021 Fargione et al. 2018	Cook-Patton et al. 2021 used data first obtained by Fargione et al. 2018
Land conversion	Avoided conversion of grassland to cropland	Cook-Patton et al. 2021 Fargione et al. 2018	Cook-Patton et al. 2021 used data first obtained by Fargione et al. 2018

Extracting Data and Standardizing Units: After sources for each practice were identified, we extracted the relevant data from each source and compiled them into a sortable Microsoft Excel file that tracked the source name and publication year, practice type, sub-practice type if applicable, region, dollar year (i.e., the year the economic analysis was done; this must be tracked in order to scale results for inflation), the year the data were collected, if the source used public datasets as part of its analysis, the datasets and version of those sets, and the mitigation potential at every potential carbon price listed in the source, in intervals of $5 USD. Once this information was collected and sorted, we converted all results into 2020 dollars by scaling the mitigation results by the inflation of U.S. currency between the dollar year of the source and 2020 U.S. dollars. If results had been reported as per-acre emissions reductions or removals, we multiplied the emissions reduction per acre by the number of acres that could support the implementation of that practice to get a total mitigation potential. Once all the data were in the same units, the results across papers were grouped by practice and formatted to prepare for graphing and analysis.

Designing regression to create best-fit curves based on distribution of data: To design the best-fit curves for each practice, we first created scatterplots of the data from each source to visually examine the distribution of results. We added to this graph an additional series composed of the average of the results from the sources at each dollar value. We examined the line connecting the points in the Average series and noted at which values, if any, the slope of the curve seemed to rapidly change. We then divided the average series into multiple graphs, one for each segment with a similar slope. In each of these separate graphs we performed a basic linear regression for that segment of line and used the resulting linear formula to interpolate missing data points within the segment. We then created a new series composed of the values at each dollar value from each segment and used the resulting series as our MACC. Most practices only required two segments: for example, $5/metric ton to $50/metric ton, and $50/metric ton to $100/metric ton and the maximum potential.

Defining "high-value opportunity" practices

This report identifies several agriculture and forestry practices that present a high-value opportunity to achieve the science-based target to reduce annual net GHG emissions by approximately 560 million metric tons of carbon dioxide equivalent (MMT CO_2e) by the year 2030, using 100-year GWPs. Some of these practices reduce or avoid GHG emissions, while others remove GHGs from the atmosphere. To be considered a "high-value opportunity," a practice's effectiveness must be measurable, verifiable, scientifically supported and certain, based on absolute impacts on GHGs. Details of these criteria are described below:

- **Measurable:** The impact of the practice on GHG emissions must be discrete and capable of being measured.
- **Scientifically supported and certain:** The impacts of the practice must be accepted as having low uncertainty by the scientific community as a method of reducing or removing GHG emissions. Practices

Table 8. Characteristics of practices that result in GHG reduction/avoidance vs. practices that remove GHGs from the atmosphere.

	Reduction/avoidance	Removal
Practice examples	Enteric methane reducing solutions, improved manure management, avoided land conversion, improved nitrogen fertilizer management.	Reforestation, improved forest management, agroforestry.
Time scale	Permanent: reduction in GHGs persists for at least 100 years.	Impermanent: removed CO_2 is eventually recycled back through the ecosystem and sequestration practices may be reversed via natural processes; non-reversal of practice adoption is assumed for any assessment of permanence.
Impact on emission reductions	Emissions are directly reduced at the source or avoided altogether.	Indirect: emissions are removed from the atmosphere, not from a point source.

that have sometimes been reported to remove GHG emissions from the atmosphere but were not agreed upon by most of the scientific community to have certain and long-term impacts, such as tillage to increase soil organic carbon, were omitted from this report.

- **Absolute vs intensity-based GHG impacts:** GHG emissions intensity refers to GHG emissions per unit of scale, such as per acre or head of cattle. To be high-value, the practice must result in absolute reductions or removals of emissions and not just a reduction in per-unit emissions. This distinction is especially important when other effects are considered, such as leakage, which refers to the net change of GHG emissions or removals that are attributable to a mitigation activity but occur outside the boundary of that activity. These include, for example, indirect emission changes upstream or downstream of the mitigation activity, or rebound effects (EDF, WWF, Oeko-Institut 2020).
- **Co-benefits:** Not every benefit of implementing a mitigation practice can be measured in terms of GHG emissions. Practices are also evaluated on the other benefits they provide for the environment or communities. For example, improving manure and nutrient management practices can also have positive health impacts for surrounding ecosystems and communities by reducing pollutants in their water due to runoff. Mitigation practices must be assessed on the good they do for the most vulnerable communities and ecosystems as well as their GHG mitigation potential.

Other evaluation factors differ between practices that reduce/avoid emissions vs. those that result in removals of GHGs from the atmosphere (Table 8).

Limitations and uncertainties

Our methods have limitations that require further research to resolve. Estimates of GHG emissions, carbon storage and marginal abatement costs are subject to uncertainty. Uncertainties in estimates of mitigation potential for specific practices arise from the models used, and estimates will be influenced by variables such as land use type (which is not always consistently classified across studies).

Key limitations and areas of uncertainty in the agriculture and forestry sectors are identified below.

- **Cost of avoided carbon dioxide emissions from the conversion of wetland and peatland to cropland.** While ceasing conversion of these land use categories to cropland is an important climate mitigation opportunity, no MACC data are available. Therefore, we could not incorporate these land use categories into the economic analyses.
- **Cost of avoided methane and nitrous oxide emissions from manure management and enteric fermentation.** MACC data for these critical mitigation opportunities are extremely limited in terms of the practices included, are based on older data, and do not contain up-to-date technologies and/or pricing and revenue streams. For example, existing manure management MACCs are based primarily on anerobic digesters, do not include the full range of current technologies, and do not take into account recent payments or credits for natural renewable gas generation from anerobic digesters. Similarly, because practices to reduce enteric fermentation through feed additives and animal drugs are an emerging technology, limited data are available on their safety, efficacy, potential emissions reductions and pricing.
- **Above- and below-ground carbon storage potential on cropland and grasslands from carbon sequestration** (i.e., reduced tillage or no-till, cover crops, cropland conversion to prairie strips or other set-asides, and management of grazing on grasslands). We did not incorporate the potential for cropland carbon sequestration into the mitigation potential and economic analyses at this stage given the current level of scientific debate and uncertainty related to net GHG flux quantification (e.g., soil organic carbon changes at depth, nitrous oxide emissions) as well as concerns related to permanence and related soil carbon accounting issues (Oldfield et al. 2021; Tumwebaze and Byakagaba 2016).
- **Above- and below-ground carbon storage potential on cropland from agroforestry** (i.e., riparian buffers, silvopasture and other perennials). Although below-ground soil carbon sequestration (and net GHG mitigation) with annual cropland conversion to perennials (including trees) is more scientifically clear, the limited total area realistically available and the potential for reversals and leakage (in which GHG emissions increase elsewhere) make this potential uncertain.

- **Uncertainty associated with mitigation potential of forestry sector NCS pathways.** The potential for leakage adds uncertainty around the potential of the avoided forest conversion NCS pathway. Regarding fire management, the absence of reliable estimates of baseline wildfire emissions makes the quantification of mitigation difficult. The constantly evolving climate makes forecasting baseline forest loss from wildfires extremely challenging, which adds an extra layer of uncertainty to this potential. Uncertainty associated with improved forest management mitigation potential arises from the potential for leakage resulting from strategies that would reduce the supply of timber or other forest products from targeted forests (Carroll et al. 2012; Fargione et al. 2018; Foley 2009). Unpredictable impacts from climate stress, disturbance intensity and drought also threaten the success of improved forest management practices and can limit the ability of these forests to sustain current or increased levels of carbon sequestration (Anderegg et al. 2022). Finally, land use competition that threatens leakage as well as the limited resources (seedlings, workforce, pre-and-post reforestation practices) available for reforestation increases the uncertainty around mitigation potential of reforestation (Fargione et al. 2021). In the boreal region, the lack of robust understanding of climate forcing impact of albedo increases the uncertainty of reforestation mitigation potential (Sjølie, Latta, and Solberg 2013).
- **Conversion of grassland and forestland to cropland.** Uncertainties are created by the use of different land classification methods across studies, as well as scientific disagreement over the amount of carbon sequestered in different landscapes and/or emitted during land use change.
- **Sampled and modeled soil carbon data** (e.g., DayCent, Century models). Estimates of cropland soil sequestration potential and net GHG flux are subject to significant uncertainty. There are also difficulties in estimating the net carbon impacts of different practices and in assessing the impacts of varied practice combinations. Because of limitations in data used to calibrate these models, they tend to include one practice at a time, and interactions between practices are not well assessed (e.g., whether effects are additive, multiplicative, or do not result in additional sequestration) (Tonitto, Woodbury, and McLellan 2018).
- **Overall uncertainty of aggregating and analyzing several MACCs.** Although MACCs are a useful tool, several levels of uncertainty are associated with such analyses. For example, MACCs are composed of several types of data, including GHG emissions associated with current/baseline practices, which vary based on specific practice used, type of crop, animal or tree cultivated, geographical differences, local weather and environmental conditions and other factors; GHG impacts of different mitigation practices, such as the difference in the quantity of GHG emissions from a sustainable practice compared with the baseline practice; and the cost of implementing the practice. Depending on how these factors are estimated, different MACC analyses of the same mitigation practices can result in different maximum potential GHG emissions at different price ranges. Despite these challenges, the trends shown in the MACCs for the mitigation practices in this report can still provide a gross estimate of the potential mitigation possible at different price ranges and can allow comparison across practices to determine the practices that give the largest GHG benefits at a given cost.

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