US Agriculture and the Net-Zero Challenge

September 2022

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The Environment Program at Walton Family Foundation is committed to protecting water resources in the face of climate change to support healthier rivers and oceans and ensure resilient, thriving communities for generations. Our program strategy reflects our determination to find lasting solutions to improve water quality and availability in three key geographies: the Colorado River Basin, the Mississippi River Basin and our oceans.

The challenges of protecting water resources during climate change are huge and vast. In order to find solutions that will work for nature and people, we must bring the power and ideas of every sector and all people together. In the Mississippi River Basin, we are working with farmers to support the transition to sustainable agriculture so they can grow food in a way that works for their businesses and consumers, while also protecting soil and water for the future.

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Executive summary

"US agriculture has a critical role to play in achieving net zero."

The United States has committed to reduce greenhouse gas (GHG) emissions by at least 50% by 2030 and to achieve net-zero emissions by 2050.[1] Meeting these targets—which is critical to limit global warming to 1.5°C to avoid the worst impacts of climate change—will require transformation in all sectors of the economy. Much attention has been paid to emissions reduction in the energy, industrial, and transportation sectors. In this report, we focus on the agriculture sector, which is often seen as both as a significant source of emissions and a particularly difficult sector in which to abate emissions.

According to the US Environmental Protection Agency, the US agriculture sector accounts for about 11% of national GHG emissions, or nearly 700 million metric tons of carbon dioxide equivalent (MMT CO_2e).[2,3] However, this inventory and sectoral categorization does not capture all emissions associated with the entire agri-food value chain; other

[1]Fifty percent reduction from 2005 baseline; United States Government 2021; White House Long Term Strategy 2021.

[2]EPA 2022.

[3]USDA, Greenhouse Gas Inventory 2022.

estimates that include land use change and pre- and post-production activities put the agri-food system's contribution at 20-25% in the US and up to 37% globally.[4] It is clear that solving the US net-zero challenge will require addressing emissions across the food & agricultural value chain.

The US Department of Agriculture (USDA) projects that, based on current policies and practices, GHG emissions and removals from agriculture will remain roughly flat through to 2060.[5] While there is increased activity across food & agriculture players to begin making the necessary changes, it will take a step-change in ambition and action to help the country meet its net-zero goals and avoid the worse impacts of climate change.[6]

This report examines a range of practices and technologies to reduce emissions in the agriculture sector and sequester carbon in the country's forest and grasslands. We outline 24 levers spanning three categories: (1) how we grow crops and raise livestock; (2) what food products we consume (and waste); and (3) how we use land and forests. Many of these levers also instill greater adaptation and resiliency into our agriculture production systems in the face of expected ecosystem strains brought on by climate change such as drought and extreme temperatures.

We outline three scenarios—reflecting conservative, moderate, and optimistic pathways—that could result in a ~1-18% reduction in net emissions by 2030 and a ~10-57% reduction by 2050.

- **Conservative scenario**—reflects incremental changes from the status quo in adoption of sustainable agricultural practices and no changes to food consumption patterns (reduction in net emissions of ~1% by 2030 and ~10% by 2050).
- **Moderate scenario**—reflects significant changes in how we farm, and modest shifts in consumption (reduction in net emissions of ~10% in 2030 and ~41% in 2050).
- **Optimistic scenario**—reflects significant technology breakthroughs along with major shifts in what people consume and reductions in food waste (reduction in net emissions of ~18% in 2030 and ~57% by 2050).

Note that these scenarios do not reflect a technical maximum or "most optimistic" scenario where we are able to achieve the theoretical maximum potential of each lever.[7] We have chosen not to include such a scenario given outstanding scientific, technical, and economic questions, e.g., on the technical potential for soil carbon sequestration, on the viability of adopting agroforestry practices, and the cost effectiveness of adopting technologies like biochar and anaerobic digesters.

Additionally, we highlight how focused efforts to use trees to capture CO_2 from the air, while avoiding emissions from changes in land use, could increase the size of the economy-wide carbon sink by as much as 9% in 2030 and up to 60% by 2050, depending on the scenario.

To achieve the optimistic scenario, collective action from stakeholders across the value chain is urgently needed to:

1. Enable markets to capture the true value of sustainable agriculture products and ecosystem services through thoughtful design of policies, incentives, and business models.
2. Invest in R&D and innovation to overcome the most urgent barriers to scaling critical technologies and practices, such as improved data gathering and measurement.
3. Empower producers to adopt sustainable agriculture practices by providing them with the technical and financial tools needed to address economic and non-economic barriers.
4. Leverage purchasing power (as governments, companies, and consumers) to signal demand for more sustainably produced goods and make more sustainable food consumption choices—by shifting to more GHG-conscious product portfolios and diets.
5. Ensure that the transition to a sustainable agriculture system is just and fair for both producers and communities that could be negatively impacted by the effort.

Achieving the reductions outlined in these three scenarios will require significant investment and concerted action on the part of all stakeholders. We estimate a cumulative net cost of ~$60-70 billion over 30 years to incentivize adoption of on-farm practices, taking into consideration farm-level upfront investment costs and ongoing operational costs, offset by potential economic benefits such as improved yields.

This number does not include investments in R&D needed to develop and scale new technologies, or the benefits and cost of the positive and negative externalities that may result from these changes. And in addition to the substantial economic barriers to adoption of climate-smart

[4]Estimates may include the production of inputs, transportation to restaurants and retailers, electricity use of consumers, and decaying food in land-fills. Tubiello 2022; Crippa, Solazzo and Guizzardi et al. 2021; Poore and Nemecek 2018; Rosenzweig, Mbow and Barioni et al. 2020; Rosenberg and Lehner 2022.

[5]USDA, Integrated Projections for Agriculture and Forest Sector Land Use, Land-Use Change, and GHG Emissions and Removals: 2016.

[6]USDA, Partnerships for Climate-Smart Commodities 2022.

[7]The OECD in 2019 summarized maximum technical potential based on analysis by Smith et al. in the 2007-2012 timeframe. Those estimates are not directly comparable to our agriculture scenarios because they include some LULUCF levers; OECD 2019; Smith 2008.

practices, there are also technical, operational, and cultural challenges that need to be addressed in order to move ahead.

The recently passed Inflation Reduction Act of 2022 is an important move forward—it contains ~$20 billion in funding for agricultural conservation programs and ~$5 billion for forest management, planning, and restoration over the next 10 years and sets the important precedent of including agriculture and other nature-based solutions in US climate measures. As the government looks to deploy this funding, it should continue to engage farmers and ranchers, researchers and environmental organizations, rural communities, and other stakeholders to shape how the funding is used and to share learnings for future climate actions.

Building a more sustainable and more equitable agri-food system is within the power of the sector's stakeholders—governments, foundations and NGOs, companies, farmers, and consumers alike. It is our hope that this report will trigger further discussion—and ultimately, action—among stakeholders on how the sector can contribute to the country's net-zero commitment and instill in the food system the environmental and economic resiliency needed to respond to the growing threat of climate change.

Envisioning a transition for US agriculture

If we are to achieve meaningful progress in arresting the current trajectory of warming and changes to climate, we must push the US agriculture sector to make the gains outlined in this report's most optimistic scenario. To get there, the US food & agriculture system in 2050 will need to look fundamentally different than it does today.

There are many possible paths that are compatible with this scenario; here is one example:

- Energized by broad consensus about the imperative to act quickly, and the realization that agriculture as a sector is lagging behind, policymakers enact historically climate-focused efforts (e.g., building on the Inflation Reduction Act with additional climate-specific efforts via the upcoming Farm Bill) that fundamentally change farm policies and invest billions of dollars in new and expanded programs to conduct research, support innovation, and significantly scale pilot programs that are working.

- Major consumer-facing food companies begin to see sustainability as a competitive advantage above and beyond their corporate social responsibility/ environmental, social, and governance commitments. These companies begin to build new business models and sustainable menus, creating demand for their sustainable products and the incentives needed to encourage other producers in the supply chain to change their practices. The increase in demand provides farmers with a growing market for new sustainable products, and that leads other players in the supply chain, including agriculture companies and distributors to transform their supply chains to deliver traceable, sustainable products to serve this market.

- Digital agriculture continues to make strides, and major agriculture companies are successful at developing data-driven insights that help individual farmers customize how they manage the full lifecycle of their crops. This drives increased profits throughout the value chain (in part because accurate data on emissions reductions is now available) and lowers emissions by replacing volume-driven sales models with new service-oriented business models that earn revenue for yield and income/impact generated, not tons of fertilizer applied. In addition, new incentives, improved agronomic knowledge, and advancements in measurement and verification enable farmers to achieve higher levels of carbon sequestration in agricultural soils.

- Advances in technology make less-GHG-intensive proteins increasingly palatable and affordable to consumers, leading to a shift away from animal-sourced foods. For remaining livestock, a technology breakthrough 10-15 years from now allows dramatic and cost-effective reductions in methane emissions from most stages of the cattle lifecycle.

- Concurrently, a major campaign to address food loss and waste at retail and by consumers kicks off. In just a few years, it begins to achieve meaningful traction along the lines of what other countries like the UK, Denmark, and Japan have achieved, through a focus on consumer education campaigns and improved labelling.

- Meanwhile, a reforestation initiative of unprecedented scale is launched, aided by an innovative combination of private financing coupled with a public guarantee for the quality and permanence of offsets generated. Trees planted in the 2020s will take decades to mature but will contribute significantly to the 2050 sequestration target.

Each of these levers taken in isolation would not be sufficient to make meaningful changes, nor could they happen in isolation without fundamental changes to the policies, technologies, and economic incentives underpinning the "optimistic" scenario we describe. But if systemic, coordinated action is taken across all stakeholders, and taken now, then the potential for this alternative vision for US agriculture is real.

Introduction

"US agricultural activities—known as 'food, fiber, feed, and fuel'—generated 11% of the country's total GHG emissions in 2020."

The need to reduce greenhouse gas (GHG) emissions cuts across every sector of the US economy. In April 2021, the Biden administration released a revised set of Nationally Determined Contributions (NDCs), pledging to reduce overall US GHG emissions to between 50% and 52% below the 2005 benchmark.[8] In support of this goal, companies in every industry, including major contributors to GHG emissions such as oil and gas, utilities, and transportation, have weighed in with their own emissions reduction targets.

Agriculture, too, is a significant emitter of GHGs and, along with land use generally, will be critical to the emissions mitigation effort. The country's agricultural activities—including growing the food and fibers we eat, wear, and export, raising and feeding livestock, and growing corn and other crops for biofuels (commonly referred to as "food, fiber, feed, and fuel")—generated 11% of the country's total GHG emissions in 2020.[9]

[8]United States Government 2021.

[9]EPA 2022; USDA, Greenhouse Gas Inventory 2022.

Emissions are even higher—an estimated 20% of all US emissions in 2019 according to the UN Food and Agriculture Organization[10]—when considering the full "agri-food system," including inputs used by agriculture (such as the GHGs emitted in the manufacture of fertilizers) and the transportation, processing and manufacturing, distribution, selling and consumption and waste agricultural products (namely food). Furthermore, the agriculture sector produces a significant portion of US emissions of methane, a potent, shorter-lived GHG gas, which, if reduced, would represent a "quick win" relative to other, longer-lasting GHGs.[11]

Forests, vegetation, and soil also play a critical role in removing and storing carbon, and the related sector often referred to as "Land Use, Land Use Change & Forestry" (LULUCF) needs to be considered alongside agriculture-especially given the increasing amounts of land devoted to farming and ranching. In 2019, the LULUCF sector removed an amount of carbon equal to 12% of US GHG emissions,[12] acting as a carbon "sink" for the entire economy. Boosting the sequestration potential of US lands will be critical in the path to net zero economy-wide by 2050.

This report draws on recent scientific literature to estimate the size of the potential impacts of emissions reduction efforts under various scenarios, and some of the costs to achieve them. It is imperative that the agriculture industry strive to reduce its GHG emissions to the extent possible. There are options available now or with the potential to be developed in the coming years to help make those reductions possible. These levers for emission mitigation include changes to soil management practices, decreases in methane emissions associated with livestock, reduction in on-farm use of fossil fuels, shifts in consumer dietary choices, reduced food loss and waste, and changes in land use. These options can make considerable contributions towards GHG reductions, while providing producers and communities at large with a range of additional benefits, including improvements in yields and cleaner air and water. To this end, we offer practical recommendations for how producers, agricultural businesses, policymakers, nongovernmental organizations (NGOs), and consumers can contribute to the effort to reduce the sector's emissions.

The urgency for action in the agriculture sector, however, is about more than just reducing its contribution to GHG emissions. It is also about instilling environmental and economic resiliency in the global food system in the face of climate change threats (notably, heat, drought, floods, and extreme weather) over the next 30 years. Adapting how we grow and what we eat will ensure we can support the global increase in demand for food and other agricultural products, keeping prices and the supply of staple foods stable.

It is our hope that this report will trigger further discussion—and ultimately, action—among stakeholders on how the sector can contribute to the country's net-zero commitment and instill in the food system the environmental and economic resiliency needed to respond to the growing threat of climate change.

[10]Tubiello 2022.

[11]Climate & Clean Air Coalition 2019.

[12]EPA 2021.

Scope & key assumptions in this report

This report has been prepared based on a set of assumptions informing the sources we relied upon and how we interpreted and presented information and analysis:

	Assumptions	Rationale
Baseline	• Use most recent EPA inventory as baseline source of emissions.[13] • Focus on "farm gate" emissions, not full agri-food system. • Focus on US production, excluding imported food.	A core question of this report is what can US agriculture contribute to meeting US NDCs; we chose the official US baseline for comparability and to facilitate easy comparison to other reports' scenarios and projections.
Projections	• Anchor in USDA projections, updated to most recent baseline year and extended forward to 2050, excluding "Building Blocks" policy change assumptions. • Make no additional projections on import/export not already incorporated into USDA 2016 projections.	USDA projections account for expected shifts in commodity demand; excluding USDA's policy change assumptions had small impact on baseline in 2050 and avoids double counting impact of mitigation levers included in our scenarios.
Levers	• Consider broad spectrum of mitigation levers for inclusion: mature, emerging, and nascent (as long as some data were available for emission factors). Did not quantify impact of frontier technologies with limited scientific literature around mitigation potential.	Goal of report was to anchor in scientific evidence across all scenarios, while still describing potential pathways to even greater reductions.
	• Anchor report and modeling in existing published analysis wherever possible, avoiding original research.	Goal of report was to anchor in scientific evidence; where certain levers had sufficient research into emission factors but lacked explicit adoption projections we validated our adoption assumptions with relevant experts, including in many cases the authors of the studies cited.
	• Do not include mitigation lever related to biofuels.	GHG impact of biofuels is debated[14], making emissions impact of any change in biofuel adoption difficult to quantify, even directionally.
	• Anchor in scenarios that consider various economic and policy constraints on adoption; do not project full technical potential.	Goal of report is to understand what, realistically, US agriculture can contribute to US national commitments.

[13]We considered other baseline years, e.g. 2005 which is used for calculating nationally determined contributions, but chose the most recent year for readers' ease of understanding and because current US agricultural emissions are not significantly different from 2005 levels.
[14]Lark, Hendricks, et al. 2021.

Our current path

“US agricultural sector emissions are likely to remain flat through 2050 without significant intervention.”

Agriculture emissions are a significant contributor to the US GHG inventory, representing 11% of overall emissions in 2020 (Figure 1) and have remained relatively flat over the past three decades (Figure 2). This trend is in contrast to most other economic sectors, which have begun to reduce their emissions over the past ten years (Figure 3).[15] Unlike other sectors, where carbon dioxide (CO_2) is the dominant greenhouse gas, agriculture emissions are mostly due to methane (CH_4) and nitrous oxide (N_2O), which are between 25 and 300 times more potent than other sources.

It is worth noting that this inventory does not account for all farm-to-table emissions related to the agriculture sector because it does not include the full scope of the supply chain, i.e., emissions that occur upstream (e.g. fertilizer production) or downstream (e.g. distribution, sales, disposal in landfills of food products) from the farm gate.[16]

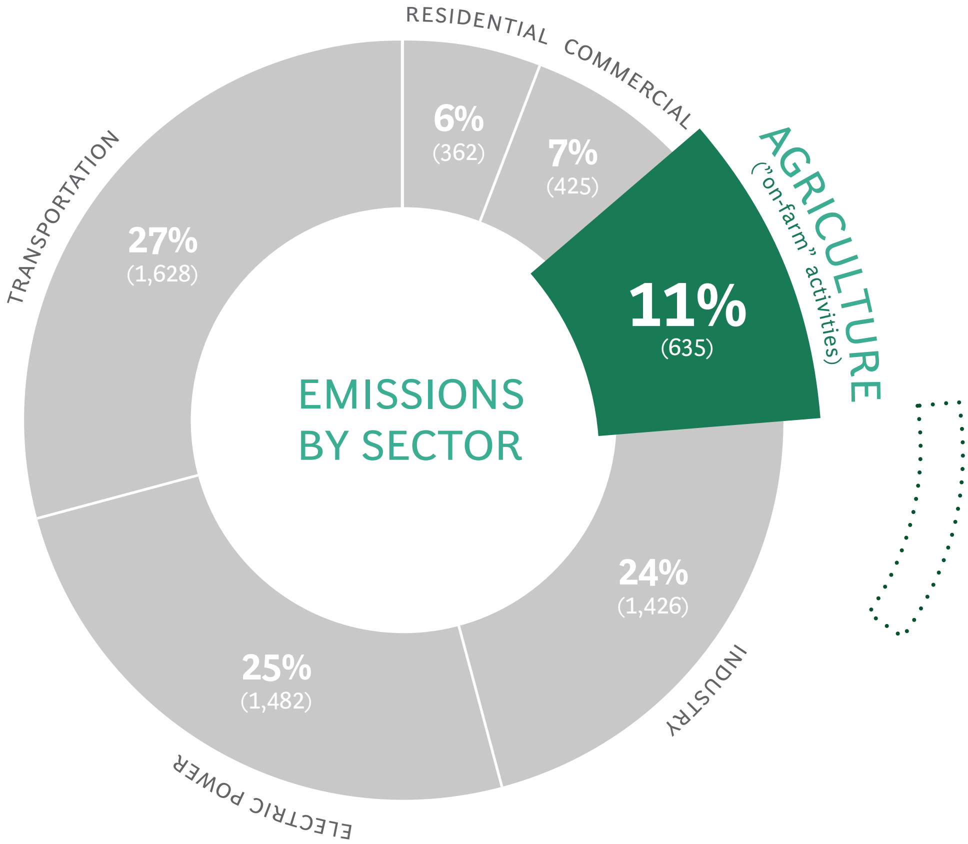
[15] EPA 2022.

[16] See Appendix 1 – Methodologies for additional commentary on how, for purposes of this analysis, we have adjusted the EPA baseline to focus on emissions that can be most directly impacted by on-farm decisions.

These emissions are captured in other sectors of the US GHG inventory[17] (e.g., food waste in landfill is captured in the Waste chapter of the US GHG inventory). If one were to account for all emissions across the agri-food value chain, then the contribution of US agriculture to total US emissions would appear even more substantial—an estimated 20% of all US emissions in 2019 according to the UN Food and Agriculture Organization.[18]

Figure 1 - US GHG Emissions by Sector, 2020

According to the EPA, agriculture accounts for 11% of US GHG emissions



LULUCF

The land use, land-use change, and forestry (LULUCF) sector is closely linked to agriculture.

In the US, LULUCF is "net sink" for emissions equal to -759 MMT, which means that the sector sequesters more carbon than it emits.

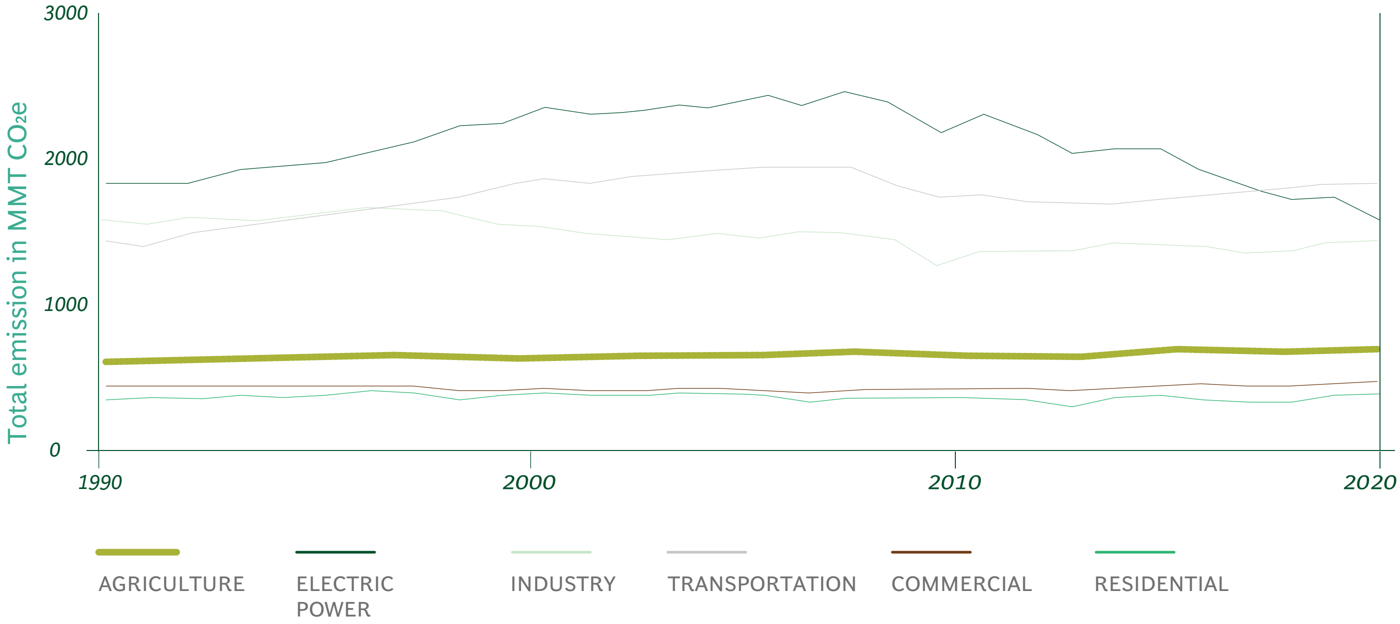
Source: EPA, 2022.

[17]EPA 2022.

[18]Tubiello 2022.

Figure 2 - US GHG Emissions by Sector, by Year, 1990-2020 (excludes LULUCF)

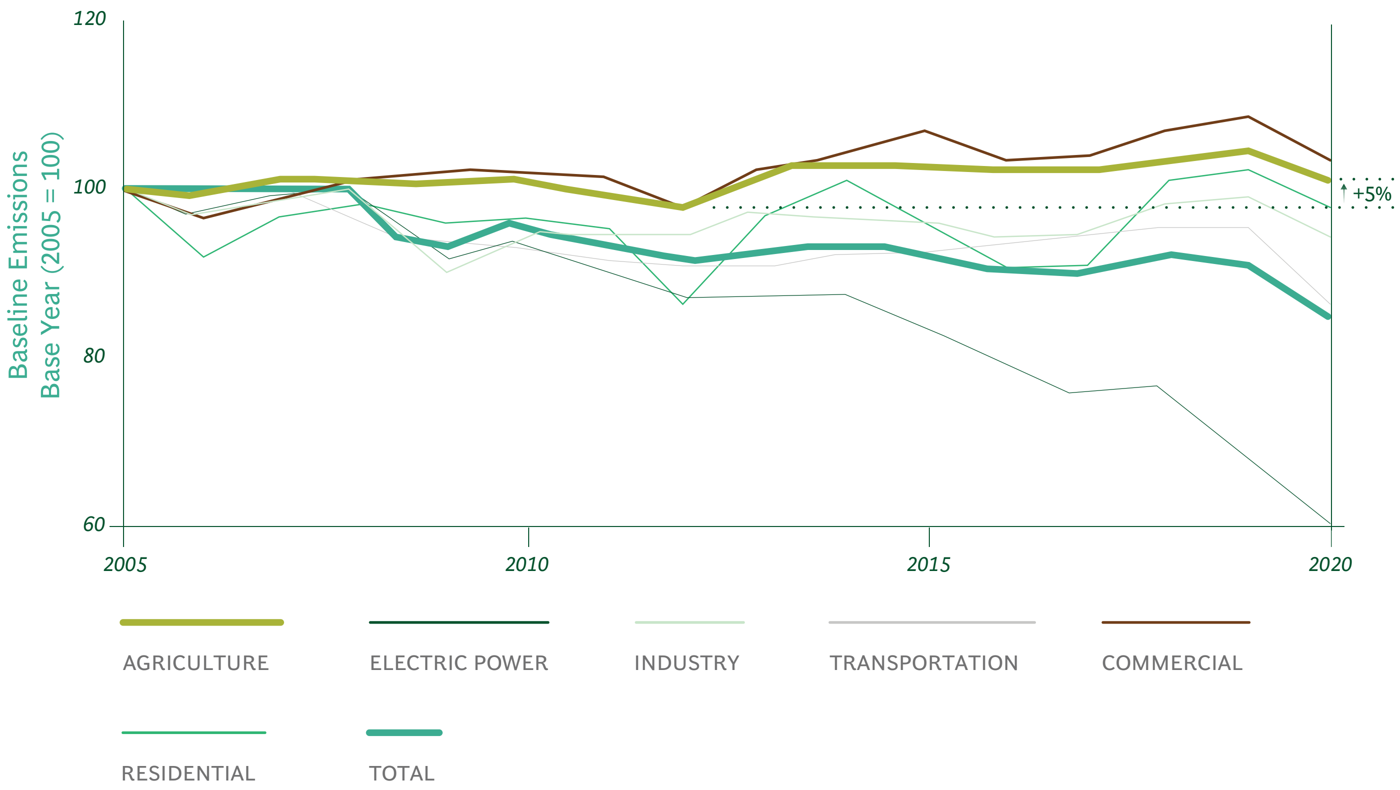
Agriculture is the fourth-largest-emitting economic sector in the US



Source: EPA, 2022.

Figure 3 - Changes in US GHG Emissions by Sector from Base Year 2005, 1990-2020

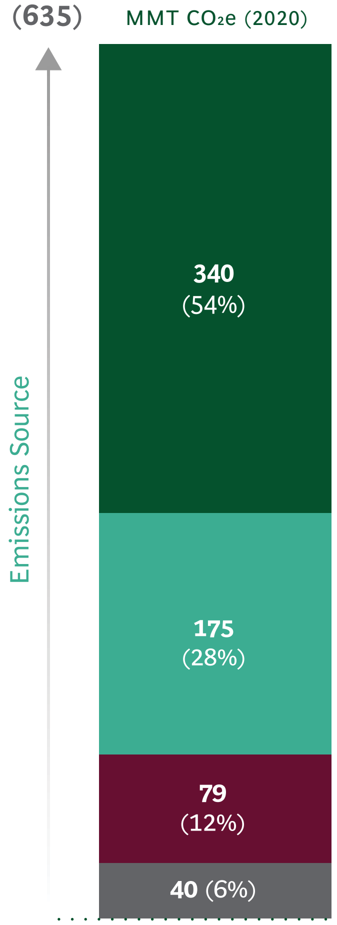
Since 2012, agriculture emissions increased by ~5%, largely driven by increased production to meet demand as population grows



Source: EPA, 2022.

Figure 4 - Drivers of US Agricultural Emissions, 2020

Soil management and how we raise livestock drive ~95% of on-farm emissions in the US



AGRICULTURE SOIL MANAGEMENT[1]

Soil management practices, which represent 54% of the agriculture sector's emissions, primarily stem from nitrous oxide which is 300 times more potent than carbon dioxide. There are several factors that drive these emissions, the most significant being the application of nitrogen fertilizers and the natural decomposition of manure from livestock deposited on croplands and grazing lands.

ENTERIC FERMENTATION

Two processes involving livestock generate another 40% of agricultural emissions. The larger of the two is **enteric fermentation,** which occurs during the digestive process in ruminant animals (notably, cattle and sheep) during which they release highly potent methane as they belch. This process occurs in the 100 million or so cattle and sheep across the US, driving around 28% of the agriculture sector's total emissions.

MANURE MANAGEMENT

The second livestock driver, **manure management,** is responsible for about 12%. Roughly 85% of this segment of emissions is driven by specific manure handling systems used in swine and dairy cattle operations.[2] Cattle operations are the larger contributor to this category due to the quantity of manure, due to their large size, and longer lifespan.

FUEL USE

The remaining ~6% of emissions stem from on-farm **fuel use**—primarily gasoline and diesel-powered equipment, but excluding electricity.

Sources: EPA, 2021; EPA, Overview of Greenhouse Gases: Nitrous Oxide Emissions, 2022; USDA, Census of Agriculture 2017; Congressional Research Service 2021.

Note: Excludes on-farm electricity use. Some figures may not sum to totals due to rounding.

[1]This includes the following categories from the EPA inventory: agricultural soil management (316 MMT), rice cultivation (16 MMT), urea fertilization (5 MMT), liming (2 MMT), and field burning of agricultural residues (1 MMT).

[2]Includes anaerobic lagoon, deep pit, and liquid/slurry systems.

Figure 4 describes the four primary drivers of agricultural emissions—soil management, enteric fermentation, manure management, and fuel use.

Based on USDA projections, we estimate agricultural sector emissions are likely to remain flat through 2050 without significant intervention.[19,20,21]

This results in an estimated 648 MMT CO_2e emitted in 2050. This flat top-line presumes that population growth will drive slight increases in livestock-related emissions, offset by an assumption that historical fuel efficiency gains in heavy equipment on farm will continue. For additional assumptions underpinning the analysis in this report, see "Scope & key assumptions in this report," p. 7.

[19]USDA, Integrated Projections for Agriculture and Forest Sector Land Use, Land-Use Change, and GHG Emissions and Removals: 2016.

[20]We have excluded from USDA's projections ~25 MMT in emission reduction expected from the "Building Blocks for Climate Smart Agriculture and Forestry" policies announced in 2016, because those impacts would likely be double counted across the mitigation levers we summarize later in this report. See Appendix 1 – Methodologies for additional detail.

[21]"Projected emissions to 2060 assume that for each livestock and crop commodity, emissions per production unit remain constant from the present to 2060. This means the projections take as given the current mix of farm and climate policies relevant to the farm sector and the current mix of production practices and technologies used on US farms." USDA, Integrated Projections for Agriculture and Forest Sector Land Use, Land-Use Change, and GHG Emissions and Removals: 2016.

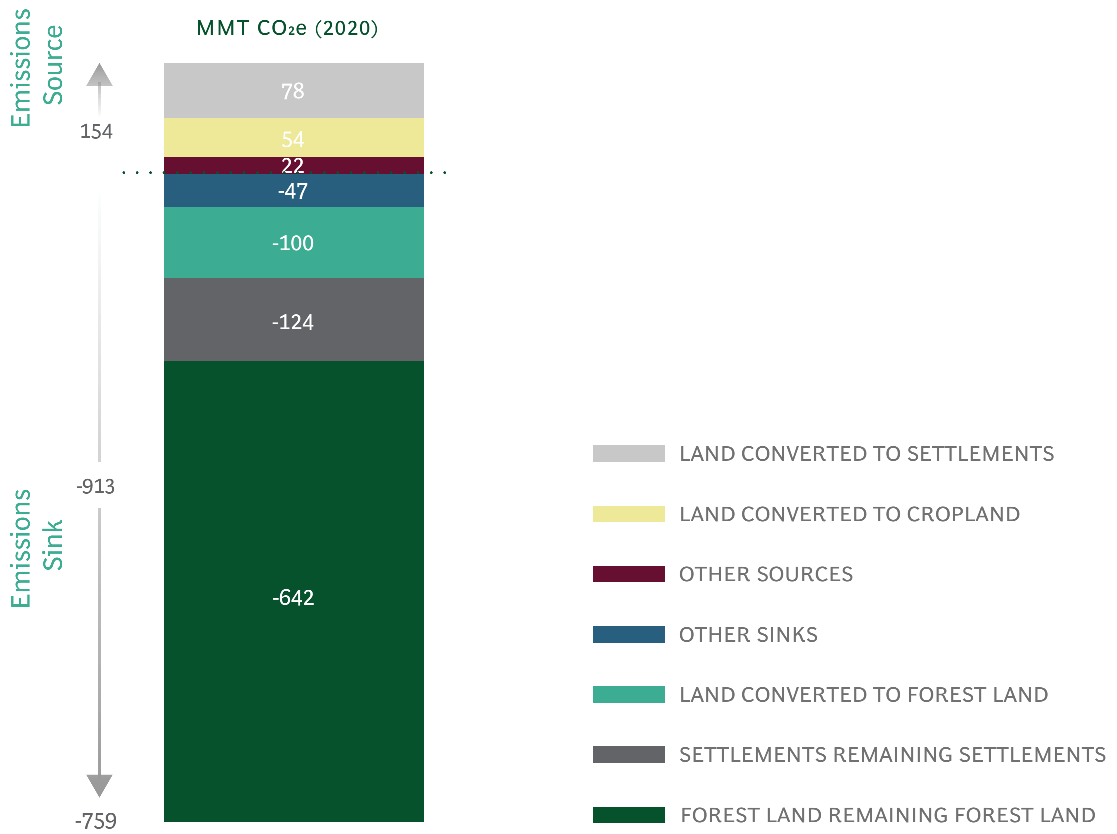
Land use, land-use change, forestry (LULUCF) emissions and sequestration

The United Nations Framework Convention on Climate Change defines LULUCF as the sector that covers "emissions and removals of greenhouse gases resulting from direct human-induced land use, land-use change, and forestry activities."[22] It is important to include the consequences of LULUCF in this report given its close relationship with US agricultural land. For example, increasing use of corn for biofuels drives increased emissions as grassland is converted to cropland.[23] In contrast, when improved agricultural technologies and practices take low-productivity land out of production, and that land is reforested, more CO_2 can be stored in sinks.[24]

Globally, the LULUCF sector has been a significant contributor to global warming, primarily due to deforestation. A century ago, as population and living standards grew rapidly, large areas of forested land in the US were converted to agricultural land to meet the country's growing food and energy needs. This meant that the LULUCF sector released more stored carbon into the atmosphere and was therefore considered a net source of emissions. However, for the past several decades, thanks to efforts conserve and expand grasslands, wetlands, and especially forests, US lands are now a net carbon sink- annual carbon sequestration within forests and other lands is greater than what is emitted from these ecosystems through the conversion of forests and grasslands into cropland and settlements.

Figure 5 - Land-Use Change and Forestry US Sources & Sinks, 2020

Land use represents a net sink of more than 750 MMT sequestered annually, partially offsetting emissions sources elsewhere in the economy



Source: EPA, 2022.

Note: Some figures may not sum to totals due to rounding.

[22] UNFCCC 2022.

[23] Salmon and Gibbs, Cropland, "Expansion outpaces agricultural and biofuel policies in the United States," 2015.

[24] Note that the LULUCF sector acts as a net carbon sink for the entire economy's residual emissions, not just for agricultural emissions. In other words, one cannot subtract the net LULUCF sink from agriculture emissions and then claim that agriculture already has net-zero emissions.

Since 2005, this net sink has remained essentially steady, falling slightly from a net sequestration of 790 MMT CO_2e in 2005 to 759 MMT CO_2e in 2020, and offsetting an amount equal to 12% of total US emissions annually.[25] Most of this annual sequestration (991 MMT CO_2e in 2020) happens on existing US forest land, and on lands newly converted to forest. This is offset by emissions (154 MMT CO_2e) that result primarily from land being converted to cropland or settlements (Figure 5).[26]

The US government, based on inputs from USDA and EPA, projects the net amount of carbon sequestered in the LULUCF sector will be between 500 to 1050 MMT CO_2e annually by 2050. In other words, there is significant uncertainty about the overall direction of the US carbon sink: it could increase or decrease by ~35% by 2050 vs. today's levels.[27] This wide range primarily reflects the different modelling approaches across various agencies,[28] as well as considerable scientific uncertainty about the capacity of US forests to continue to act as a sink, in part due to differing points of view about future land use changes between sectors and disturbance events (e.g., fires), and the difficulties of estimating the complexities related to the sequestration potential of ageing US forests.

For this report, we will take the midpoint of this projected range (i.e., 775 MMT CO_2e in 2050) when illustrating the LULUCF baseline in visuals and when discussing percentage increases and decreases in the LULUCF sink.

[25]EPA 2022.

[26]EPA 2022.

[27]White House Long Term Strategy 2021.

[28]White House Long Term Strategy 2021.

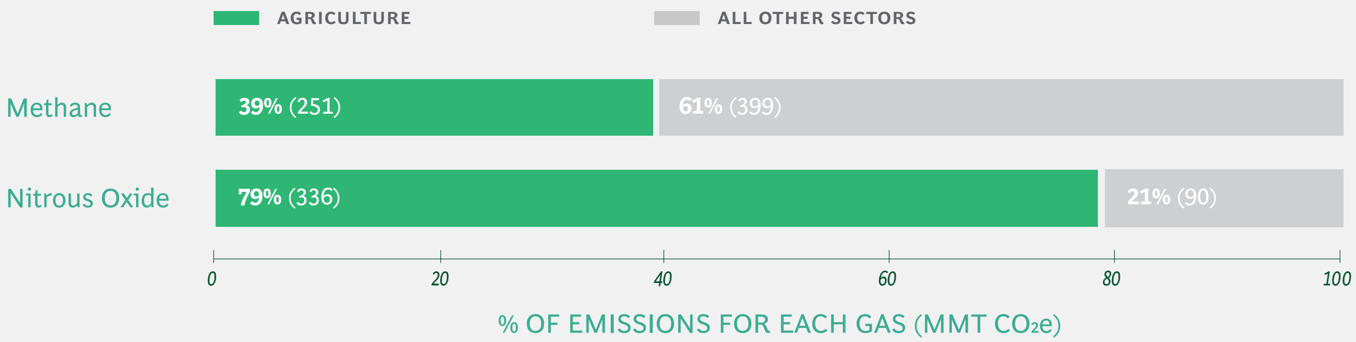
Methane and nitrous oxide are main GHGs of concern

Nearly all agriculture emissions come from two gases that are far more potent than CO_2: methane (CH_4; 25-28x more potent over 100 years vs. CO_2, with a half-life of only 9 years in the atmosphere[29]) and nitrous oxide (N_2O; ~300x more potent than CO_2). In turn, a significant portion of US emissions of these gasses come from farming: agriculture accounts for 39% of total US methane and 80% of nitrous oxide emissions.[30]

Of the two gases, methane is particularly important to address: the combination of a highly potent GHG with short half life means that any emissions avoided today can have a relatively quicker impact on mitigating global warming compared to mitigating other GHGs.[31]

Figure 6 - Share of CH_4 and N_2O Emissions, by Sector, 2020

A significant portion of US methane emissions, and nearly all nitrous oxide emissions, come from agriculture

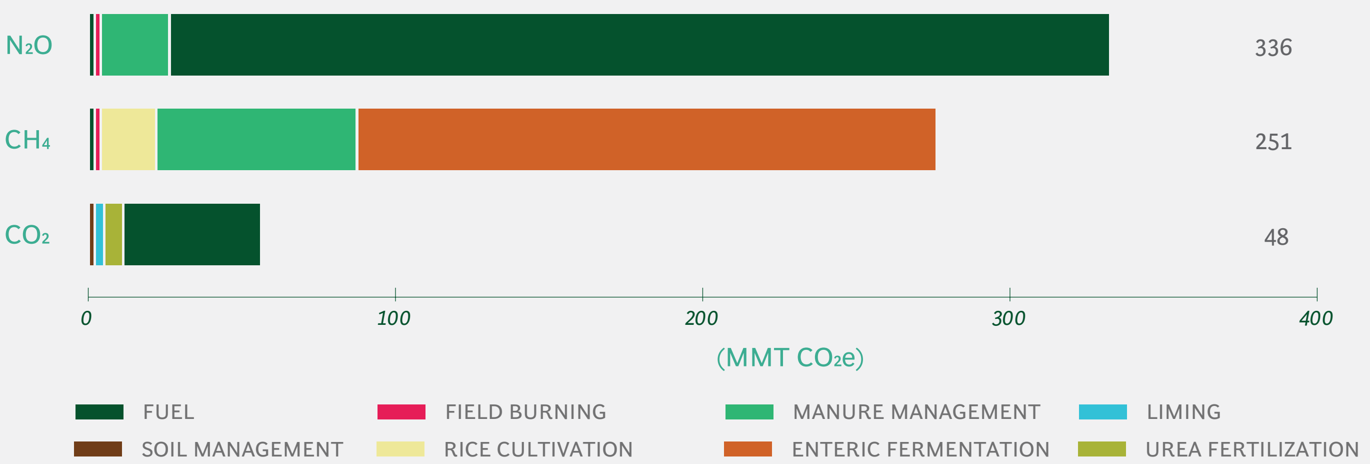


Source: EPA, 2022.

In agriculture, most methane emissions are driven by livestock (via enteric fermentation and manure), while fertilization of crops and grasslands is the main source of nitrous oxide. Actual CO_2 emissions in the agriculture baseline are almost exclusively a result of on-farm fuel use (Figure 7).[32]

Figure 7 - US Agriculture Emissions by Gas and Emission, 2020

Primary sources of agriculture emissions are N_2O (mostly soil management) and CH_4 (mostly enteric fermentation)



Source: EPA, 2022.

[29] IPCC, AR5, 2014.

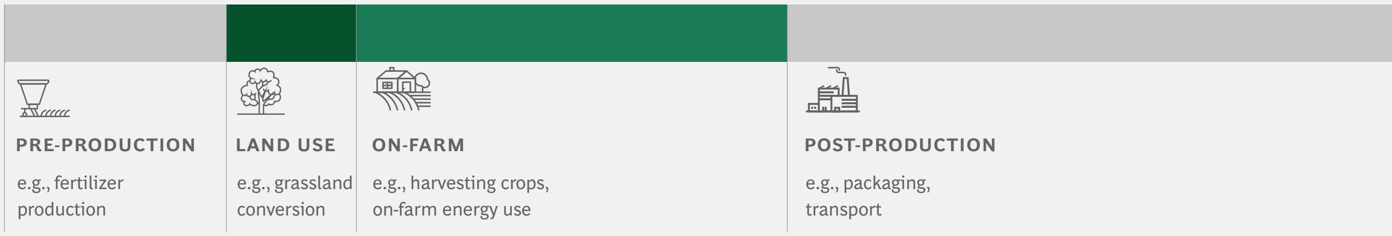
[30] EPA 2021.

[31] IPCC, AR5, 2014.

[32] Within the agriculture sector baseline. LULUCF also generates CO_2 emissions through land use changes.

Figure 8 - Our Report Addresses Approximately Half of the Emissions from the Agri-Food Value Chain

% indicative share of emissions from agriculture activities



Note: Land-use segment is indicative of the relative size of the sources from land use, but excludes the net impact from sinks.

A recent FAO report estimated that agri-food systems—including farm gate emissions, land use change, and pre- and post-production activities—may account for 20% of US emissions.[33] As a general principle we have adopted a scope for this report that generally focuses on farm gate and land use-related activities and decisions (FAO estimates farm gate + land-use change emissions to be approximately 45% of end-to-end agri-food system emissions globally), while also taking into account potential downstream changes in the demand for food that could lower agricultural production (through reductions in food loss and waste and changes in diet).[34]

For example, we include in our baseline emissions the fuel used to power heavy machinery on farms based on the economic sector methodology used by the EPA.[35] We exclude, however, emissions from on-farm consumption of electricity, upstream from the farm (such as from the production of fertilizers), and downstream from the farm (including the entire transportation, distribution, and selling segments of the value chain, as well as methane from food spoilage in landfills).

We believe this framework, which is consistent with the inventory approach taken by the EPA, provides the most directly relevant, comparable, and recognizable baseline from which to assess the emissions reduction potential of the levers and actions that we analyze.[36]

[33]Tubiello 2022.

[34]Note: Our baseline intentionally excludes emissions reductions from the USDA “Building Blocks” for Climate-Smart Agriculture and Forestry (a set of policies in place to address emissions at various stages of agriculture production established in 2016) to avoid the risk of double counting the impacts of the levers used in our model.

[35]EPA 2021 Table 2-10.

[36]For additional details on our methodology, please see: Appendix 1 – Methodologies.

A better path to 2050

Reducing emissions in the US agriculture sector presents unique challenges relative to other sectors for several reasons:

1. Agricultural emissions are scientifically complex, involving natural and biological processes which will always emit some amount of greenhouse gasses.

2. There are currently no silver bullet technologies or solutions on the horizon—progress will require many different mitigation solutions across a range of agricultural practices and demand drivers.

3. It is socially, economically, and politically complicated: transformative change will require aligning a complex set of stakeholders and political and economic incentives across the agri-food ecosystem.

We have reviewed extensive scientific and technical literature to compile a set of 24 levers for emissions reduction or carbon sequestration across three categories: changes in how we produce, changes in what and how we consume, and changes in how we use land.[37]

Figure 9 - Twenty-Four Levers to Change How We Grow and Consume Food, and How We Use Land

Changes	Actions	Levers
Changes to how we Grow	Adopting More Sustainable Soil Management Practices	• Cover cropping • Reduced/no-till farming • Fertilizer application rate changes • Fertilizer timing changes • Precision fertilization (VRT) • Fertilizer type changes (anhydrous to urea) • Managed-intensive grazing • Legume interseeding • Silvopasture • Alley-cropping • Windbreaks • Biochar application • Rice cultivation and water management practices
	Improving Manure Management	• Anaerobic digesters • Improved storage and handlings
	Reducing Methane from Livestock Farming	• Technologies to reduce livestock methane • Selective breeding for lower GHG emitting livestock
	Reducing Fossil Fuel Use	• Zero-emissions on-farm machinery and equipment
Changes to what and how we Consume	Diet Changes	• More GHG-conscious diets
	Waste Changes	• Less food waste at retail & consumer levels
Changes to how we use our Land	Increasing Sequestration Potential of US Lands	• Reforestation • Improved forest management • Avoid grassland conversion • Conservation of peatlands and wetlands

[37] These levers represent a range of changes to how we grow agricultural products, i.e. practices or technologies a producer might adopt in the future that would reduce on-farm emissions or increase sequestration of carbon in soil. We also included levers related to how we consume food and how we use land.

We excluded levers that, although proven effective in other countries, had limited evidence specific to and may not prove as effective in the US agricultural context, e.g., changes to irrigation tactics (shifting from gravity fed to pressurized systems), multi-story cropping (a form of agroforestry), and alternative crop rotations (such as perennial integration).

We also excluded levers that had very small in impact on emissions or where the scientific debate was so strong as to prevent selection of a clear range of potential emissions factors (such as the GHG impact of corn ethanol-derived biofuels, where evidence is mixed: USDA has said ethanol carbon intensity is 39% lower than gasoline, however a recent study found that due to emissions from land use changes, ethanol is likely 24% more carbon-intensive than gasoline. See Lark, Hendricks, et al. 2021. Given the uncertainty, we chose not to size any emissions impacts from potential future increases or decreases in the volume of corn ethanol produced in the United States.

The conservative scenario leads to emissions reductions of 10% from the EPA/USDA-derived baseline forecast for 2050, and no gains in LULUCF carbon sequestration. The moderate scenario provides a 41% decrease in emissions and a 9% increase in LULUCF carbon sequestration. The optimistic scenario offers a 57% reduction in emissions and a 60% increase in LULUCF carbon sequestration.

In addition to the emissions reductions and sequestration gains, the 24 levers provide a range of broader benefits for farmers, communities, and society at large, from adaptation and resiliency to gains tin water conservation and purification.

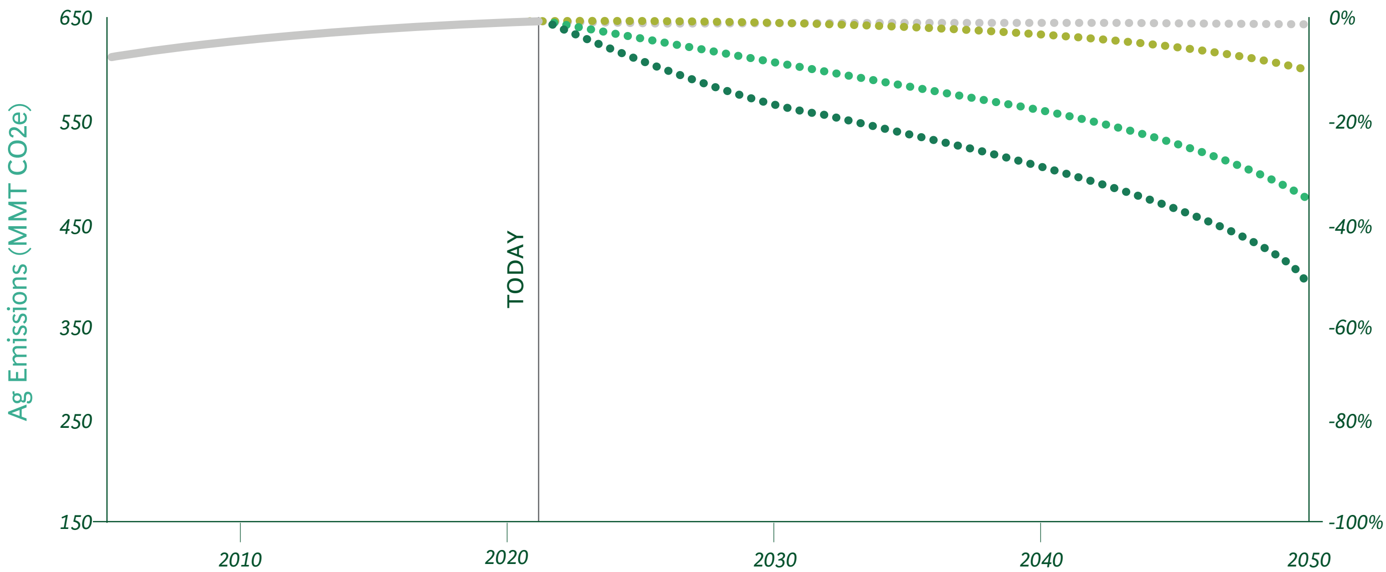
Figure 10 - Overview of Scenarios for Emissions Reduction

		CONSERVATIVE SCENARIO 10% Reduction in Agriculture Emissions	MODERATE SCENARIO 41% Reduction in Agriculture Emissions	OPTIMISTIC SCENARIO 57% Reduction in Agriculture Emissions
Overall Principles in 2050…		**Incremental changes** from stakeholders to reduce emissions to the extent feasible/economical	**Fundamental changes** to how food is grown, and land is used…	… along with **fundamental changes to consumer behaviors**
Ease of Adoption	Easier	• Adoption of addressable base reaches **50%**	• Adoption of addressable base reaches **80%**	
	Moderate	• Adoption of addressable base reaches **30%**	• Adoption of addressable base reaches **50%**	
	Harder	• Adoption of addressable base reaches **10%**	• Adoption of addressable base reaches **30%**	
Technology & Science		• **Minimal improvement in tech**; some levers remain expensive & niche • GHG factor for emissions factors **resolves to low end of range**	• 20 mature & developing technologies achieve **expected commercial scale**, however 4 nascent technologies fall short • GHG factor **resolves to high end of range**	• All technologies achieve expected commercial scale • GHG factor resolves to high end of range
Consumption		• **No change** to US diets • **No change** to levels of food loss & waste	• GHG conscious diets **limited to core adopters** (~20% population) • US reduces food loss & waste at **level similar to other countries**	• **A growing minority** of the country prefers GHG conscious diets (~40% population) • US achieves **ideal case reductions** in food loss & waste
Forestry & Land -Use Change		• Increased pressure on forests due to climate change and other factors offset any gains holding **size of carbon sink flat**	• Best efforts to reforest, improve practices, avoid land conversion for land that can be reforested at **<$10t CO_2e/ac** • No new policy or programmatic initiatives	• Aggressive funding to reforest land that can be reforested at **<$50t CO_2e/ac** • Lower meat consumption relieves pressure to create new grazing land

The degree to which each of the three categories of levers can impact emissions and sequestration varies. For example, we project that changes to how we grow our food could eliminate ~40% (258 MMT CO_2e) of projected business-as-usual agricultural emissions, with an additional 17% (110 MMT CO_2e) reduction from changes to what and how we consume food, for a total optimistic scenario reduction of 57% of agricultural emissions (Figure 12). Changes in how we use land—limiting the amount of uncultivated land converted to agriculture and increasing the amount of forest and grassland restores without negatively impacting the supply of agricultural products—have the potential to increase sequestration by 60% in 2050 under the optimistic scenario (Figure 13).

Figure 11 - Scenarios for a Better Path: Up to 57% Reduction Under an Optimistic Scenario

Four possible scenarios of emissions reductions between now and 2050



BASELINE

Drawing from USDA and EPA projections; assumes demand growth countered by productivity gains, with no policy changes from today

CONSERVATIVE

Incremental changes from stakeholders to reduce emissions to the extent feasible/economical

—

10%

REDUCTIONS BY 2050

MODERATE

Conservative plus coordinated action across stakeholders to change how food is grown and land is used

—

41%

REDUCTIONS BY 2050

OPTIMISTIC

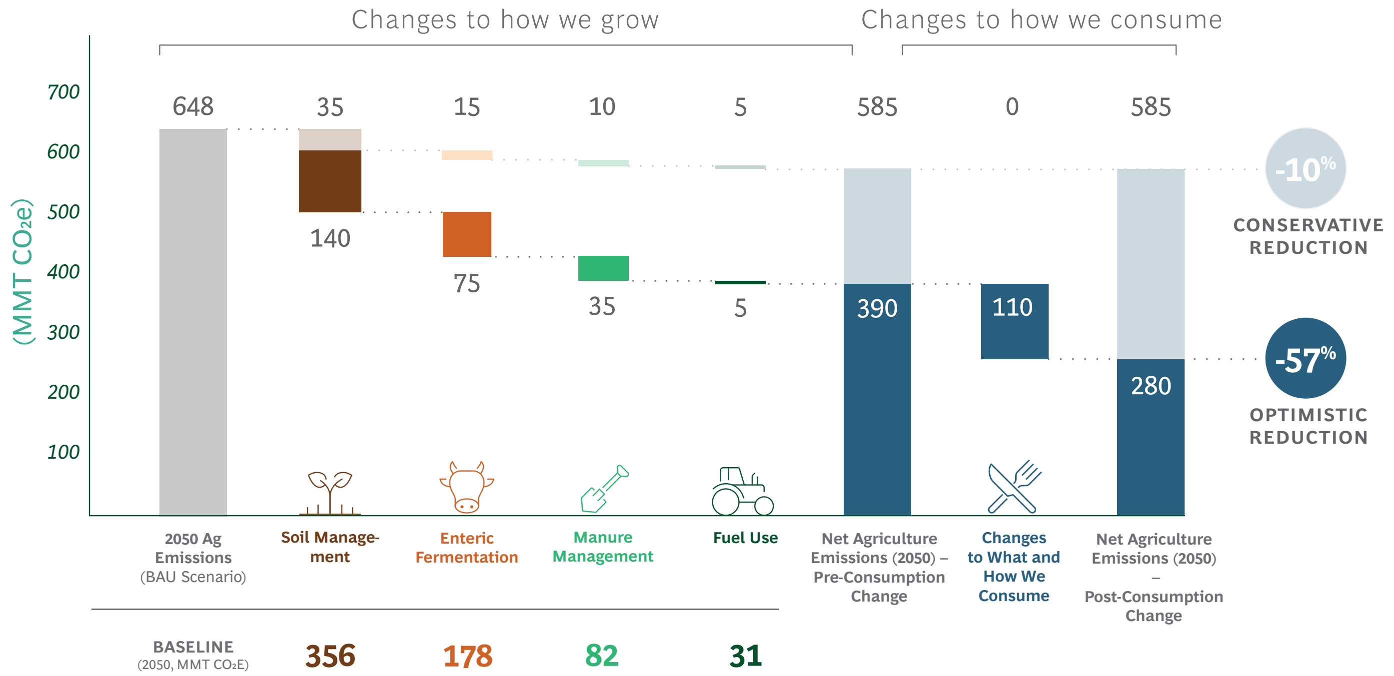
Moderate plus fundamental changes to consumer behavior and all technologies achieve expected commercial scale

—

57%

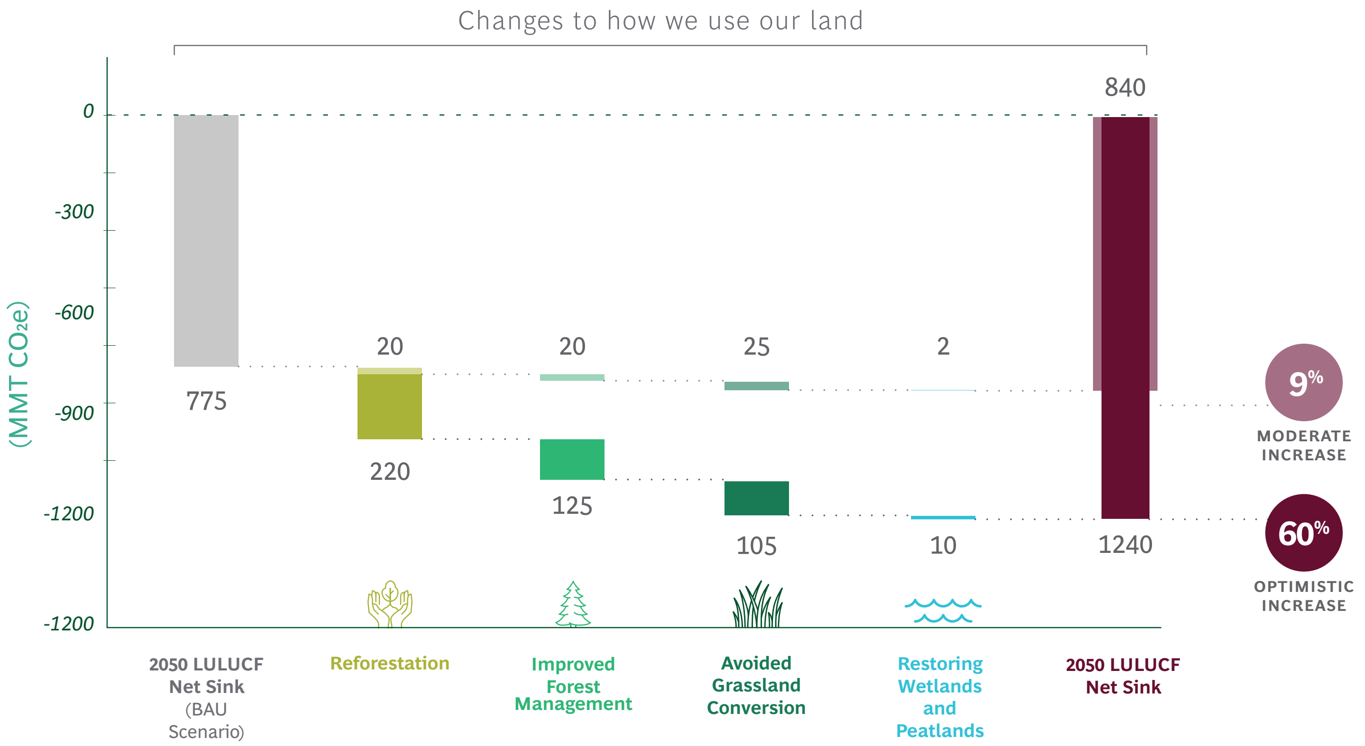
REDUCTIONS BY 2050

Figure 12 - Summary of Potential Impact in 2050: How We Grow and Consume Food



Note: Some figures may not sum to totals due to rounding.

Figure 13 - Summary of Potential Impact in 2050: How We Use Land



Note: Some figures may not sum to totals due to rounding.

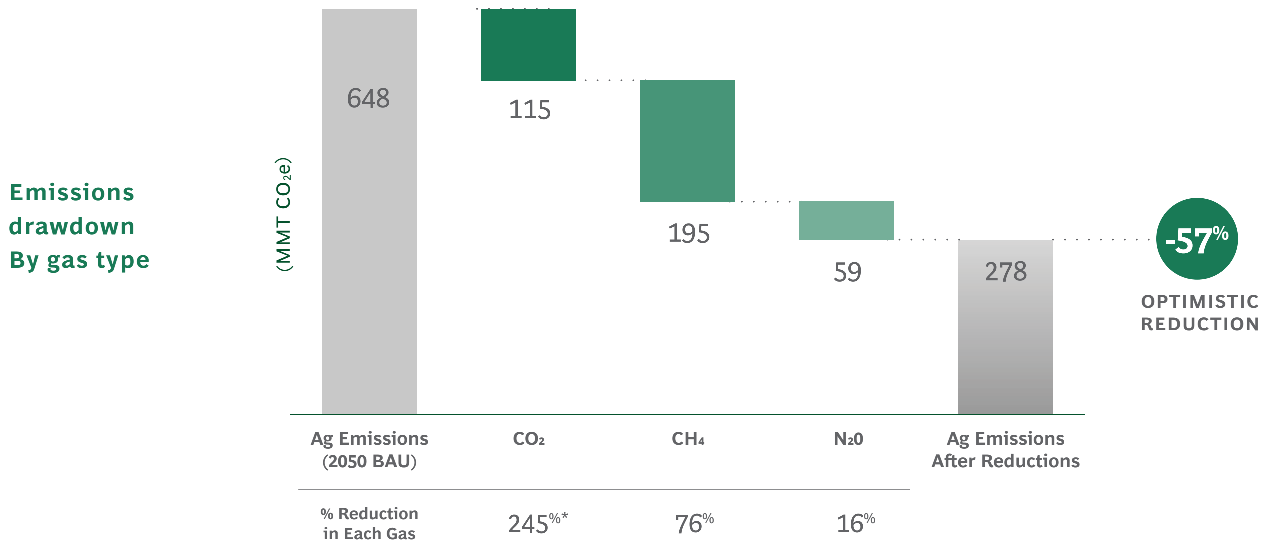
Agricultural emission reduction impacts by gas and technology stage

Looking in detail at the reduction potentials can provide useful insights into the assumptions underlying each scenario. We break out for the optimistic scenario the impact of agricultural reductions by type of greenhouse gas and the maturity of technology for the levers pulled (Figure 14).

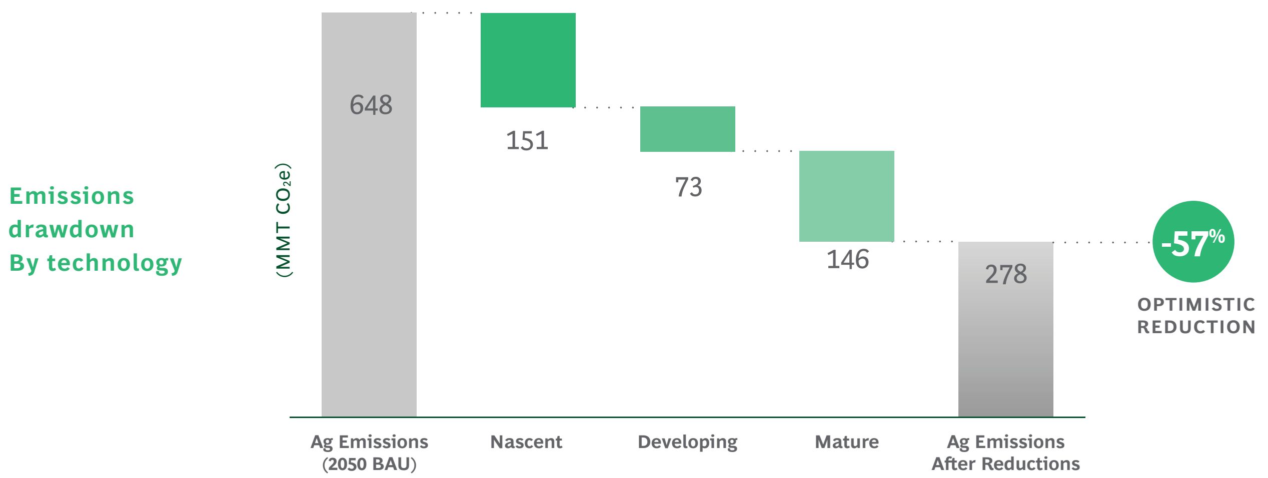
Gas type: If achieved, the reductions outlined above under our optimistic scenario would eliminate 76% of methane-derived agriculture emissions by 2050. This exceeds the overall reduction potential of 57% across all gases, and depends largely on successful development and commercialization of technologies for managing enteric fermentation in livestock.

Lever technology maturity: The optimistic scenario's reductions can be achieved through existing mature technologies like cover cropping and reduced tillage, technologies that are developing but not yet at scale such as precision fertilization and alley cropping, and emerging technologies with high potential in the future, like livestock feed enhancements (see "Critical technologies to scale by 2050," p. 44). This does not include even more novel "frontier" technologies which have not been sized (see our later discussion of frontier technologies in Section 4).

Figure 14 - The Optimistic Scenario, by Gas and Technology, in 2050



*CO_2 reduction >100% because of impact of soil carbon sequestration; in formal carbon accounting this would be captured in "cropland remaining cropland" or other LULUCF categories, but we show here for clarity as to the magnitude of impact the levers have on the agricultural emissions baseline.



Note: Some figures may not sum to totals due to rounding.

Detailed summary of levers

The following section discusses in detail each of the 24 levers to change how we grow, how we consume, and how we use land, providing a high-level description of how each lever works to reduce emissions or increase carbon sequestration, highlighting relevant context such as barriers to adoption of that practice, and estimating the potential emissions impact per lever under each of the three scenarios. These levers are organized by emission driver, as shown in Figure 12, beginning with levers for changing how we manage agricultural soils, which comprise more than half of the total number of distinct levers described in this report (13 of 24) and one-third of the potential reduction in the agriculture emissions baseline under the optimistic scenario.

On-farm: Changes to how fields & soils are managed

We looked at six sets of practices for croplands and grasslands management that if scaled could drive an annual reduction of ~33-141 MMT CO_2e by 2050. While there are a wide range of possible levers that could be used globally, this report sought to focus specifically on those that had the most relevance for the US context and have sufficient scientific consensus on their emissions reduction/sequestration potential. We have chosen to not include practices and technologies that are still novel or where there is significant debate on the impact (e.g., enhanced weathering).

Figure 15 - Summary of Levers Related to Agricultural Soil Management

Action	Lever	Description	MMT CO_2e reduction (% reduction)		
			CON.	MOD.	OPT.
Scaling use of regenerative field management practices	Reduced/No Till Practices	Reducing or eliminating the disturbance of soil by tilling machinery	5 0.4%	15 2.1%	15 2.1%
	Cover Cropping	Planting on croplands that would otherwise have been left fallow for certain parts of the year	10 1.7%	45 7.0%	45 7.0%
Optimizing nutrient management practices	Reduce Application Rate	Reducing the overall rate of nitrogen application on fields	2 0.2%	5 0.7%	5 0.7%
	Fertilizer Timing Changes	Shifting timing of fertilizer application to when plants are in the highest demand for it	1 0.2%	5 0.4%	5 0.4%
	Precision Fertilization Variable Rate Technology (VRT)	Applying a precise amount of nutrients to crops at variable rates across a field	2 0.3%	5 0.9%	5 0.9%
	Switch Fertilizer Types	Switching from anhydrous to urea fertilizers, which produce less N_2O	5 0.6%	10 1.8%	10 1.8%
Improving management of grazing lands	Prescribed or Managed Grazing	Optimizing movement of grazing animals through pasture	< 1 0.0%	5 1.2%	5 1.2%
	Legume Interseeding	Incorporating legumes such as alfalfa into existing cover on pastures	2 0.2%	5 1.0%	5 1.0%
	Silvopasture	Planting trees and shrubs on pasture	< 1 0.1%	15 2.1%	15 2.1%
Incorporating more trees on farmland	Alley Cropping	Planting trees in rows alongside companion crops	2 0.3%	5 1.0%	5 1.0%
	Other Agroforestry Practices	Planting tree windbreaks or riparian forest buffers on the perimeter of fields	2 0.3%	5 0.7%	5 0.7%
Soil amendments to sequester carbon	Biochar Application	Applying biochar, a byproduct of biomass burned in the absence of oxygen, to fields	1 0.2%	15 2.1%	15 2.1%
Rice and water management	Improve Rice Cultivation	Deploying water management techniques such as alternate wetting and drying (AWD) and midseason drainage	5 0.4%	5 1.0%	5 1.0%

CON. = CONSERVATIVE SCENARIO MOD. = MODERATE SCENARIO OPT. = OPTIMISTIC SCENARIO

Scaling use of regenerative field management practices

Changing the way our agricultural soils are managed can significantly draw down GHG emissions, particularly when practices are implemented that enable carbon to build up in soils and improve the overall health and productivity of the land. Two well-established practices are commonly cited as having the largest potential impact: cover cropping and conservation tillage such as reduced or no-till farming. Collectively, we believe these practices have the potential to yield between 15 and 60 MMT CO_2e/yr by 2050, depending on which of the three scenarios is considered.[38]

Cover cropping is a broad definition for the practice of planting various crop varieties, such as legumes, on croplands that would otherwise have been left fallow for certain parts of the year, thereby drawing in more carbon to the soil.[39] Most US cropland is a good candidate for some form of cover cropping system, however today cover cropping is used on only 5% of that land.[40,41] These low levels of adoption are driven primarily by farm economics as cover cropping can increase costs and potentially reduce yields in the short term.[42] If this challenge is addressed through various shifts in policy and business practice, we expect adoption to increase significantly, especially in light of the added resiliency benefits from the practice.

Reduced or no-till farming reducing or eliminating the disturbance of soil by tilling machinery is far more widely adopted in the US today; more than 60% of the cropland dedicated to the 5 largest commodity crops use some form of conservation tillage.[43,44] That said, across these farms, there is still significant opportunity for more farms to transition to a fully no-till system, which can yield the biggest impact.

The benefits of these regenerative practices extend far beyond GHG emissions and are likely to be even bigger drivers of adoption than soil carbon sequestration alone. For instance, they have been shown to improve overall crop yield, reduce erosion, increase water-holding capacity of soil and reduce the need for fertilizer application.[45,46] While the long-term benefits are significant, financial incentives need to be re-aligned in order to scale up their adoption, especially for the 40% or so of farmers who lease land and thus may not have as strong an interest in taking on the short-term risks involved.[47]

[38] Note: There remains some scientific debate around the precise sequestration potential of these practices, therefore our model ranged the emissions factors significantly between the conservative and optimistic scenarios to account for the potential that they prove to be less or more effective.

[39] Moore et al. 2021.

[40] The exception being extreme northern climates where there may be insufficient time between harvest and first freeze for any existing cover crop to be viable.

[41] USDA, Census of Agriculture 2017.

[42] Moore et al. 2021.

[43] USDA ERS, Tillage Intensity and Conservation Cropping in the United States 2018.

[44] Refers only to 5 main crop varieties in US (corn, soybeans, wheat, sorghum & cotton).

[45] USDA, Cover Crops - Keeping Soil in Place While Providing Other Benefits 2022.

[46] Fargione et al. 2018.

[47] USDA, Farmland Ownership and Tenure 2017.

Soil carbon sequestration on agricultural lands

Several of the practices outlined in this report reduce net emissions at least in part by increasing the amount of carbon stored in the soil (soil carbon sequestration). This is an area of growing interest in recent years as traditional agribusiness players (e.g., Bayer, Nutrien), newer agtech players (e.g., Indigo Ag, Nori), and food companies (e.g., Nestle, General Mills, Land O'Lakes through Truterra, among many others) are starting to establish programs for soil-based carbon offsets and insets. Despite this interest, there remain significant scientific and technical debates and questions on how much carbon can be stored feasibly in agricultural soils, even as the benefits of those practices on factors like soil health and water management are well established.[48]

Globally, estimates for the technical potential for soil carbon sequestration range significantly, e.g., from 4-8 to 55 Gt CO_2 per year.[49] These estimates tend to represent the maximum technical potential for carbon sequestration in soil, assume the high end of impact across existing studies and perfect adoption of practices across nearly all relevant land regardless of economic or practical considerations, which are factors not considered in our most optimistic scenario.

In the US, WRI has estimated the potential for US agricultural soil carbon sequestration at 100-200 MT CO2e/year by 2050.[50] Beyond differing assumptions about adoption potential, there also remain significant debates about the per acre potential for carbon removal, reflecting fundamental soil science questions that will require additional research and better measurement.

In this report, including in the optimistic scenario, we have used per-acre sequestration estimates and adoption rates that are in the mid-range of the available scientific literature. We chose this approach to remain consistent across the report and anchored in the scientific literature while recognizing that there are many estimates of soil carbon sequestration potential that significantly exceed what we have included here. We hope that in the coming years, additional investment in scientific studies, tests and pilots, and improved measurement will help clarify the potential for soil carbon sequestration and lead to further investment to support adoption of the most-effective practices and technologies.

[48]For instance, in May 2020, WRI posted a blog post entitled "Regenerative Agriculture: Good for Soil Health, but Limited Potential to Mitigate Climate Change;" Paustian, et al quickly responded with a point-by-point note entitled "Climate Mitigation Potential of Regenerative Agriculture is significant!"

[49]Moyer et al. 2020.

[50]Mulligan et al. 2020.

Improving management of grazing lands

In addition to how we manage the soils of our croplands to store carbon, there are a number of levers that seek to do the same with grasslands used for pasture.[51] Three tactics in particular have shown promise in the United States. Taken together, they have the potential to reduce between 2-25 MMT CO_2e/yr by 2050.

Managed or prescribed grazing can encompass several different practices, which largely involve the optimized movement of grazing animals through pasture. It is commonly considered a regenerative practice, like cover cropping or no-till farming, because the interplay of grazing animals and grasses can have synergistic environmental characteristics.[52,53]

Legume interseeding is a practice whereby legumes like alfalfa are incorporated into existing cover on pastures, as they have been shown to promote carbon sequestration in soils without the need for added nitrogen fertilization.[54,55] They are also a good source of protein for livestock, contribute to biodiversity, reduce erosion, and improve water quality.[56]

Silvopasture is a practice that involves the planting of trees, forage and livestock on the same land.[57] Its use is growing in many parts of the world, such as South America, but still nascent in the US.[58,59] Increased adoption globally is driven by a wide range of benefits beyond carbon sequestration potential. The value in adopting silvopasture is often more driven by the adaptation and resiliency benefits it brings, such as improving soil health through water retention, improving animal health by providing shade, and allowing producers to diversify and supplement their income if they use tree varieties that can be harvested.[60] It does, however, require upfront investments that may include fencing, water infrastructure, or planting trees. It may also require changes in management that can deter broader adoption.

Incorporating more trees on farmland

Agroforestry involves the incorporation of tree varieties into traditional croplands through several different practices. Trees have an incredible capacity to absorb and store carbon, due in part to their large size, but mostly because of their permanence: unlike annual crops such as corn, trees are left year after year to build up carbon in their biomass.[61] Trees integrated into croplands also have considerable benefits for the health of the overall ecosystem and communities. For instance, they can protect against soil erosion from harsh winds, improve filtration of water to reduce agricultural runoff into waterways, improve flood control and diversify farmer income.[62] Therefore, the interventions described below, while able to contribute between 4 and 10 MMT CO_2e/yr by 2050, are likely to be adopted for reasons far beyond CO_2 sequestration.

Alley-cropping, sometimes referred to as intercropping, is the practice of planting trees alongside companion crops, both of which are harvested.[63] Given that the practice can be adapted and tailored to many regions in the US, the overall CO_2 sequestration potential is significant.[64] Further, growing a variety of crops in close proximity instead of traditional monocropping systems can create additional benefits for producers, such as a more diversified revenue streams.[65]

[51] USDA, Managing Agricultural Land for Greenhouse Gas Mitigation within the United States 2016.

[52] The practice can be as simple as rotating cattle from one part of pasture to another during different points of the year to allow for forage regrowth or require more complex systems of grazing to optimize grassland health.

[53] Henderson et al. 2015.

[54] Henderson et al. 2015.

[55] USDA, Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States 2013.

[56] USDA, Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States 2013.

[57] Smith et al. 2021.

[58] Silvopasture is commonly categorized as an Agroforestry as well – we've categorized it under Grazing Management as adoption is driven by ranchers with grazing animals as opposed to farmers of croplands; See Smith et al. 2021.

[59] Project Drawdown 2017.

[60] Smith et al. 2021.

[61] Jacobson and De Stefano 2018.

[62] Smith et al. 2021.

[63] Fargione et al. 2018.

[64] Fargione et al. 2018.

[65] USDA 2022.

Other common forms of agroforestry, including windbreaks and riparian forest buffers—which involve the establishment of trees on the perimeters of fields or along streams and wetlands—also have significant for economic, environmental, and community benefits.[66] By nature of their placement and function however, the footprint of these systems is typically small so as to not reduce cropland or disrupt operations by requiring different equipment or harvesting methods. This limits their GHG mitigation impact to a maximum of around 5 MMT CO_2e/yr in the optimistic scenario.[67]

Amending soil to sequester carbon

There is an emerging wave of research exploring a variety of technologies that involve applying different materials to croplands to increase their carbon sequestration potential.

One technique, which has been studied for years, is **biochar**, a form of charcoal that is produced when biomass is burned in the absence of oxygen.[68] Biochar has the ability to sequester additional carbon and provide nutrients when applied broadly to soils.[69] However, biochar is currently prohibitively expensive, due to high transportation costs if produced at centralized facilities rather than at the farm level.[70] Realizing the full potential of biochar will require significant R&D to identify alternatives methods that can bring costs down or financial programs to support adoption. If it can be made economically viable, however, at or below the voluntary carbon price, we believe its CO_2e sequestration potential could reach around 15 MMT CO_2e by 2050.[71]

More frontier technologies that are not yet ready for scale also exist, such as **enhanced weathering**,[72] which imitates and accelerates a natural chemical process by which rain, which is slightly acidic, weathers rock and in the process sequesters carbon. The process can be accelerated by applying ground rock particles (known as silicate)[73] to croplands and letting the rain do its work with the added benefit of decreasing soil nutrient loss.[74] However, producing the silicate is challenging because it requires significant energy and increases in mining activity, so more R&D is required to validate if this practice is feasible in the United States.

Improving water use in rice cultivation

Rice grown in standing water generates anaerobic conditions in the soil, producing both methane and nitrous oxide emissions. Already, the rice industry has significantly reduced emissions by 41% between 1980 and 2015.[75] The EPA reports further mitigation potential of between 2 and 3 MMT CO_2e by 2030, driven by the continued adoption of water management techniques such as alternate wetting and drying (AWD) and midseason drainage.[76] Projecting forward, we estimate that this would lead to a further reduction of between 3 and 6 MMT CO_2e by 2050.

[66] USDA 2022.

[67] Fargione et al. 2018.

[68] Fargione et al. 2018.

[69] Fargione et al. 2018.

[70] Fargione et al. 2018.

[71] Assumes we use 50% of available biomass (~120M tons currently not being used for other purposes) to produce biochar.

[72] Note: Enhanced weathering was not included in the quantitative model as there is insufficient research on its potential for GHG mitigation in the US.

[73] Moosdorf, Renforth and Hartmann 2014.

[74] Beerling et al. 2020.

[75] The Rice Foundation 2018.

[76] EPA, "Global Mitigation of Non-CO_2 Greenhouse Gases: 2010-2030," 2013.

Figure 16 - Summary of Levers Related to Livestock Emissions

Action	Lever	Description	MMT CO_2e reduction (% reduction)		
			CON.	MOD.	OPT.
Improved handling of manure	Anaerobic Digesters	Systems that capture methane from manure and convert it into biogas for fuel	10 1.3%	20 3.2%	20 3.2%
	Improved Storage and Handling	Adapting current manure management systems to reduce methane emissions, such as adding covers to existing tanks, ponds, and lagoons	2 0.3%	15 2.1%	15 2.1%
Reducing methane emissions from cattle digestion	Livestock Diet Supplements	Feed additives and treatments that curb methane release from belches	15 2.1%	15 2.1%	60 9.0%
	GHG-Focused Genetic Selection & Breeding	Selectively breeding cattle to promote lower methane production from the digestive process	2 0.3%	2 0.3%	20 2.9%

CON. = CONSERVATIVE SCENARIO MOD. = MODERATE SCENARIO OPT. = OPTIMISTIC SCENARIO

Improved handling of manure

Solutions for tackling the methane produced from manure are typically targeted at confined dairy cattle and swine operations, that use anaerobic lagoon, deep pit or liquid/slurry systems, as they account for 85% of methane emissions in the US.[77] Generally, the alternative solutions to address those emissions, which include anaerobic digesters and systems to improve storage and handling such as solids separators, are ready for scale once market forces make it financially attractive. The challenge, however, with the set of solutions that exist today is that they tend to require significant capital investment and a certain size operation to be viable.[78] We believe that across the interventions described below, between 10 and 35 MMT CO_2e could be abated annually by 2050.[79]

Anaerobic digesters

Anaerobic digesters, which are used on less than 10% of dairy farms in the US today, capture biogas that would otherwise have been emitted.[80,81] This process produces two by-products: digestate, which can be sold as a nutrient-dense fertilizer, and biogas, which can be sold as a more sustainable energy source to power things like heating.[82] Further, in some cases producers can accept other forms of organic waste streams from off site, such as food waste from neighboring processing plants, creating additional revenue from tipping fees as well as a pathway to mitigate methane emissions from organic waste decomposing in landfills.[83] Digesters are not without drawbacks, however. They often face climate equity challenges given their potential to create air pollution in the communities in which they operate. Further, they require a certain scale and an effective manure collection process to be feasible, therefore are not viable for smaller operations.[84]

77 USDA, Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States 2013.

78 USDA, Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States 2013.

79 Note: This estimate excludes the additional emissions reduction potential from decreased fossil fuel use for electricity generation, as electricity generation was not included in our agriculture baseline.

80 EPA, Basic Information about Anaerobic Digestion (AD) 2022.

81 USDA, Agricultural Resource Management Survey 2018.

82 EPA 2018.

83 EPA 2018.

84 USDA, Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States 2013.

Improved Storage and Handling of Manure

Farms can also adapt current systems to reduce methane emissions, such as adding a cover to an existing tank, pond, or lagoon.[85] These practices can have significant community benefits, such as improved air and water quality.[86] Further, they can be more amenable to small and mid-size operations where anerobic digester systems are not economical.

For the subset of livestock operations representing the remaining 15% of methane emissions from manure that are not amenable to these solutions (such as livestock operations that use solids systems instead of liquid systems), alternative solutions like compost are viable.[87]

Reducing methane emissions from cattle digestion

Tackling enteric fermentation is very challenging, and a scalable solution for curbing its emissions has yet to be found. Due to the pressing need to reduce the GHG impact of the beef industry, many studies have been done to understand how to minimize methane production during digestion. So far, two interventions have the most promise: Livestock feed amendments to reduce methane from digestion and selective breeding. Both are still nascent, but if they can be made commercially viable—cost effective, reliable, and without negative health effects for livestock or humans-our analysis suggests it could reduce emissions by between 15 and 75 MMT CO_2e/yr by 2050.[88,89]

Livestock Amendments to Reduce Methane from Digestion

Enhancements to livestock feed have the potential to reduce methane production within the digestive tract. Improved grinding of feed and increased fat content have been shown to reduce emissions in global studies, but the impact in the US is likely small, as feeds are already highly optimized.[90] Recent studies suggest that more innovative levers, such as algae additives, methane inhibitors like 3-NOP[91] or masks to capture methane from belches,[92] could potentially reduce methane emissions by as much as 95%, but these methods will require further investment in R&D.[93]

GHG Selective Breeding

GHG selective breeding is built on the understanding that there are certain genetic traits in cattle and other ruminant animals that lead to higher or lower levels of methane production through enteric fermentation.[94] Studies suggest that some cattle can produce up to 20% less methane based on their genetics, and scientists believe that if breeders select for these traits, in addition to traditional factors size, we could significantly reduce the methane emissions for our future cattle populations.[95,96]

[85] USDA, Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States 2013.

[86] USDA, Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States 2013.

[87] Dennehy 2017.

[88] Note: Feed additive solutions are only considered viable for cattle under intensive management (e.g., receiving feed through feedlots), thus our estimates only apply to that population.

[89] Kataria 2015.

[90] USDA, Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States 2013.

[91] DSM 2019.

[92] Bloomberg 2021.

[93] Roque et al. 2019.

[94] USDA, Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States 2013.

[95] Bell et al. 2010.

[96] Harmsen 2019.

Figure 17 - Summary of Levers Related to On-Farm Machinery and Equipment

Lever	Description	MMT CO_2e reduction (% reduction)		
		CON.	MOD.	OPT.
Zero-emissions on-farm machinery and equipment	Adopting new technologies such as green hydrogen, battery electric, and biofuel-powered farm vehicles and machinery	3 0.5%	3 0.5%	5 0.8%

CON. = CONSERVATIVE SCENARIO MOD. = MODERATE SCENARIO OPT. = OPTIMISTIC SCENARIO

Under the business-as-usual (BAU) scenario, we project that by 2050, farms will emit around 30 MMT CO_2e/yr related to fuel use—primarily diesel fuels and fuel oils consumed in crop and livestock operations.[97] These fuels are used to power trucks, tractors, and heavy machinery for a range of agricultural activities, from tilling to harvesting. We believe the fuel efficiency of diesel-powered vehicles will continue to improve. Therefore, we have built the expected efficiency improvement into the BAU scenario, and do not include it as a separate lever.

In addition to fuel efficiency, there is considerable potential for further fuel use emissions reductions, driven by the use of new technologies such as green hydrogen, battery-electric systems, and biofuel to power farm vehicles and machinery. Given the lack of consensus on the value of biofuels and their underlying emissions reduction potential,[98] this lever includes only green hydrogen and battery-powered farm vehicles and machinery, with a focus on hydrogen, given the limitation of batteries to produce the power required for larger-farm equipment and machinery.[99] While still nascent, these technologies hold significant promise, and large equipment manufacturers are rapidly scaling investments and developing commercial proof of concepts for both, with the expectation that they will dominate the market by 2050.

We estimate an additional 3 to 5 MMT reduction in CO_2e emissions from the adoption of these technologies by 2050. The low range assumes that 30% of annual sales in 2050 will be vehicles and machinery powered by these technologies, based on comparable studies;[100] the high range assumes a 50% share. The higher adoption rate depends on additional technological advances and supportive regulations. Given the approximately 15-year life of farm machinery and equipment, however, there will likely be a significant lag in actual emissions reductions while the installed base of legacy equipment is replaced.

[97] USDA, Trends in US Agriculture's Consumption and Production of Energy: Renewable Power, Shale Energy, and Cellulosic Biomass 2016.

[98] Lark, Hendricks, et al. 2021.

[99] Searchinger et al. 2019.

[100] Bloomberg 2021.

Figure 18 - Summary of Levers Related to Consumption

Action	Lever	Description	MMT CO_2e reduction (% reduction)		
			CON.	MOD.	OPT.
Changes to what and how we consume	Reduce food loss and waste	Reducing food loss and waste, primarily at the consumer and retailer stages of the value chain	-	35 5.2%	45 6.6%
	Dietary change toward lower-GHG proteins	Shifting diets to less-GHG-intensive proteins and alternative proteins from conventional proteins like beef and dairy products	-	35 5.4%	70 10.6%

CON. = CONSERVATIVE SCENARIO MOD. = MODERATE SCENARIO OPT. = OPTIMISTIC SCENARIO

Up to this point, levers have focused on the farm-level practices and technologies that can be adopted to reduce agricultural emissions. Agricultural emissions can also be reduced through changes in the demand for crops and animal-based foods. For this report, we have considered the mitigation potential of reducing food loss and waste, and shifting diets toward less-GHG-intensive proteins[101,102]

Reducing emissions through less food loss and waste

In the US, 35% of food goes unsold or uneaten.[103] According to ReFED, the food that goes to waste annually amounts to around 130 million meals and, critically, represents fully 4% of US GHG emissions.[104] Waste takes place across the food supply chain, with 65% occurring in homes and consumer-facing businesses, and 35% occurring on farms and in manufacturing centers.[105]

With changes in food date labeling (e.g., "use by" labels only appearing on food that poses safety risks) and consumer behavior (e.g., campaigns on the benefits of freezing uneaten foods), there is significant opportunity to reduce food loss and waste, which in turn would reduce the amount of food needed, and thus lower agriculture emissions on farms through lower demand and therefore lower production of food.[106]

We estimate that reducing food loss and waste by between 33% and 50% by 2050, could reduce agricultural emissions by 35 to 45 MMT CO_2e/yr by 2050. This would be driven primarily by a reduction of 50% to 75% in waste from the retail and consumption stages of the food chain, as the challenges related to reducing waste on the farm (from extreme weather events, for example) and in the

[101] For purposes of this report, since our focus is primarily on-farm actions, we present those size estimates unaltered so they can be understood independently of any demand reductions. Our demand reduction figures have been reduced proportionately from what we believe is achievable independent of on-farm actions, so that the two categories can be added together without double counting on-farm reductions for demand that no longer exists. This means that, viewed in isolation, our demand reduction estimates understate the true potential of demand reduction actions on their own.

[102] When calculating demand reductions, we exclude from our baseline those emissions from exports and agriculture production used for nonfood purposes (e.g., energy crops, fibers), given domestic food demand changes cannot influence these emissions.

[103] ReFED, "New Data from ReFED Reveals Amount of Food Waste Has Leveled Off After Increasing 11.9% Since 2010," 2021.

[104] ReFED, Roadmap to 2030: Reducing US Food Waste by 50% and the ReFED Insights Engine 2021.

[105] ReFED, Roadmap to 2030: Reducing US Food Waste by 50% and the ReFED Insights Engine 2021.

[106] ReFED, Roadmap to 2030: Reducing US Food Waste by 50% and the ReFED Insights Engine 2021.

manufacturing process are significant.[107] The conservative scenario anticipates a 50% reduction in waste, assuming that the US would follow a reduction path similar to that achieved by comparable developed countries such as the UK and Japan. The optimistic scenario assumes a 75% reduction in retail and consumer waste, projecting forward to 2050 from the EPA's goal of reducing food waste at the consumer and retail levels by 50% by 2030.[108] These reductions do not account for the additional reduction in emissions that would occur due to decomposing food in landfills, as these emissions are not in scope for the EPA baseline we have adopted.

While targets have been set and progress has been made in other countries, the US has not made significant progress in reducing food loss and waste.[109] Significant private, public, and philanthropic investment in and prioritization of better management of retail waste, educating and changing consumer culture, and promoting food donations will be required to realize these ambitions. Without such efforts, it is hard to envision a path that would lead to substantial reductions in food loss and waste in the United States.

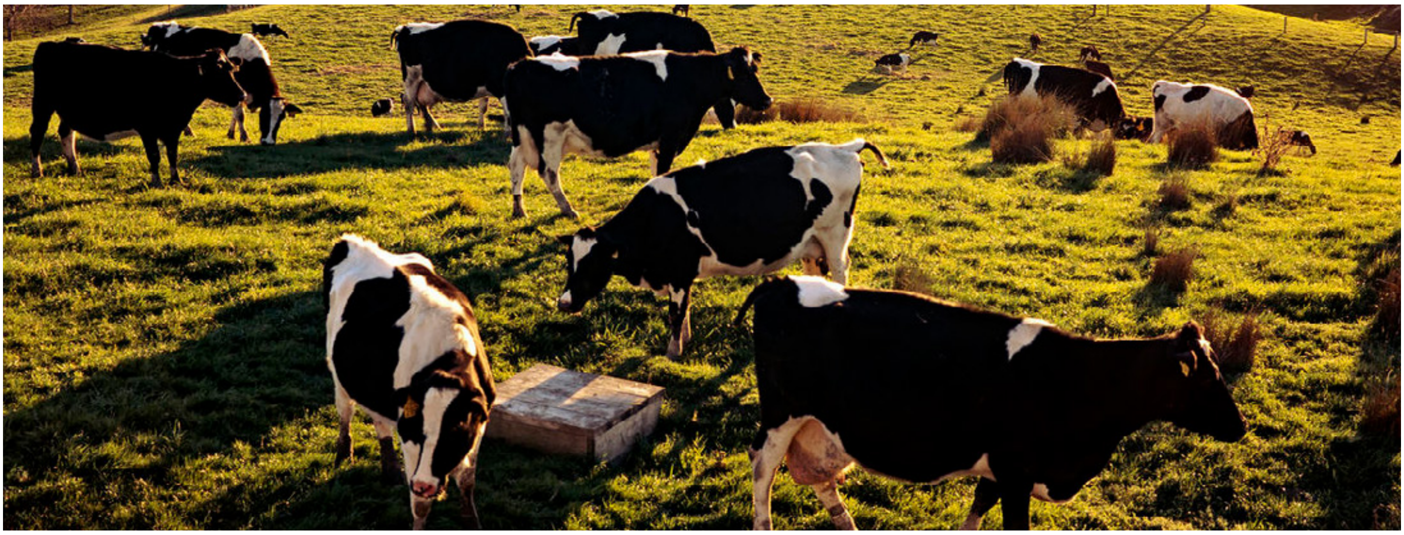
Reducing emissions through shifting to less-GHG-intensive diets

In the past decade, alternative proteins have become a viable alternative to consumers' favorite animal-based protein products. Soon, they will likely match animal protein in taste, texture, and price, and once they do, adoption is expected to increase. The fundamental question about adoption is: how much and how soon? Answers to these questions will give insight into any potential future reductions in agricultural emissions resulting from a future decline in the number of beef and dairy cattle, pigs, and chickens raised annually.

Building on previous BCG analysis (covering a time period through 2035) and projecting this out to 2050, we expect conventional protein demand to fall from business-as-usual levels by between 17% and 40% by 2050, depending on which scenario comes to pass.[110] This would equal a reduction of between 35 and 70 MMT CO_2e/yr in agriculture emissions by 2050, which accounts for the reduction in emissions from livestock and the increased emissions associated with soil management from increased demand for crops. At the low range, this would be promoted by ongoing public concern for sustainability, driving ESG-sensitive capital investment and consumer demand for alternative proteins, leading to continued technological progress to reach parity with animal proteins. At the high range, additional technological step-changes would be required in nascent technologies (e.g., cell-based alternative proteins), and more supportive regulations would need to be in place to further incentivize production.

While our report modelling focuses on shifting from conventional protein to alternative proteins (e.g., plant-based, microorganism-based, and animal-cell based) shifting consumption of high-GHG-intensive meats such as beef to less-GHG-intensive meats such as chicken would also lead to significant emissions reduction benefits.

We recognize that any discussion concerning reductions in the number of cattle, pigs, and chickens raised annually in the United States is a sensitive one. These sectors are the heart of many agriculture communities in the US and if a shift away from conventional protein is to occur as projected above, then this transition needs to be managed with the right level of support for these farmers. See "Ensuring a just transition to sustainable agriculture production," p. 45.



[107] ReFED, Roadmap to 2030: Reducing US Food Waste by 50% and the ReFED Insights Engine 2021.

[108] EPA 2022.

[109] Douglas, "Despite pledge, US still wastes more than a third of its food - EPA," 2021.

[110] BCG 2021.

Figure 19 - Summary of Levers Related to Land Use and Forestry

Lever	Description	MMT CO_2e reduction (% reduction)		
		CON.	MOD.	OPT.
Reforestation	Reforesting historically forested lands	-	20 3%	220 29%
Improved Forest Management	Adopting a variety of practices, including harvest rotation and improved fire management	-	20 3%	125 16%
Avoid Grassland Conversion	Avoiding conversion of grassland and shrubland to cropland	-	25 3%	105 14%
Conserve/ Restore Peatlands, Wetlands	Connecting salt marshes and mangroves with the sea, and rewetting drained peatlands and replanting vegetation	-	2 0.5%	10 2%

CON. = CONSERVATIVE SCENARIO   MOD. = MODERATE SCENARIO   OPT. = OPTIMISTIC SCENARIO

The decisions we make about how land is used in the US will be critical to our ability to reach our net-zero goals. The capacity of the country's forests, grasslands, and wetlands to sequester carbon is essential to this effort. By devoting more of our land to sequestration and improving the management of existing land, we can make real progress toward our goals.

The importance of LULUCF carbon sequestration cannot be understated. Multiple studies illustrate that most additional sequestration can be achieved at <$50 per ton of CO_2e.[111,112,113] We can go a long way to achieving optimistic adoption of these LULUCF levers by solving three large obstacles: improving the economics (for example, through defining a market price for carbon or through the development of a carbon offset market that will pay farmers to implement these levers), addressing the implementation challenges (including constraints on the availability of the forestry workforce and seedling production capacity), and recognizing the cultural impediments (such as a farmers' familiarity with forestry, ability to integrate forests into their operations and how forests align with their identity).

Reforestation

The single largest lever for increasing LULUCF carbon sink capacity in the US is the reforestation of previously forested lands.[114,115] However, despite strong public and bipartisan political support for reforestation initiatives, the weighting of reforestation as a critical climate change solution is the subject of much debate. While the World

[111]Cook-Patton, Gopalakrishna and Daigneault et al. 2020.

[112]Van Winkle, et al. 2017.

[113]Fargione et al. 2018.

[114]Fargione et al. 2018.

[115]The White House 2016.

Economic Forum's One Trillion Trees initiative continues to gain momentum,[116] many scientists have warned against viewing reforestation as a silver bullet for mitigating climate change.[117]

In this report, we refer to reforestation as the conversion of some historically forested lands back to forests.[118] Several studies have comprehensively surveyed feasible areas for reforestation[119,120,121] and we have primarily leveraged Cook-Patton et al.'s estimates for reforestation in this report.[122] These opportunity areas are primarily in private pasture, floodplain, and shrubland. At optimistic levels of reforestation, ~26 Mha of pasture would be reforested, which represents 13% of all pastureland in the United States.[123] In order for this to happen without implications for food production, this would require some reductions in demand for conventional protein (e.g., beef, dairy) or reduction in waste associated with livestock, in line with the assumptions made in our diet and waste change levers.

Adopting this lever could lead to between 20 and 220 MMT CO_2e in additional forest carbon sequestration annually by 2050.[124] The large range in estimates reflects the willingness of private landowners to reforest their land, and the range of the potential costs involved. Furthermore, the full realization of this lever would require careful program design and management to ensure that the sequestration gains remain permanent and additional deforestation does not occur in the United States, or other countries.[125]

Improved forest management

Improving forest management practices offers further gains in carbon sequestration.[126] The term encompasses a variety of practices, including fire reduction management, denser tree planting, and managing harvest rotation periods. The US Mid-Century Strategy for Deep Decarbonization notes that there are significant discrepancies in the very few assessments of the practice that attempt to quantify the size of the opportunity. The Mid-Century Strategy notes that most studies estimate its mitigation potential to be significantly lower than that of reforestation; others, however, argue that its potential could be more than double reforestation's potential.[127]

Estimates for the impact of improved forest management practices vary significantly in published studies, but could lead to between 25 and 125 MMT CO_2e/yr in additional forest carbon sequestration by 2050.[128,129] As with reforestation, government support and careful program design and management will be needed to realize the full sequestration potential of improved forest management, and to ensure minimal leakage due to disturbances that inadvertently release GHGs from forests, for example.

Avoided grassland conversion

Fully 85% of new cropland in the US is converted from grassland and shrubland, resulting in an estimated rate of grassland loss of 1.7 million acres/yr.[130] By conserving belowground soil carbon stocks, slowing grassland conversion offers a real opportunity to both avoid increased agricultural emissions and increase soil carbon sequestration.[131] While there is some debate about future cropland use in the United States, FAO projects a decrease in cropland in North America of 7.1 million acres by 2028.[132] Given this projected decrease in cropland, it is unlikely that additional grassland will be needed for cropland conversion through 2050, which would provide

[116] One Trillion Trees 2022.

[117] Brancalion and Holl 2020.

[118] We exclude "afforestation" – defined by the IPCC as "planting of new forests on lands which, historically, have not contained forests."

[119] Van Winkle, et al. 2017.

[120] One Earth 2020.

[121] The White House 2016.

[122] Cook-Patton, Gopalakrishna and Daigneault et al. 2020.

[123] Cook-Patton, Gopalakrishna and Daigneault et al. 2020.

[124] Cook-Patton, Gopalakrishna and Daigneault et al. 2020.

[125] Brancalion and Holl 2020.

[126] The White House 2016.

[127] The White House 2016.

[128] Sohngen and Brown 2008.

[129] Latta, Adams and White 2011.

[130] Lark, Salmon and Gibbs, Cropland expansion outpaces agricultural and biofuel policies in the United States 2015.

[131] Gurgel, Reilly and Blanc 2021.

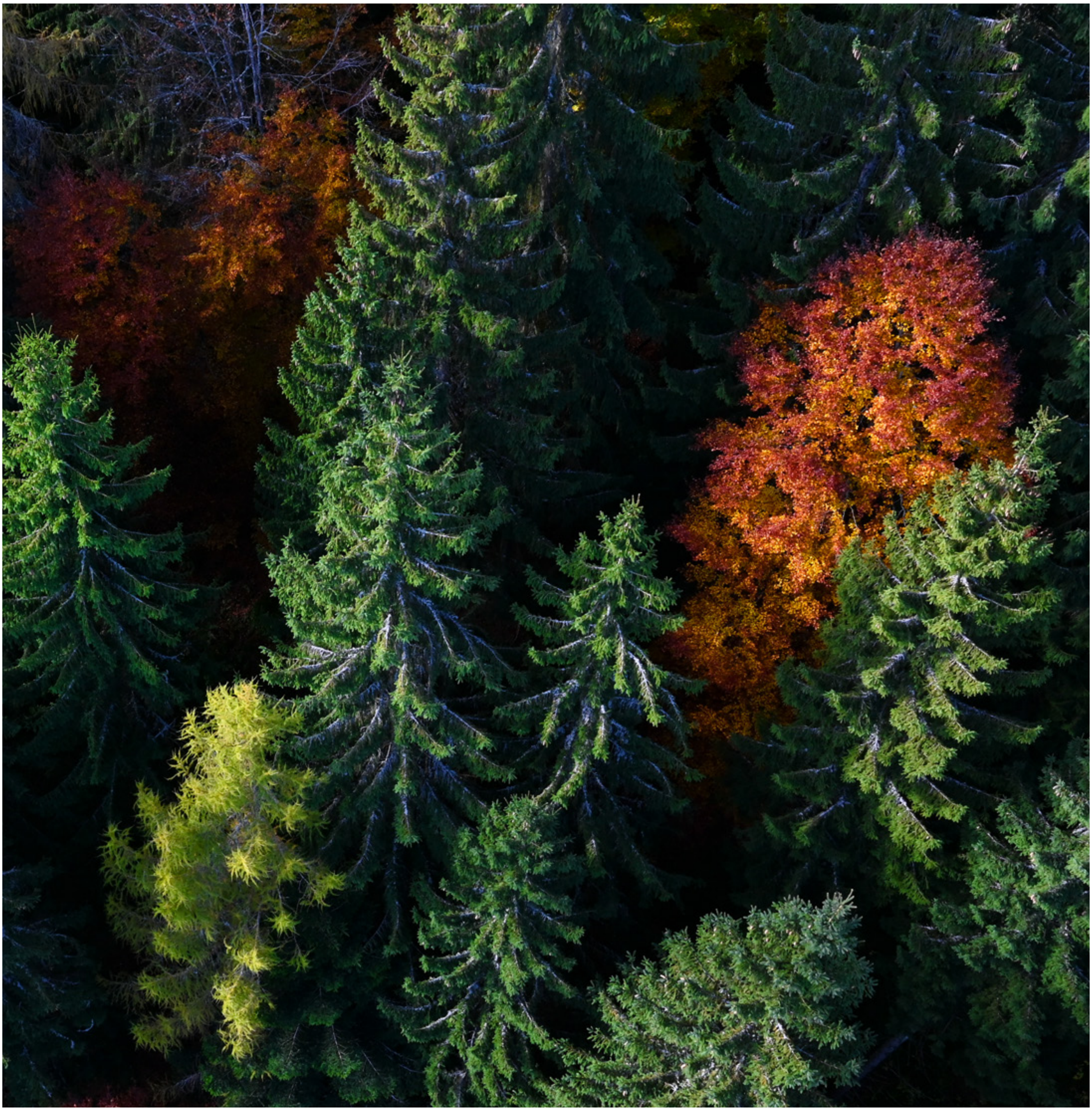
[132] Fargione et al. 2018.

additional sequestration benefits from avoided conversion of between 25 and 105 MMT CO_2e/yr by 2050.

However, several scenarios may make it difficult to realize this full benefit. For example, if there is a significant increase in demand for biofuels, and therefore cropland, avoiding grassland conversion would be difficult. While we have not modelled this for this report, it is important to recognize the interdependences related to this lever.

Restored wetlands and peatlands

Lastly, wetland and peatland restoration involves the effort to restore former or degraded wetlands and peatlands to their original functions. Tidal wetland restoration involves reconnecting salt marshes and mangroves with the sea, thereby improving their salinity and reducing their methane emissions. Peatland restoration involves rewetting drained peatlands and replanting vegetation. The mitigation potential for these practices is between 2 and 12 MMT CO_2e by 2050-up to 7 MMT from peatland restoration and up to 5 MMT from wetland restoration.[133]



[133]Fargione et al. 2018.

Frontier technologies & practices

Our optimistic scenario estimates of a reduction in agriculture-related emissions of between 10% and 57% in the US by 2050 are built on the quantitative assessment of our 24 levers. These levers include a mix of mature technologies as well as technologies still nascent or under development but likely to scale in the next 10 to 15 years.

Beyond those more developed solutions, there are a number of technologies and practices that hold promise but are still in the very earliest R&D stages, and thus hard to predict how they will evolve. These "frontier technologies" include:

- Alternative biofuels, such as kelp, that can be processed for their oil more efficiently than crops like corn, and without the associated land use, fresh water for irrigation, or fertilizers.[134]
- Innovations in genetics that would enable crops to sequester more carbon or take up nutrients like nitrogen more efficiently.[135]
- Integration of solar and crop farming to both power operations on the farm with renewable energy and to provide supplemental income when excess energy is sold back to the grid.[136]
- While not explicitly sized for their impact in this report, these frontier technologies will be critical if we are to achieve greater agricultural emissions reductions than even the 57% anticipated in our optimistic scenario.

[134]Project Drawdown 2017.

[135]Innovature 2020.

[136]Metsolar 2021.

What it will take

"A concerted and coordinated effort is needed to realize these ambitious emissions reductions."

Achieving a nearly 60% reduction in US agriculture and land-use emissions by 2050 is possible. To get there, however, a number of barriers must be addressed in the near term. The process of scaling up each of our 24 levers faces its own set of obstacles, and these obstacles generally fall into four categories: farm economics; technology maturity and expertise; operational constraints; and cultural considerations (Figure 20). The following section outlines the coordinated action across stakeholders needed to overcome these barriers, beginning with a general perspective on overall costs, since economics stands to be the most difficult barrier to overcome today.

Figure 20 - Achieving Optimistic Scenario Hinges on Overcoming Several Barriers to Drive Farm Adoption

We see four common types of barriers to adoption of these practices and technologies—key actors can target actions to overcome these barriers

Farm barriers to adoption		Illustrative example	Potential mitigating actions
Farm Economics	Upfront CAPEX; net economics to implement; policies and incentive structures	Cover crops, especially those that do not yield a marketable product, require seed investment and labor that may not be profitable in near term	• Government re-alignment of incentives to promote adoption of regenerative practices • Private sector commitments and support (including financing) for suppliers to manage risks of adoption
Technology Maturity	Technology maturity; scientific and real world validation of efficacy	Methane-reducing feed additives (e.g., red seaweed) are still relatively nascent; additional investment may be needed to commercialize and bring costs down.	• Private sector investment to bring down costs and create a viable market for known solutions • Public and nonprofit investment to fund academic research on frontier technologies
Operational Considerations	Changes to long-standing/ well-known practices; additional requirements	Agroforestry practices like alley-cropping require a fundamental shift in farm operations, pivoting from single commodity business to multi-crop system	• Expand government support programs (e.g., agriculture extension) to assist in overcoming implementation challenges
Cultural Context	Commonly held beliefs; risk aversion	Concerns about reducing yields may lead to reluctance to try practices & technologies that optimize N fertilizer application rates.	• Private sector advancement of innovative business models to promote soil health and emissions reduction vs. pure volume sales model

Calls to action

A concerted and coordinated effort is needed from three key stakeholder groups—the public sector, nonprofits and philanthropists, and the private sector (including corporations, producers, and consumers)—to create the conditions under which we can realize the ambitious on-farm emission reductions called for, and make concerted efforts to support conservation and reforestation necessary to increase how much carbon is sequestered in forests and on agricultural land.

There are three sets of actions we believe are most critical in achieving the optimistic scenario (Figure 21):

- Support producers to transition to climate-smart practices
- Foster opportunities to capture value from climate-smart practices and technologies
- Invest in innovation and scaling of key technologies and practices

Figure 21 - Realizing a Better Path: Three Sets of Actions to Unlock the Optimistic Path to 2050

Support producers to transition to climate-smart practices

- Provide technical & on-the-ground support to overcome knowledge, operational & cultural challenges
- Provide economic/financial incentives and support for transition or to overcome unfavorable economics
- Engage farmers as part of the solutioning (e.g., in R&D, in pilots & program design)

Foster opportunities to capture value from climate-smart practices and technologies

- Align ambition and strategic agenda with sustainability goals to capitalize on new value
- Develop & optimize markets systems and incentive structures to promote sustainable practices
- Strengthen financial tools that create value for ecosystem services

Invest in innovation and scaling of key technologies and practices

- Invest in R&D to drive breakthrough innovations and accelerate commercial scale of key technologies
- Fund basic and applied research to validate critical unknowns in the science
- Improve data collection & measurement to enable sustainability claims (e.g., carbon measurement, traceability)

Each stakeholder group" has a different but equally has a different but equally critical role to play in creating the enabling conditions needed to overcome current barriers and spur widespread adoption.

Public Sector: Governments (both executive and legislative at all levels) will play an especially critical role in establishing the enabling conditions for adopting sustainable agriculture practices. They must do so by stepping in to overcome barriers using various forms of policy and regulation, both one-time measures like the Inflation Reduction Act of 2022, as well as more recurring vehicles such as the Farm Bill, where and when it is financially unattractive for the private sector to do so—a condition that many emissions-reduction levers face, to varying degrees. One major intervention the federal government can consider is the redesign of current programs that have significant influence on farm economics, such as the federal crop insurance program, with the goal of making sure that outcomes are positive for producers, the food system, and the environment. Just as importantly, governments should endeavor for policy measures to support fair and just transitions, especially for vulnerable groups.

Philanthropic & Nonprofit Sector: Like the public sector, the nonprofit and philanthropic community can play an important role by supporting efforts that may not be economically attractive. They can also be helpful in addressing barriers where government lacks resources and the private sector is less well-equipped or willing, such as developing on-the-ground partnerships with local NGOs and funding research into new innovations. Further, they can step in to represent the interests of stakeholders such as low-income communities and small-holder producers who may be negatively impacted by change but have little or no political or economic voice in the matter.

Private Sector: Companies across the food and agriculture value chain have a critical role to play in accelerating the transition to a sustainable food, fuel, and fiber system by 2050. For example, food & agriculture companies can continue to set ambitious science-based emissions reduction targets and work to reduce both their own Scope 1 and 2 emissions as well as partner with their suppliers and customers to reduce Scope 3 emissions.

Agriculture companies can invest in digital technologies and explore ways to move towards business models that reward sustainable outcomes vs. volume of sales. Food manufacturers and retailers can innovate and promote more sustainable products while designing programs that support and reward their suppliers for more sustainable practices. And investors can look for (and create) opportunities to provide capital to projects and companies working towards more sustainable outcomes.

Producers: Farmers and ranchers may find it challenging to adopt more sustainable practices and technologies for a variety of economic and non-economic reasons. However, they can still look to take advantage of opportunities to learn about the costs and benefits of moving to more sustainable practices and look to take a longer-term view on the economics. Farmers and ranchers who have successfully transitioned to more climate smart agriculture should look to share their learnings with the broader community. Alignment and support from landowners, who lease to producers ~40% of the farmed land in the US, is especially critical to ensure that the producers who farm their land are able to equip it for future resilience.[137]

Individual Consumers: While a significant driving force of adoption will stem from public, private, and philanthropic/nonprofit players, individuals have an especially important role to play in using their collective political and economic power to influence other stakeholders to pursue the actions outlined above. Specifically, they can demand that industry players provide transparency into the emissions of agricultural products and use that information to buy and consumer more sustainable products, minimize the amount of food they waste, and work with nonprofits and vote to shape change locally.

[137]EPA, Farmland Ownership and Tenure 2014.

Figure 22 - Four Phases of Innovation to Achieve the 2050 Optimistic Scenario

The 24 levers that must be pulled to achieve the 2050 optimistic scenario are at varying stages of development

Mature (39% of 2050 optimistic reduction goal)

These technologies and techniques are scalable today, but face significant economic, operational, and cultural barriers.

Example: Cover cropping, reduced nitrogen application

Developing (20%)

These proven technologies and techniques require additional scientific research to ensure value and further innovation to make them economically viable.

Example: Biochar, improved manure storage & handling

Nascent (41%)

While promising, these technologies are still in the trial phase and not ready to scale up in the near term. Significant additional R&D investment will be required to bring them to market.

Example: Zero-emissions farm equipment

Frontier (not included in optimistic reduction scenario)

This category includes breakthrough technologies that do not yet have a clear path to scale, but are urgently needed to reduce agricultural emissions.

Example: Innovations in fertilizer and crop genetics to reduce N_2O

Achieving breakthroughs in the development of nascent technologies is critical if we are to reach the 2050 goals

Nascent tech	Evolution by 2050
Innovations in the reduction of enteric fermentation	• **Today:** Significant research is being conducted into a range of technologies, notably algae-based feed additives and selective breeding, but their current value lacks a consensus on their scientific validity. • **Vision for 2050:** Widespread adoption on dairy farms and feedlots of feed additives that drastically cut methane inexpensively; the majority of pasture-grazed cattle bred to produce less methane during enteric fermentation.
Alternative proteins	• **Today:** Growing range of plant-based products have come to market, but they still generally lack price, taste, and texture parity with animal-based proteins. • **Vision for 2050:** Innovation in microorganism- and animal cell-based proteins enable the production of products indistinguishable from animal meat and dairy products.
Zero-emissions farm equipment	• **Today:** Manufacturers are experimenting with alternatives such as extension plug-in, but adequate battery storage technologies remain elusive and ethanol biofuel is not meaningfully more and ethanol biofuel is not meaningfully more sustainable than the fossil fuels used today. • **Vision for 2050:** Equipment has largely shifted away from dependence on fossil fuels, relying primarily on alternatives such as green hydrogen and sustainable biofuels, such as fuels derived from kelp; hybrid farm vehicles and equipment likely, but fully electric vehicles will remain a small share of the market.

Ensuring a just transition to sustainable agriculture production

Just as the livelihoods of coal miners in the United States have been and will continue to be affected by the transition to a renewable energy economy, so too will the livelihoods of farmers and ranchers be transformed by the coming changes in the food we grow and how we grow it. The need to reduce the US agriculture sector's GHG emissions must be balanced with the potential benefits, while sustaining and improving the lives of those who grow our food. Doing so will help ensure a just and equitable transition for those who grow our food, while solidifying public approval for the need for action on agriculture's contribution to mitigating global warming.

We are already seeing some of the ramifications of these transformations. According to the USDA, the number of dairy farms in the US is down by half since 2003. This is driven in part by the ongoing shift away from dairy products, and especially cow's milk. This has negatively impacted some dairy workers and rural communities.

While the world is still working to define what exactly a "just transition" means, a few priorities and principles have emerged, including:

- Ensure that the benefits of the transformation are distributed equitably across the sector.
- Implement local economic development tools for affected communities.
- Provide income support for farmers and ranchers during the transition.
- Deliver education and training that provides new career opportunities for those affected.
- Involve farmers and their communities in all plans to mitigate the impact of the agriculture transformation.

This report does not take a position on specific policies that should be enacted. We do, however, believe strongly that ensuring a just transition for all affected must be a critical component of a successful transition to a less GHG-intensive agriculture sector.

What it will cost

Approach to estimating costs

No obstacle to reducing US agriculture's GHG emissions and boosting LULUCF sequestration is more important than the economics involved. This remains an obstacle, in large part because for an individual farmer or land owner, the costs of adopting many of these levers outweigh the benefits—and in many cases, are projected to remain that way even in 20-30 years, when accounting for expected technological advances and cost improvements (in other words, the marginal cost of abatement for most of these levers is expected to still be a positive number).

Figure 23 - Examples of Costs and Benefits

Costs of adopting agriculture and land-use levers include…	Basic scientific research costs to develop greater understanding of climate-smart agricultural practices • Example: Research into the yield benefits of cover cropping
	Commercial research and development costs to bring ideas to commercial scale • Example: Research into GHG-focused genetic selection and breeding of cattle
	On-farm costs to adopt climate-smart practices on farm • Example: Cost of purchasing anaerobic digesters
	Other costs • Examples: Government program and transaction costs; higher costs to consumers
Benefits of adopting agriculture and land-use levers include…	**Commercial revenue** from selling new products • Example: New revenue for companies selling zero-emission on-farm machinery and equipment
	On-farm benefits from increased farming revenue or cost savings • Example: Savings on fertilizer from better timing of its usage
	Other benefits • Examples: Environmental benefits of lower GHG emissions

FOCUS OF THIS SECTION

In this report, we have chosen to focus our analysis on the net economic costs and benefits of adopting on-farm practices and technologies. This represents farmers' potential economic costs and benefits when adopting new practices or investing in new technologies. If it is a net cost then the return on investment does not make sense for a farm, and the practice will not be adopted. We have chosen to only cost levers related to changes to how we grow crops (e.g., cover cropping) and livestock (e.g., GHG-focused genetic selection and breeding) and how we use our land (e.g., reforestation) given the wide range of available literature (e.g., from the USDA) on the marginal abatement costs of these practices. But we have not projected costs related to the consumption levers, because these costs—and their benefits—are distributed across multiple stakeholders, and the number of studies that have explored these costs in depth is limited.

To conduct this analysis, we have examined the on-farm economics of each lever, primarily based on USDA's analysis of marginal abatement costs for each of these practices,[138] and supplementary literature and analysis where needed. It is important to recognize that each lever is not the same, and the economics of each lever varies depending on the underlying differences in the maturity of the technology required and the types of practices involved:

1. Assuming adequate industry investment and government support, some levers could realize net benefits to farmers.
   - Zero-emission on-farm machinery and equipment, for example, will require significant upfront costs (both R&D and capital investments by farmers who buy them) as well as ongoing maintenance costs, but will generate cost savings for farmers in the form of lower fuel costs.

2. At current prices, however, most levers would result in a net cost to farmers, due to unfavorable economics (i.e. costs greater than \$50/ton of CO_2e avoided/ sequestered).
   - New kinds of fertilizers used by farmers, for example, carry no material upfront costs, but there are ongoing costs to purchase nitrogen inhibitors, and they bring no material economic benefits to farmers compared with traditional fertilizers.

It is important to recognize that this analysis of on-farm economics costs and benefits does not provide a comprehensive view of all the costs and benefits that would be involved in these decisions. For example, additional R&D spending would need to be made. The Breakthrough Institute estimates that increasing US agriculture research spending by ~\$40B over 10 years could prevent 154 MMT CO_2e/yr by 2050 (although this represents global emissions reductions as the benefits of additional US R&D are dispersed across countries).[139] Furthermore, a host of social benefits would be realized that are not accounted for. If one takes the current administration's ~\$50 per ton estimates on the social cost of carbon,[140] implementing all 700 MMT CO_2e of reductions and additional sequestration from all levers (excl. demand) would create \$35 billion in annual social benefits by 2050.

What it will cost

How we grow: In the optimistic scenario, considering the caveats above, we estimate that adopting all levers related to how we grow crops and livestock would reduce agriculture emissions by 35%, at a net cost of \$65 billion over 30 years: approximately \$200 billion to \$250 billion in on-farm costs offset by \$150 billion to \$200 billion in on-farm benefits. A substantial portion of the cost would need to be spent in upfront years, and the benefits gained over time. As noted above, we assume separate non-farm investments (e.g., commercial R&D) are being made to bring many of these technologies to scale, and this net cost estimate does not account for those cost.

Importantly, almost all the levers, other than a few that currently require the development of still-nascent technologies, can be implemented within our optimistic scenarios for ~\$50 per ton of CO_2e or less.[141]

How we use our land: Under the optimistic scenario, if all the levers related to how we use our land were adopted, LULUCF sequestration would increase by 60% by 2050, for a net cost to landowners of \$350 billion over 30 years. This net cost would entail primarily upfront costs; however, there would be some opportunity for landowners to harvest timber.

As with the production levers, all of the land-use levers would achieve of emission reductions per the optimistic scenario at abatement costs of less than ~\$50 per ton of CO_2e.

[138] USDA, Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States 2013.

[139] Trambley 2021.

[140] Eilperin and Dennis 2021.

[141] In our modeling, we have adjusted this price of carbon for inflation to today's dollars for studies that are more than 5-10 years old.

Mechanisms for closing the farm-level economic gap

The bottom line is that while these levers can be achieved at surprisingly low costs relative to the benefits to society that would be created, adopting these new practices and technologies in aggregate will not be net economically beneficial to farmers. This means that for adoption of these practices to take place, one or a combination of things would need to happen to overcome the economic barriers:

- Government intervenes directly, e.g., via direct subsidies and tax credits, and voluntary or mandatory carbon prices.
- Industry players pay farmers, directly or indirectly, for ecosystem services including emissions reduction or carbon sequestration in the form of carbon offsets or insets.
- The agricultural supply chain establishes price premiums for low-emission products, and proceeds are used to compensate farmers for the expense of emissions reductions.
- Farmers/ranchers accept (without other compensation listed above) some reduction in farm-level profit margins.

Achieving the optimistic scenario—that is, reducing agriculture emissions (excluding any reduction due to changes in consumption) by ~235 MMT CO_2e annually in 2050—would cost approximately $65B across the next ~30 years. To put this figure into perspective, this represents:

- $2 billion per year, or 40% of the $5 billion we currently spend annually on government agriculture conservation projects[142]
- ~1% of the projected global spending on carbon offsets annually by 2050[143]
- ~1% increase in the price of agriculture products by 2050[144]

While this report does not take a position on who pays for this and through what mechanisms, it is critically important to recognize that without the actions on the part of government, industry, and consumers described above, the agriculture sector will not materially reduce its GHG emissions by 2050.

[142] USDA, Budget Summary 2022.

[143] Watson 2020.

[144] USDA, 2022 Farm Sector Income Forecast 2022.

Beyond emissions

"The benefits of the 24 levers extend far beyond their contribution to reducing emissions."

The primary focus of this report is to quantify the potential GHG emissions reduction possible in the US over the next three decades and describe what it will take to achieve those reductions. The benefits of the 24 levers, however, extend far beyond their contribution to reducing emissions, and in some cases may be an even bigger driving force of adoption. For instance, climate adaptation and resiliency benefits such as improvements in water management (e.g., storm protection) or soil ecosystems (e.g., erosion control) are likely to spur adoption of many conservation practices where the worst ecological outcomes are expected.[145]

[145]Fargione et al. 2018.

Infusing resiliency into the US agriculture system

According to the IPCC, negative climate impacts caused by man-made emissions to date are irreversible in the near term, therefore over the next 20 years we must expect and prepare for an increasing quantity and intensity of ecosystem strains such as drought and extreme heat in some regions to excessive precipitation in others.[146] Such strains have already started to take a toll on the US agriculture and land use sectors, which are especially reliant on predictable climate conditions (precipitation, temperature etc.). For example, projections for the southwestern US indicate it may experience frequent shortages in precipitation, increasing the risk of drought.[147]

Unless we can instill more resilience into the agriculture production system, the expected declines in yield will likely cost society billions by driving both food prices and crop insurance pay-outs up. A recent study found that between 1995 and 2020, insurance payments to farmers due to flooding and drought rose 300% and 400%, respectively,[148] and according to the USDA the overall cost of insuring crops could increase as much as 37% by 2080 if farmers don't adapt their practices for climate change impacts.[149]

Adopting the conservation practices and regenerative agriculture systems discussed in this report, such as cover cropping and silvopasture, can act as a cost-effective risk management strategy for many US farms and ranches. Many of these practices have resiliency benefits in addition to sequestering carbon. For instance, conservation practices like cover cropping or reduced/no-till farming can reduce erosion of topsoil and improve soil's capacity to retain water, reducing demand for water for irrigation in drought-prone regions.[150,151] Some of these practices, such as alley-cropping, can also diversify farm production, increasing revenue streams, and lowering the financial risk of crop failure.

Improved resiliency will also benefit society at large. For example, lower water usage means less competition with the agriculture sector for water in drought-prone regions and strategically planted and trees and increased water-holding capacity of soils means more protection from natural disasters such as mudslides and floods.[152] Further, overall resiliency means a more secure food supply and more stable prices.[153]

Additional benefits for producers and society

Additional economic and ecological benefits include the ability to grow more food on less land through technologies such as precision fertilization, maintaining productivity without the need to convert more land to agricultural purposes.[154] Improved farm yields, and their potential associated revenue increases, also have trickle-down benefits for the broader economy in the form of increased spending and tax revenues.[155,156] Beyond the farm, benefits can extend into the broader communities by way of air and water quality improvements, including reductions in the odor and pollution from manure lagoons and in the amount of less nitrogen and herbicides leaching into waterways.[157]

Potential risks to mitigate as levers scale

It is also important to acknowledge, however, that in some cases the levers pose risks. Examples could include increased food prices due to the higher prices of sustainably produced inputs, temporary supply shortages as farms adapt to new practices that could impact short-term yield, and air pollution from anaerobic digesters near communities. It is especially important to consider that the implementation of new farming practices and technologies could result in the uneven distribution of benefits to stakeholders. Without careful intervention, the most vulnerable could suffer the brunt of the costs, both economic and societal. However, many of these risks can be partially mitigated with the right programs and policies in place, as discussed in the following section.

[146] IPCC, AR6 2022.

[147] National Integrated Drought Information System n.d.

[148] Sixty percent of which was government funded.

[149] Crane-Droesch, et al. 2019.

[150] EPA 2018.

[151] EPA 2018.

[152] Fargione et al. 2018.

[153] Fargione et al. 2018.

[154] USDA, Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States 2013.

[155] Soil Health Institute n.d.

[156] Waite 2020.

[157] Fargione et al. 2018.

Conclusion

The common perception is that the US agriculture sector will be unable to significantly reduce the 11% of the country's annual GHG emissions for which it is directly responsible. But we believe strongly that it can—and indeed must—do so, while reforming the country's overall land use policies at the same time. Our goal in this report has been to provide a realistic estimate of both the considerable challenges involved in abating US agriculture sector's GHG emissions to the extent possible and a realistic pathway to getting there.

The degree to which we are able—and willing—to pull some or all of the 24 levers described above will largely determine the agriculture sector's contribution to mitigating global warming. The combination of levers that leads to the most conservative abatement scenario offers GHG reductions of almost 10% above current levels; the most optimistic scenario provides reductions of more than 50%.

Achieving the optimistic scenario will be challenging, given the very ambitious combination of levers that need to be pulled. Yet we believe strongly that it should remain the goal of all stakeholders in the US agriculture sector. We may not be able to reach it, but the closer we come, the greater the sector's contribution to the country's overall effort to reduce its carbon footprint, slow the effects of climate change, and build greater adaptation and resiliency for our agri-food systems and our communities.

Appendix 1 - Methodologies

General note on methodology

This report was produced by synthesizing scientific reporting around GHG emissions and mitigation within the agriculture and land use sectors. It relies on data and reports published by official US government sources (e.g., EPA, USDA) and is supplemented with scientific literature and expert interviews. Since the report drew from multiple sources and methodologies, we emphasized a clear, consistent approach to synthesizing inputs in ways that would enable comparison of the relative impact of one lever over another, and a clear understanding of the size of the potential for that lever to reduce GHG emissions.

There are inherent challenges with any GHG emissions projections for agriculture and land use practices because measurement is exceedingly difficult. Carbon dioxide, nitrous oxide, and methane interactions within soil systems are highly complex and still not fully understood, thus accurately quantifying them at scale is an imperfect science at present. For instance, nitrogen levels in soils can fluctuate minute to minute based on external factors such as water, temperature, vegetation etc. so it is difficult to estimate the precise emissions at an aggregated, national level.[158] Therefore, the baseline and emissions reduction projections in this report are likely directionally correct but could be specifically wrong in some cases. Considering that, this report evaluates three potential future scenarios ranging conservative to optimistic, with one distinguishing factor between them (among others) being uncertainty around emissions factors.

Baseline & business-as-usual (BAU) scenario

In developing this report, we used the EPA emissions inventory as our baseline.[159] While there are several issues and critiques of this inventory,[160,161] it represents the best comprehensive baseline available and is the baseline that US commitments are made on.

To evaluate GHG mitigation levers within the agriculture and land use sectors, we first established a BAU scenario, projected from today's baseline through to 2050. This report uses the USDA Integrated Projections from 2015 to 2060 baseline scenario as the primary source for growth rate projections used in our BAU scenario.[162] The USDA baseline projections evaluate two key variables to estimate future emissions: 1) population and export growth to serve as a proxy for demand across commodities and 2) productivity increases in commodity production. For the purposes of this report, we did not include the effects from the "Building Blocks" initiatives that the USDA Integrated Projections cite, to avoid any double counting with the levers. Together these factors simulate the total estimated amount of production required by commodity, from which associated emissions are assigned.[163]

The USDA projections focus on the three main categories of agriculture emissions (Soil Management, Enteric Fermentation, and Manure Management), and we drew from additional sources and assumptions to project the other categories (e.g., FAOSTAT and other sources as noted in footnotes throughout the report).

For our analysis, we adopted the same growth rates used in by USDA's 2060 reference scenario (as published in 2016, but we have applied them to the average of the most recent five years of GHG inventory actual emissions to account for any recent trends). USDA projections did not explicitly model expected changes in on-farm fuel use, our baseline assumes continued improvement in fuel efficiency enables a ~1% decline in fuel-related emissions annually. This assumption was based on historical on-farm fuel use emissions reductions between 2014-2019 and forecasts by the USDA for future renewable energy trends.[164]

Mitigation levers

This report evaluated 24 levers that have been examined through published scientific review. No attempt has been made to quantify certain frontier/experimental technologies and techniques that are likely to develop over the next 30 years and may have significant contributions to GHG mitigation (e.g., enhanced weathering, kelp biofuels). Each of the 24 levers was sized based on 1-2 anchor sources that focused on the US context, prioritizing the most recent and most cited where possible. Each lever was sized independently, using similar logic to isolate three key drivers from the underlying source reports:

[158] Paustian, et al. 2016.

[159] EPA 2022.

[160] Hayek and Miller 2021.

[161] Rosenberg and Lehner 2022.

[162] USDA Integrated Projections report because it uses the same methodology as the USDA GHG Inventory estimates.

[163] The USDA Integrated Projections report does not assume any changes in emissions intensity by commodity.

[164] Schultz, et al. 2021, Congressional Research Service 2021.

Technical Threshold: This represents the total addressable base in the US where the lever is technically feasible and not cost-prohibitive by 2050 (e.g., <$100t CO_2e), based on cited figures in anchor scientific reports and vetted with experts.

Producer Adoption Potential: Evaluated by assessing current share of technical threshold met and using several data points to quantify the low and high range for potential incremental adoption by producers in 2050. The primary factor to estimate adoption was understanding current barriers to scale, which tend to fall into four broad categories; Farm Economics (e.g., CAPEX net profit, timeline to realize gains), Technology Maturity & Expertise (e.g., tech scalability timeline, scientific consensus, farm-level technical knowledge/capacity), Operational Requirements (e.g., fundamental changes to processes) and Cultural Contexts (e.g., risk aversion, pervasive community opinions). Each lever was evaluated across the four barrier categories and assigned a Low, Moderate, or High assessment, based on the degree of difficulty to overcome it. A secondary factor influencing adoption assumptions was the broader societal co-benefits and risks associated with the lever beyond GHG mitigation (e.g., adaptation and resiliency) that are likely to also have influence on how much scale certain practices can achieve. An adoption assumption range was then assigned to reflect both factors in the model. In general there was limited scientific literature estimating adoption potential, so we validated our assumptions through discussion with experts including where possible the authors of the main reports we cited.

GHG Factor: Quantifying the unit level (e.g., per head, per acre) GHG mitigation potential is more straightforward for certain levers such as those related to Manure Management, Enteric Fermentation, or Fuel Use, where emissions are easier to measure and published literature is robust. Measurement for other levers however, such as Soil Management or LULUCF where GHG emissions interact within a highly complex ecosystem, are significantly more challenging to measure as a result. For some levers, significant scientific debate persists around the precise GHG mitigation potential. While we have focused our quantitative assessment on those levers that have the highest level of consensus among the US scientific community and strong supporting literature, we recognize that more research is required to fully understand the implications of each. To account for these discrepancies in scientific literature, we have applied ranges to all the GHG emissions reduction estimates, which are reflected in the three scenarios. In general, our conservative scenario takes the lower bound of credible published GHG factors for a given lever, while the moderate and optimistic scenarios use the upper bound. Because each lever was evaluated independently, there are instances where certain levers shared interdependencies (e.g., changes in diet affect supply of agricultural commodities and their associated emissions). We've carefully assessed these instances and adjusted estimates accordingly to avoid double-counting in aggregate, but this may tend to understate the impact of a given lever in isolation from other levers. This is primarily applicable to the "GHG selective breeding" lever and to both of the demand-related levers (food loss/waste reduction, diet changes) which are sized based on a smaller baseline that accounts for reductions from agricultural emission-related levers.

Costs: Our cost analysis primarily relies on marginal abatement costs cited from the USDA's 2013 report titled "Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States"[165] and Fargione et al.'s 2020 paper titled "Natural Climate Solutions."[166] We take given marginal abatement costs or the "break-even price" (e.g., $50 per ton) for each lever and multiply it by the emissions that could be abated at these levels annually to reach a total net cost number annually. Where various technologies have since become more developed or we are modelling further technology changes into the future, we have made adjustments to the costs from the literature.

[165]USDA, Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States 2013.

[166]Fargione et al. 2018.

To understand more about this methodology, the USDA[167] provides specific guidance on their methodology and an excerpt of this has been provided below:

Methodology for Estimating Break-Even Price

Each mitigation option is characterized by its capital and recurring costs (e.g, operation and maintenance costs), cost savings or revenues, emissions reduction efficiencies, and equipment lifetime.

Table - Cost Characteristics of Mitigation Technology and Management Practise Options

Characteristic of options	Unit	Definition
Equipment Lifetime (T)	Years	Average technical lifetime of an option
Emission Reduction (ER)	mt CO_2 -eq	Absolute amount of emissions reduced by an option (as modelled) in a given year
Capital Cost (CC)	$	Total fixed capital cost of an option
Recurring Cost (RC)	$	Annual operating and maintenance costs, including reductions in costs resulting from the option (e.g., savings in fertilizer costs, savings from on-site generation of elecricity)
Revenue (R)	$	Net changes in revenues (e.g. changes in crop field)

As mentioned in the body of the report, these costs therefore only represent on-farm costs and benefits, and do not account for other costs that would be needed in the transition (e.g., research and development costs).

Given limited information is available to disaggregate costs and benefits from a marginal abatement cost or a break-even price, we have made assumptions related to the expected benefit on farms we expect from these costs in order to infer the cost and benefit component of the "net cost" figures. Additional caveats include that these costs could change over time in ways we have not accounted for. For example, the costs could decrease faster than the original studies' anticipated as a result of significantly increased spending by industry on R&D to make these practices more economically viable.

[167]USDA, Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States 2013.

Appendix 2 - Contributors and acknowledgments

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Appendix 3 - References

1 Trillion Trees. 2022. https://www.1t.org/about-US.

BCG. "Food for Thought: The Protein Transformation." 2021.

Beerling et al. Potential for large-scale CO_2 removal via enhanced rock weathering with croplands. Nature, 2020.

Bell et al. Effect of breeding for milk yield, diet and management on enteric methane emissions from dairy cows. Animal Production Science, 2010.

Bloomberg. "Cargill Backs Cow Masks to Trap Methane Burps." 2021.

Bloomberg. "Electric Vehicle Outlook." 2021.

Brancalion, and Holl. Tree planting is not a simple solution. Science, 2020.

Climate & Clean Air Coalition. "Global Methane Alliance." 2019.

Congressional Research Service. "Greenhouse Gas Emissions and Sinks in US Agriculture." 2021.

Cook-Patton, Gopalakrishna, and Daigneault et al. Lower cost and more feasible options to restore forest cover in the contiguous United States for climate mitigation. One Earth, 2020.

Crane-Droesch, Andrew, Elizabeth Marshall, Stephanie Rosch, Anne Riddle, Joseph Cooper, and Steven Wallander. Climate Change and Agricultural Risk Management Into the 21st Century. Economic Research Service, USDA, 2019.

Crippa, Solazzo, and Guizzardi et al. Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food, 2021.

Dennehy, Conor. "Greenhouse Gas Emissions from Different Pig Manure Management: A Critical Analysis," Frontiers of Environmental Science & Engineering Techniques, 2017

Douglas. Despite pledge, US still wastes more than a third of its food - EPA. Reuters, 2021.

Douglas. US crop insurance payouts rise sharply as climate change worsens droughts, floods. Reuters, 2022.

DSM. "Summary of scientific research on how 3-NOP effectively reduces enteric methane emissions from cows." 2019.

Eilperin, and Dennis. Biden is hiking the cost of carbon. It will change how the US tackles global warming. Wall Street Journal, 2021.

EPA. Basic Information about Anaerobic Digestion (AD). 2022.

EPA. "Farmland Ownership and Tenure." ERS, 2014.

EPA. "From Farm to Kitchen: The Environmental Impacts of US Food Waste." Office of Research and Development, 2021.

EPA. "Global Mitigation of Non-CO2 Greenhouse Gases: 2010-2030." Office of Atmospheric Programs, 2013.

EPA. "Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2016." 2018.

EPA. "Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2019." 2021.

EPA. "Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2020." 2022.

EPA. "Market Opportunities for Biogas Recovery Systems at US Livestock Facilities." 2018.

EPA. "Overview of Greenhouse Gases: Nitrous Oxide Emissions." 2022.

EPA. "United States 2030 Food Loss and Waste Reduction Goal." 2022.

Fargione et al. Natural climate solutions for the United States. Science Advances, 2018.

Gurgel, Reilly, and Blanc. Agriculture and forest land use change in the continental United States: Are there tipping points? iScience, 2021.

Harmsen. Non-CO2 Greenhouse Gas Mitigation in the 21st Century. Utrecht University, 2019.

Hayek, and Miller. "Underestimates of methane from intensively raised animals could undermine goals of sustainable development." Environmental Research Letters, 2021.

Henderson et al. Greenhouse gas mitigation potential of the world's grazing lands: Modeling soil carbon and nitrogen fluxes of mitigation practices. Agriculture, Ecosystems and Environment, 2015.

Innovature. "Why Gene Editing Is A Climate Change Solution." 2020.

IPCC. "AR5." 2014.-. AR6. 2022.

Jacobson, and De Stefano. Soil carbon sequestration in agroforestry systems: a meta-analysis. Agroforestry Systems, 2018.

Kataria. Use of feed additives for reducing greenhouse gas emissions from dairy farms. Jai Hind College, Microbiology Research, 2015.

Lark, Hendricks, Gibbs, and Smith. Environmental outcomes of the US Renewable Fuel Standard. University of Wisconsin-Madison, 2021.

Lark, Salmon, and Gibbs. "Cropland expansion outpaces agricultural and biofuel policies in the United States." 2015.

Latta, Adams, and White. Simulated effects of mandatory versus voluntary participation in private forest carbon offset markets in the United States. Journal of Forest Economics, 2011.

Metsolar. "What is agrivoltaics? How can solar energy and agriculture work together?" 2021.

Monke, J., Stubbs, M., Bracmort, K., Hoover, K. (2022). Inflation Reduction Act: Agricultural Conservation and Credit, Renewable Energy, and Forestry (CRS Insight No. IN11978).

Moore et al. Combatting Climate Change on US Cropland. American Farmland Trust, 2021.

Moosdorf, Renforth, and Hartmann. Carbon Dioxide Efficiency of Terrestrial Enhanced Weathering. Environmental Science & Technology, 2014.

Moyer et al. "Regenerative Agriculture and the Soil Carbon Solution." 2020.

Mulligan, J., A. Rudee, K. Lebling, K. Levin, J. Anderson, and B. Christensen. 2020. "CarbonShot: Federal Policy Options for Carbon Removal in the United States" Working Paper. Washington, DC: World Resources Institute.

National Integrated Drought Information System. Droughts in the 20th- and 21st-Century United States. n.d.

OECD. "Enhancing Climate Change Mitigation through Agriculture." 2019.

One Earth. "Lower cost and more feasible options to restore forest cover in the contiguous United States for climate mitigation." 2020.

Osmond, Deanna. Best Management Practices for Agricultural Nutrients. 2017.

Paustian, Keith, Johannes Lehmann, Stephen Ogle, David Reay, G. Philip Robertson, and Pete Smith. "Climate-smart Soils." Nature, 2016.

Poore, and Nemecek. Reducing food's environmental impacts through producers and consumers. Science, 2018.

Project Drawdown. The Most Comprehensive Plan Ever Proposed to Reverse Global Warming. 2017.

ReFED. "New Data from ReFED Reveals Amount of Food Waste Has Leveled Off After Increasing 11.9% Since 2010." 2021.

ReFED. "Roadmap to 2030: Reducing US Food Waste by 50% and the ReFED Insights Engine." 2021.

Roque et al. Effect of the macroalgae Asparagopsis taxiformis on methane production and rumen microbiome assemblage. anim microbiome, 2019.

Rosenberg, and Lehner. The Climate Crisis and Agriculture. Environmental Law Reporter, 2022.

Rosenzweig, Mbow, and Barioni et al. "Climate change responses benefit from a global food system approach." Nat Food 1 (February 2020): 94-97.

Searchinger et al. "Creating A Sustainable Food Future." 2019.

Sheriff, Glenn. "Efficient Waste? Why Farmers Over-Apply Nutrients and the Implications for Policy Design." Review of Agricultural Economics, 2005: 542-557.

Smith et al. "Silvopasture in the USA: A systematic review of natural resource professional and producer-reported benefits, challenges, and management activities." USDA, 2021.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., & Smith, J. "Greenhouse gas mitigation in agriculture." Philosophical transactions of the Royal Society of London, 2008: Series B, Biological sciences, 363(1492), 789–813.

Sohngen, and Brown. Extending timber rotations: Carbon and cost implications. Climate Policy, 2008.

Soil Health Institute. Goal by 2040. n.d.

Stockton, Matt, and Tessa Burford. "Fertilizer Prices Forecasted to Continue Increase: What to Know." Institute of Agriculture and Natural Resources at the University of Nebraska-Lincoln, 2021.

The Rice Foundation. "US Rice Industry Sustainability Report: The Sustainability Story of US Rice. Impressive History, Bright Future." 2018.

The White House. "United States Mid-Century Strategy for Deep Decarbonization." 2016.

Trambley. Breakthrough Institute Urges House and Senate Agriculture Committees to Boost Ag R&D Funding in Infrastructure Bill with $40B Investment to Fight Climate Change. The Breakthrough Institute, 2021.

Tubiello, F. N., Karl, K., Flammini, A., Gütschow, J., Obli-Laryea, G., Conchedda, G., Pan, X., Qi, S. Y., Halldórudóttir Heiðarsdóttir, H., Wanner, N., Quadrelli, R., Rocha Souza, L., Benoit, P., Hayek, M., Sandalow, D., et al. "Pre- and post-production processes increasingly dominate greenhouse gas emissions from agri-food systems." Earth Syst. Sci. Data 14 (2022): 1795–1809.

UNFCCC. "Glossary of climate change acronyms and terms." 2022.

United States Government. "USA Nationally Determined Contribution." 2021.

USDA. "2022 Farm Sector Income Forecast." 2022.

USDA. "Agricultural Resource Management Survey." 2018.

USDA. "Budget Summary." 2022.

USDA. "Building Blocks for Climate Smart Agriculture and Forestry." 2016.

USDA. "Census of Agriculture." NASS, 2017.

USDA. "Cover Crops - Keeping Soil in Place While Providing Other Benefits." NRCS, 2022.

USDA ERS. ARMS Farm Financial and Crop Production Practices. 2015.

USDA. "Farmland Ownership and Tenure." ERS, 2017.

USDA. "Greenhouse Gas Inventory." 2022.

USDA. Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States. NRCS, ICF, 2013.

USDA. "Integrated Projections for Agriculture and Forest Sector Land Use, Land-Use Change, and GHG Emissions and Removals:." 2016.

USDA. Managing Agricultural Land for Greenhouse Gas Mitigation within the United States. ICF, 2016.

USDA. "National Agroforestry Center." 2022.

USDA. "Partnerships for Climate-Smart Commodities." 2022.

USDA. "The greenhouse gas benefits of corn ethanol – assessing recent evidence." 2019.

USDA. "Trends in US Agriculture's Consumption and Production of Energy: Renewable Power, Shale Energy, and Cellulosic Biomass." ERS, 2016.

Urea Decreases Nitrous Oxide Emissions. SSSAJ: Volume 74: Number 2, 2010.

USDA, and USDA ERS. "Tillage Intensity and Conservation Cropping in the United States." 2018.

Van Winkle, Baker, Lapidus, and Ohrel et al. US Forest Sector Greenhouse Mitigation Potential and Implications for Nationally Determined Contributions. US Forest Sector Greenhouse Mitigation Potential and Implications for Nationally Determined Contributions, RTI Press Publication, 2017.

Waite. 6 Ways the US Can Curb Climate Change and Grow More Food. World Resources Institute, 2020.

Watson. Global carbon offsets market could be worth $200 billion by 2050: Berenberg. S&P Global Commodity Insights, 2020.

White House Long Term Strategy. "Pathways to Net-Zero Greenhouse Gas Emissions by 2050." 2021.

Woodbury, Tonitto, and Carter. Predicting greenhouse gas benefits of improved nitrogen management in North American maize. Journal of Environmental Quality, 2020.


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