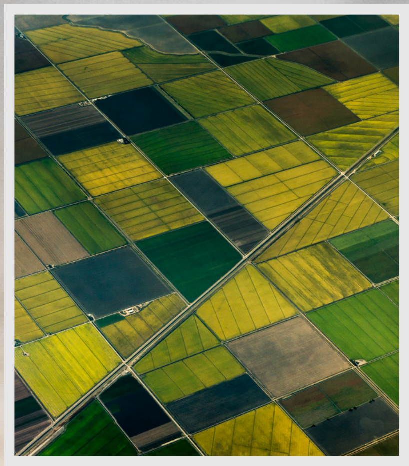
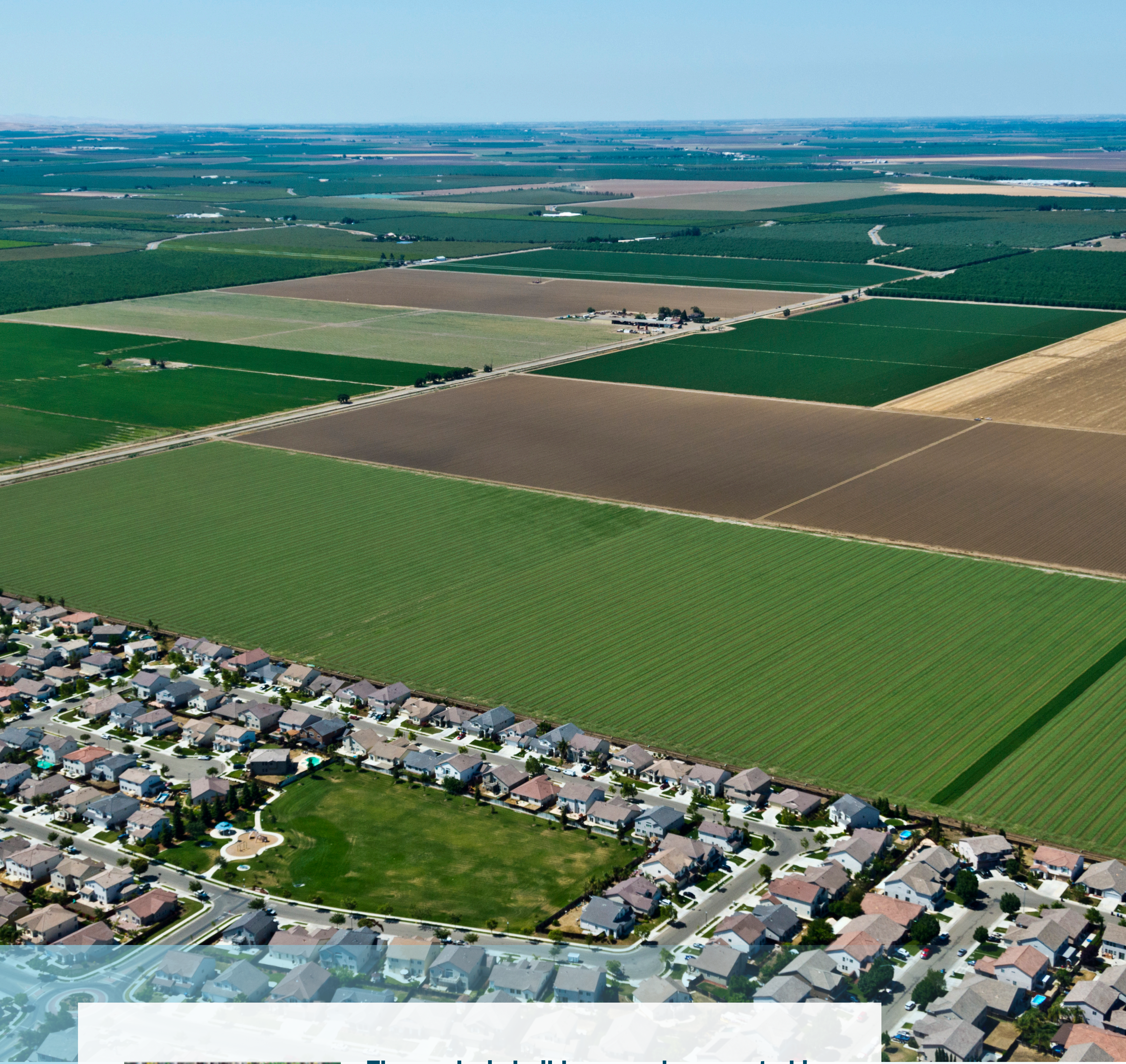



Greenhouse Gas Mitigation Potential in the U.S. Forestry and Agriculture Sector

EPA

EPA 430-R-23-004
March 2024





The analysis builds on work presented in the 2005 report Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture to provide a contemporary perspective on greenhouse gas abatement options for the U.S. land use sectors using updated and expanded modeling frameworks.

ACKNOWLEDGMENTS
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This report is dedicated to the memory of Darius M. Adams.

PEER REVIEW
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DATA AVAILABILITY
Data from the analyses in this report can be accessed on the EPA website.

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Executive Summary

The forestry and agriculture sectors are central pillars of federal and state regulations and strategies aimed at greenhouse gas (GHG) emissions and removals.

Recent federal policies have recognized the value of land-based abatement strategies by allocating funds to preserve forest as natural sinks, enhance land storage capacity, and increase forest resilience. For instance, the Inflation Reduction Act (IRA) directs large investment in land-based mitigation programs; the Infrastructure Investment and Jobs Act (IIJA) allocates a share of the funds into forest-based projects (e.g., reforestation); and the U.S. Department of Agriculture Climate Smart Commodities Program is designed to incentivize activities that reduce agricultural emissions and improve soil health (IIJA, 2021).

Insights into future potential mitigation trends of the land sector, and the environmental, economic, and other conditions that drive those trends, are necessary for the design of effective mitigation policies, as these trends can influence the magnitude and costs of the mitigation portfolio in the short, medium, and long terms across sectors.

This report provides updated estimates of the GHG mitigation potential associated with various abatement activities in the agriculture and forestry sector in the United States between now and 2050. The analysis builds on work presented in the 2005 U.S. Environmental Protection Agency (EPA) report Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture (EPA, 2005) and integrates new modeling tools and frameworks to provide a contemporary perspective on GHG abatement options for the U.S. land use sector.

The report uses three economic models of the land sector with detailed biophysical sectoral coverage and spatial data: the Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOMGHG), the Global Timber Model (GTM), and the Global Biosphere Management Model (GLOBIOM). Each model has been extensively applied in the literature for a variety of objectives, including projecting land management, market, and environmental changes across different policy, environmental, and macroeconomic scenarios, and has been used in various official government modeling applications. Each model provides different perspectives into the report by focusing on only the land sector in the United States (FASOMGHG), the global land sector (GLOBIOM), and the global forestry sector (GTM).

A total of 24 land-based mitigation activities across eight GHG emission categories have been identified across the three models. All three models explicitly capture important feedbacks that occur when market changes influence the opportunity costs of investing in land-based mitigation options, and hence affect the resulting potential magnitude and cost of different GHG mitigation activities over time.

A forest along the Lost Coast in Mendocino, California.

Recent federal policies have recognized the value of land-based abatement strategies by allocating funds to preserve forest as natural sinks, enhance land storage capacity, and increase forest resilience.

To evaluate net mitigation potential for different GHG categories (or specific activities) in the land sector, model-specific baseline scenarios with no mitigation pricing policies in place are run using harmonized parameters (e.g., key socioeconomic drivers). Under this scenario, only market and biophysical conditions drive future land use and land management decisions. To model mitigation activities, each model includes 10 alternative GHG price path scenarios and selects the optimal emission path and combination of mitigation activities in response to the prices based on tradeoffs between land use, markets, and GHG reductions.

Two modern hog barns in Northwest Iowa.

Key Takeaways

Though the U.S. land sector is projected to remain a net sink through midcentury, land use GHG emissions are projected to increase over time under the baseline scenarios.

In the baseline, the U.S. Agriculture, Forestry, and Other Land Use (AFOLU) sector is expected to remain a net GHG emissions sink, with projected net CO_2 sequestration of about 90 million metric tons of CO_2 equivalents per year (Mt CO_2e yr^{-1}) in FASOMGHG and 120 Mt CO_2e yr^{-1} in GLOBIOM in 2050. Baseline results generally align with national GHG inventory historic values.

In the forestry sector, the three models project that the carbon sink will either remain relatively constant or decline over time as forests age and harvesting activities grow, driven by an increase in population and corresponding demand for forest-based products.

In 2050, the expected average annual carbon sequestration rate is 405 Mt CO_2 yr^{-1} in FASOMGHG, 431 Mt CO_2 yr^{-1} in GLOBIOM, and 641 Mt CO_2 yr^{-1} in GTM (compared to an estimated rate of 688 Mt CO_2e yr^{-1} in 2020 in the EPA Greenhouse Gas Inventory 2023) (EPA, 2023).

In the agricultural sector, which includes both crops and livestock, both FASOMGHG and GLOBIOM project an increase in GHG emissions over time as rising populations and gross domestic product (GDP) lead to increases in demand for agricultural commodities, despite projected increases in crop yields.

continued

Across 10 mitigation scenarios, emissions reduction in the AFOLU sector are projected to be 32–364 Mt CO_2e yr^{-1} in FASOMGHG and 163–309 Mt CO_2e yr^{-1} in GLOBIOM in 2050 for GHG prices ranging from $7/t CO_2e to $243/t CO_2e.

In 2050, at a GHG price of $100/t CO_2e, the AFOLU sector (including both agriculture and forestry) is projected to abate about 250–350 Mt CO_2e yr^{-1}.

Across all models, forest-based activities offer the highest level of mitigation potential. In GLOBIOM, forest management provides, on average, more than half of the mitigation from the land sector, while afforestation has the largest share of total mitigation in FASOMGHG and GTM. Under prices higher than $50/t CO_2e, in GLOBIOM and FASOMGHG, the forestry sector is still the primary contributor to mitigation, but its share declines as more land-based activities become cost-effective in livestock and cropping systems.

In all mitigation scenarios, the agricultural sector remains a net emitter of CO_2e; however, emissions reductions of up to 16% from croplands and 18% from livestock activities are feasible by 2050, while still maintaining production.

The forest sector has the capacity to reach net sequestration of 1 Gt CO_2e yr^{-1} in 2050 under half of the mitigation scenarios in GTM.

To achieve the U.S. Long Term Strategy (LTS) goal of net-zero emissions by 2050 requires important contributions from land-based activities and other carbon removal activities. The findings presented in this report show that the forest sector has the capacity to significantly increase net sequestration over the next three decades; however, reaching a level of around 1 Gt CO_2e yr^{-1} in 2050 could require investments of more than $15 billion per year between the present and 2050.

The land sector alone has the capacity to reduce its methane emissions by 30% below current levels in 2030.

The Global Methane Pledge launched in 2021 by the United States and the European Union aims at reducing global methane emissions by 30% below 2020 levels by 2030. The results in this report show a potential reduction in U.S. methane emissions of 30–33% relative to 2020 by 2030 from the land sector only (the global pledge includes all methane-intensive sectors). This level of methane abatement could be achieved under GHG prices higher than $116/t CO_2e in 2030.

continued

Under annual investments of $2 billion in the next decade, the land sector can deliver around 50–78 Mt CO_2e annual mitigation at an average cost of about $25 per ton.

Under cumulative investments of $20 billion in the next decade directed to all land-based activities, the expected cumulative abatement could reach a maximum of 800 Mt CO_2e. This works out to a per-ton average mitigation cost of about $25.

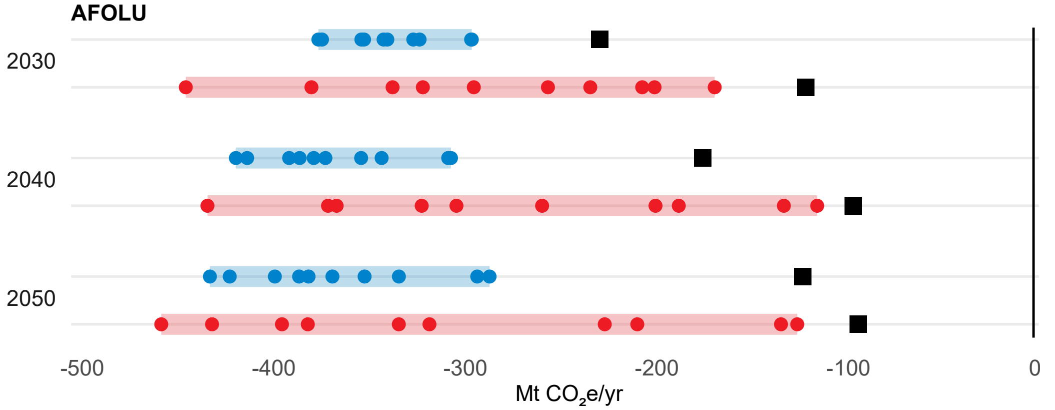
Mitigation potential of the land sector in the report is within the lower bound range of 5–1,168 Mt CO_2e presented in the literature because the models account for land use competition, tradeoffs between mitigation activities, and market dynamics that may not be reflected in other studies.

In the literature, estimated abatement varies significantly due to different approaches and assumptions with a range of 5–624 Mt CO_2e of potential mitigation from the land sector under GHG prices below $35/t CO_2e. For prices up to $200/t CO_2e, the potential range is even greater with projections of 550–1,168 Mt CO_2e.

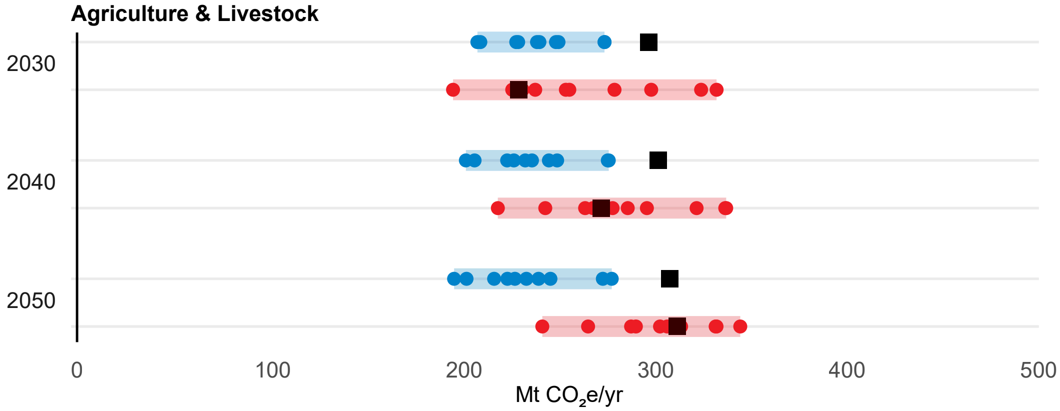
The mitigation potential from recent techno-economic analyses, which usually sum across a range of mitigation activities and sources, is higher than the results in this report where there is an explicit representation of economic tradeoffs, land use competition, and market responses. This effect is significant under higher GHG prices. Moreover, some of the recent bottom-up studies include new mitigation options (e.g., biochar) that are not included in the models used for this report because of the lack of data in the Inventory of U.S. Greenhouse Gas Emissions and Sinks (GHGI).

Field of mustard seed cover crop, used as weed suppression and pest control in Santa Cruz County, California.

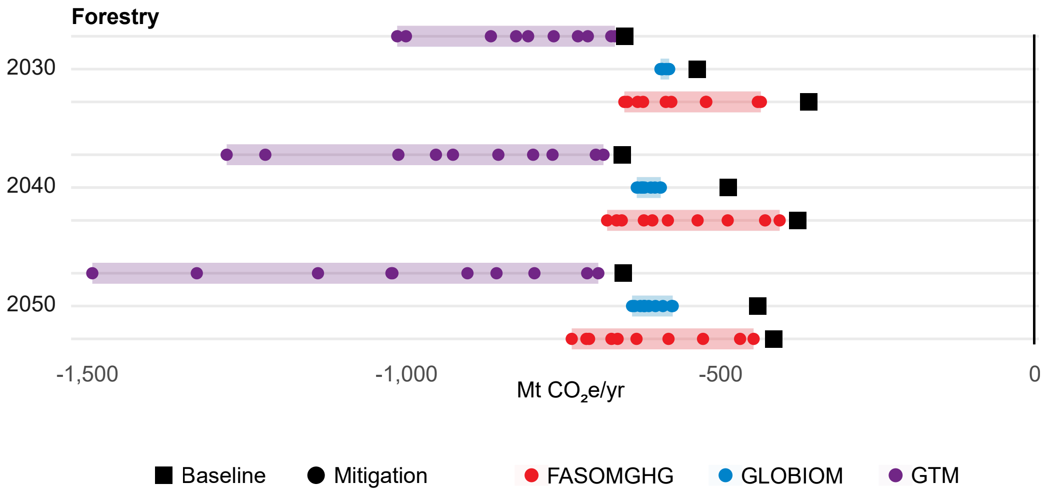
FIGURE ES-1 By the numbers



The U.S. AFOLU sector could remain a net sink in 2050 under business-as-usual conditions (without additional mitigation policies targeting GHG emissions). Under GHG mitigation scenarios, it could increase its net sequestration up to 309–364 Mt CO_2e relative to the baseline in 2050 depending on the model.



In the U.S. agricultural sector, which includes both crops and livestock, GHG emissions are projected to increase over time, converging to a similar value in 2050 under the baseline scenario. Under GHG mitigation scenarios, GHG emissions are projected to decline by a maximum of 85–110 Mt CO_2e relative to the baseline in 2050 depending on the model.



The U.S. forestry sector will either maintain a constant flux of net sequestration or slowly decline its sequestration over time under the baseline scenario. Under GHG mitigation scenarios, forest net sequestration could increase by a maximum of 200–832 Mt CO_2e relative to the baseline in 2050 depending on the model.

All figures show absolute emissions under baseline and mitigation scenarios for net emissions from agriculture, forestry, and other land use (AFOLU) in FASOMGHG and GLOBIOM; net emissions from forestry in FASOMGHG, GLOBIOM, and GTM; and net emissions from agriculture and livestock for FASOMGHG and GLOBIOM. Each figure has a different x-axis scale. Results are presented in terms of atmospheric accounting. Therefore, positive flux equates emissions; negative flux represents sequestration. Initial values in each model differ due to varying GHG pools included in each model, as discussed in Chapter 2, such as FASOMGHG including emissions from on-farm fuel consumption, which GLOBIOM does not. Additionally, GTM and GLOBIOM include representation of Alaska, while FASOMGHG does not.

Future research should expand the sensitivity test presented in the report and include additional climate change impacts on land to assess the sensitivity of these findings to changing climate conditions.

Heavy rains and storms in the Midwest have caused field flooding and corn crop damage.

Looking Forward

The mitigation scenarios simulated in the report represent an optimal framework in which all the agents are subjected to GHG prices, they respond to the price mechanism in a rational way with perfect information, there are no transaction costs associated with their mitigation actions, and free riding is not possible. Future efforts could expand the sensitivity tests presented in the report, including comparing the potential from incentivizing single land-based mitigation activities to the potential found from the approach presented in the report.

The models respond to the price mechanism by selecting the most cost-effective composition of mitigation actions across a range of 24 options, which represent the activities used on a largescale at the present. Further research should expand the portfolio of GHG reduction activities available for the land and other sectors (e.g., bioenergy production, wetland conservation, agroforestry, biochar) and strategies available to maintain and enhance land sink and resilience (e.g., land conservation) and those that seek to address food security issues.

The models used for the analysis include economic and biophysical characteristics of land and function as if climate conditions will affect land productivity and availability following historical trends. Future research should expand the sensitivity test presented in the report and include additional climate change impacts on land to assess the sensitivity of these findings to changing climate conditions. These efforts could include the role of changing temperature and precipitation patterns, fluctuations in crop growing regions, and changes in occurrences of natural disasters such as drought, floods, and fires.

For each GHG price pathway, each model provides the cost-effective composition of land-based mitigation activities without considering macroeconomic costs and benefits. The report does not estimate the social and economic benefits of reducing GHG emissions from the atmosphere in terms of avoided climate damages and the role of land adaptation strategies. Future research should include these additional layers of analysis by estimating, for example, the benefits in terms of avoided carbon emissions and potential co-benefits on biodiversity together with equity and environmental justice considerations on where land-based activities will be implemented.

1 Introduction

The forestry and agriculture sectors are central pillars of global and U.S. greenhouse gas (GHG) emissions and removals portfolios.

GHGs associated with the land sector include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). For comparison, amounts of these gases are often presented as carbon dioxide equivalents (CO_2e). Land management and land use change (LUC) activities can increase an area's ability to hold carbon and act as a carbon sink or can increase GHG emissions to the atmosphere. Carbon sinks represent net removals of CO_2 from the atmosphere via sequestration, which is defined as increasing carbon content in a carbon pool other than the atmosphere (Intergovernmental Panel on Climate Change [IPCC], 2000). According to the IPCC, lands globally constituted a net carbon sink of –6.6±5.2 gigatons (Gt) CO_2e annually from 2010 to 2019 (IPCC Working Group III, 2022). Agriculture, forestry, and other land use (AFOLU) also represents a source of emissions. About 22% (13 Gt CO_2e) of total net global anthropogenic GHG emissions in 2019 came from AFOLU, half of which were a result of land use change activities (largely deforestation, though estimated global deforestation rates are declining). Compared with other sectors, GHG emissions estimates from the land sector are generally more uncertain, largely due to the uncertainty of the data underlying estimated emissions and sequestration in land use, land use change, and forestry (LULUCF), which depend on biological variation, differences in biophysical conditions, and heterogeneity in management systems across regions (IPCC Working Group III, 2022).

Land-based activities are globally recognized as having substantial GHG mitigation potential, and these activities have received renewed focus in many countries' GHG reduction commitments made as part of the Paris Agreement (United Nations Framework Convention on Climate Change, 2015) and the last two IPCC special reports (IPCC, 2018, 2019b). The recent IPCC 6th Assessment Report stated that there is high confidence on the substantial mitigation (and adaptation) potential from opportunities in AFOLU that could be upscaled in the near term across most regions (IPCC Working Group III, 2022). In that report, the mitigation potential of AFOLU activities is projected as 8–14 Gt CO_2e yr^{-1} between 2020 and 2050, at costs below \$100/t CO_2e, and 30%–50% of the potential is available at less than \$20/t CO_2e. The largest share (4.2–7.4 Gt CO_2e yr^{-1}) is projected to come from reduced deforestation, improved management, and restoration of forests and other ecosystems. Improved crop and livestock management and carbon sequestration in agriculture represent other key mitigation strategies with a potential of 1.8–4.1 Gt CO_2e yr^{-1}.

In addition to increased international focus on this topic, the United States has recognized that dedicated programs and policies focusing on its land sector, including efforts to reduce emissions from natural disturbances and to bolster the health of vital ecosystems, have the potential to confer

Forest hillside landscape after selective logging of mature trees with seed trees remaining, Pennsylvania.

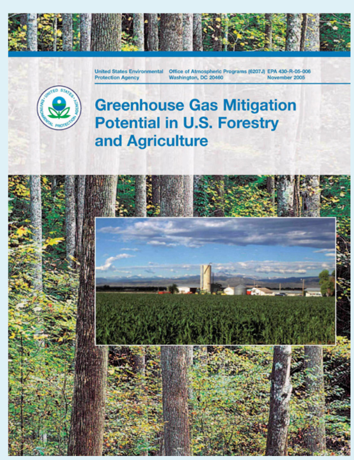
The Long-Term Strategy proposes avoided forest land conversion, shifts to longer harvest rotations, reforestation on degraded forested lands, and reduced natural disturbance through management, all of which can result in both near- and long-term net carbon benefits.

substantial climate benefits and play an important role in meeting the nation's decarbonization goals. To advance those goals, U.S. federal actions—like the release of the U.S. Long Term Strategy (LTS) (U.S. Department of State & the U.S. Executive Office of the President, 2021) and the passage of legislation like the Infrastructure Investment and Jobs Act (IIJA, 2021) and the Inflation Reduction Act (IRA, 2022), which include funding for actions addressing climate change—seek to substantially augment efforts to capitalize on lands-based mitigation opportunities. Specifically, the LTS proposes avoided forest land conversion, shifts to longer harvest rotations, reforestation on degraded forested lands, and reduced natural disturbance through management, all of which can result in both near- and long-term net carbon benefits. While managers of agricultural lands can implement practices such as reduced tillage, rotational grazing, and residue management to reduce emissions from crop and livestock production, most of these activities result in near-term emissions reductions. The IRA is a major step in supporting these activities by providing nearly $20 billion in investment to natural and working lands to preserve, restore, and conserve vital landscapes, as well as investments in innovative on-farm activities to reduce emissions. The United States has also endorsed the Global Methane Pledge, a multilateral agreement to take voluntary actions consistent with a collective effort to reduce global CH_4 emissions by at least 30% from 2020 levels by 2030. In the AFOLU context, this agreement applies primarily to CH_4 emissions from rice cultivation and livestock production. There are also dedicated actions taking place at the local and state levels (The U.S. Conference of Mayors and the Center for Climate and Energy Solutions, 2017; U.S. Climate Alliance, 2022). Increased levels of public and private policy enactment and investments in natural climate solutions may increase the acreage, productivity, and overall health of, and realized mitigation from, U.S. forested and agricultural lands.

The goal of this report is to provide estimates of the GHG emissions mitigation potential associated with various abatement activities in the agriculture and forestry sectors in the United States over the next several decades, with particular focus on results in 2050.

This report identifies and estimates mitigation options and related costs that can be used to support informed prioritization of abatement activities, target investments, and improve the likelihood of achieving an overall GHG reduction goal. This information is therefore valuable to a broad range of stakeholders, including the designers of national and regional GHG mitigation and land management programs, private land managers, private-sector investors, the broader research community, and the public.

The analysis builds on work presented in the 2005 U.S. Environmental Protection Agency (EPA) report *Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture* (EPA, 2005) to provide a contemporary perspective on GHG abatement options for the U.S. land use sectors using updated and expanded modeling frameworks.
Like the original report, this report evaluates GHG emissions mitigation potential via simulated future conditions and outcomes using an economic modeling framework that uses biophysical data and modeling, cost parameters, elasticities, and other inputs to explore the relationships among drivers of decisions related to agricultural production activities, forestry management, and other related land use and land use change activities.



This report expands on the 2005 EPA report because that report employed only one model, a domestic partial equilibrium (PE) model of the U.S. forest and agriculture sectors with land use competition between them and limited linkages to international trade (Forest and Agriculture Sector Optimization Model with Greenhouse Gases, FASOMGHG).

Specifically, this report expands on the 2005 EPA report because that report employed only one model, a domestic PE model of the U.S. forest and agriculture sectors with land use competition between them and limited linkages to international trade (Forest and Agriculture Sector Optimization Model with Greenhouse Gases, FASOMGHG). This analysis applies an updated version of FASOMGHG and two additional economic models, the Global Biosphere Management Model (GLOBIOM) and the Global Timber Model (GTM). All three models explicitly capture important feedbacks that occur when market changes influence the opportunity costs of investing in land use sector mitigation, and hence affect the resulting potential magnitude and cost of different GHG mitigation activities over time. Each model is well established in the economics, agricultural, forestry, and land use literature (see Chapter 2 for detailed information on these models). Since the use of FASOMGHG in the 2005 EPA report, that model and the other two models applied in this study have been expanded and updated to incorporate additional mitigation options as well as improved underlying scientific data and methods from key data sources like the U.S. Forest Service's Forest Inventory and Analysis (FIA) database (U.S. Forest Service, 2017). The improved methods and data inputs, along with an expanded suite of tools used, allow for a more robust assessment of mitigation potential than the previous report.

Another key aspect of these three models is that they can directly incorporate a monetary incentive to reduce GHG emissions and increase carbon sequestration, and track the estimated land use, market, and GHG consequences of incentivizing the reduction of GHG emissions in forestry and agricultural activities relative to a baseline scenario (without mitigation policy). A GHG price mechanism is an appropriate and broadly applied mechanism for deriving the cost-effective portfolio of mitigation actions available in the targeted sector (for this report, the sector is land). Moreover, price-based mechanisms could be used to emulate different programs—such as direct investments on all or specific land-based activities—and estimate their possible outcomes. Moreover, results in the report are presented as marginal abatement cost curves (MACCs), which represent the annual GHG mitigation (in CO_2e) associated with each GHG price incentive across different price levels in each model.

The use of MACCs is a well-known and often-applied approach in the literature to illustrate the estimated amount of emissions reduction potential at varying GHG price levels (e.g., EPA, 2005, 2019b). Model-derived MACCs and total abatement levels are good candidates for informing high-level policy or investment analysis that seeks to understand full opportunity costs of mitigation investment within the context of complex market or macroeconomic systems. MACCs represent an extremely valuable policy tool to measure the mitigation potential under a selected GHG price or the required GHG price to meet a defined level of emissions reduction in different time periods and across activities (see Lubowski et al., 2006).

Though the number of studies published on this topic has been increasing recent years, many of those studies are techno-economic and/or provide a synthesis of other studies (Fargione et al., 2018). This report complements such studies and offers fresh insights as to cost-effective competitive potential of land-based GHG mitigation options domestically by applying well-known models with interactive biophysical and economic components.

Young pine stand growing in Governor Knowles State Forest in Northern Wisconsin.

1.1 Report Objectives

The goal of this report is to contribute a new assessment of the estimated cost-effective potential GHG emissions reductions and additional carbon sequestration associated with specific activities in the agriculture and forestry sectors in the United States over the next several decades.

We estimated these reductions and additional sequestration by comparing the GHG outcomes and economic activities associated with a set of alternative future scenarios across three economic land use models with the projected business-as-usual or baseline trajectory of each model. The estimated mitigation results presented in this report are additional to the projected baseline activities and related GHG emissions or sequestration rates. The results produced are shown as MACCs for the land sector as well as disaggregated by gas, activity, and region to provide detailed descriptions of the mitigation potential of different activities across models, time, and space.

Specifically, this report seeks to examine the following questions:

- What is the magnitude of total U.S. GHG mitigation potential from a range of forestry and agriculture activities over time and at different levels of GHG reduction incentives?
- How does the portfolio of forestry and agriculture mitigation activities change over time given the differing growing cycles of different crops and tree species and related carbon dynamics?
- What are the most efficient mitigation options, taking economic opportunity costs, implementation costs, and market impacts into consideration?
- What is the estimated mitigation potential for different GHGs, specifically CH_4 as a potent short-lived climate forcer vs. the long-lived gases CO_2 and N_2O?
- What is the estimated regional distribution of GHG mitigation opportunities?
- How do baseline trends impact mitigation potential?
- How do leakage and other potential effects from mitigation activities affect overall mitigation outcomes?
- How do mitigation results from global systems models (e.g., GLOBIOM and GTM) compare to those from a domestic model (e.g., FASOMGHG)? How does the inclusion of global market feedback and resource utilization impact net mitigation results for the United States?
- How does the different treatment of time among models (dynamic recursive vs. forward-looking) affect the results?

All three models explicitly capture important feedbacks that occur when market changes influence the opportunity costs of investing in land-based mitigation options, and hence affect the resulting potential magnitude and cost of different GHG mitigation activities over time. The alternative future scenarios applied for this analysis are GHG price incentives (presented in \$/t CO_2e) that target reduced GHG emissions and increased carbon sequestration, while capturing resource competition and market feedback between the forestry and agriculture sectors. These scenarios emulate a hypothetical federal-level policy that aims to address climate change by mitigating net GHG emissions and promotes adoption of climate-smart activities on managed U.S. lands at the minimum cost.

It is important to note that simulated future scenarios like those presented in this report are not meant to serve as predictions—rather, they estimate potential future outcomes under specified future conditions, offering policymakers insights about what GHG emissions and land use outcomes may result from varied future conditions and policy designs and their potential distribution across activities, space, and time. The scenarios represent a stylized ideal future where all agents respond in a rational way to the price incentives which are applied globally (in case of global models) to all land-based GHG emitting activities. The scenarios assume perfect information, no transaction costs associated with mitigation activities, and no free-riding. In addition, there are other policy instruments to advance climate change mitigation outside GHG price incentives used for this analysis. GHG prices have been selected for the study to simulate future projections under an economically efficient (optimal) framework in which all emitting activities pay an equal fee and all activities that increase sequestration receive an equal reward. By covering all the agents under the same price, this instrument drives abatement to be implemented in a cost minimization way where the maximum mitigation is achieved per dollar invested. This optimal framework could be compared to other policy designs to understand their effects and inform and support the policy-making decision process. Finally, the report provides some examples of different policy designs and their effects on future land mitigation potential in the focus boxes presented in Chapter 3.

The study harmonizes, to the extent possible, model inputs and parameters. Employing three different models with harmonized data and parameters, such as macroeconomic variables and application of a single set of scenarios, reduces the implicit bias inherent in single-model projections and improves understanding of systems-level sensitivity to key parameters, which increases confidence in the main findings. Furthermore, it allows for isolation of the effects of climate change mitigation actions and their costs. Use of models with different functional forms in a harmonized effort can also provide important insights on why model results differ and enable researchers to identify and better understand the drivers of those differences to improve future model development and applications, including supporting policy design and implementation.

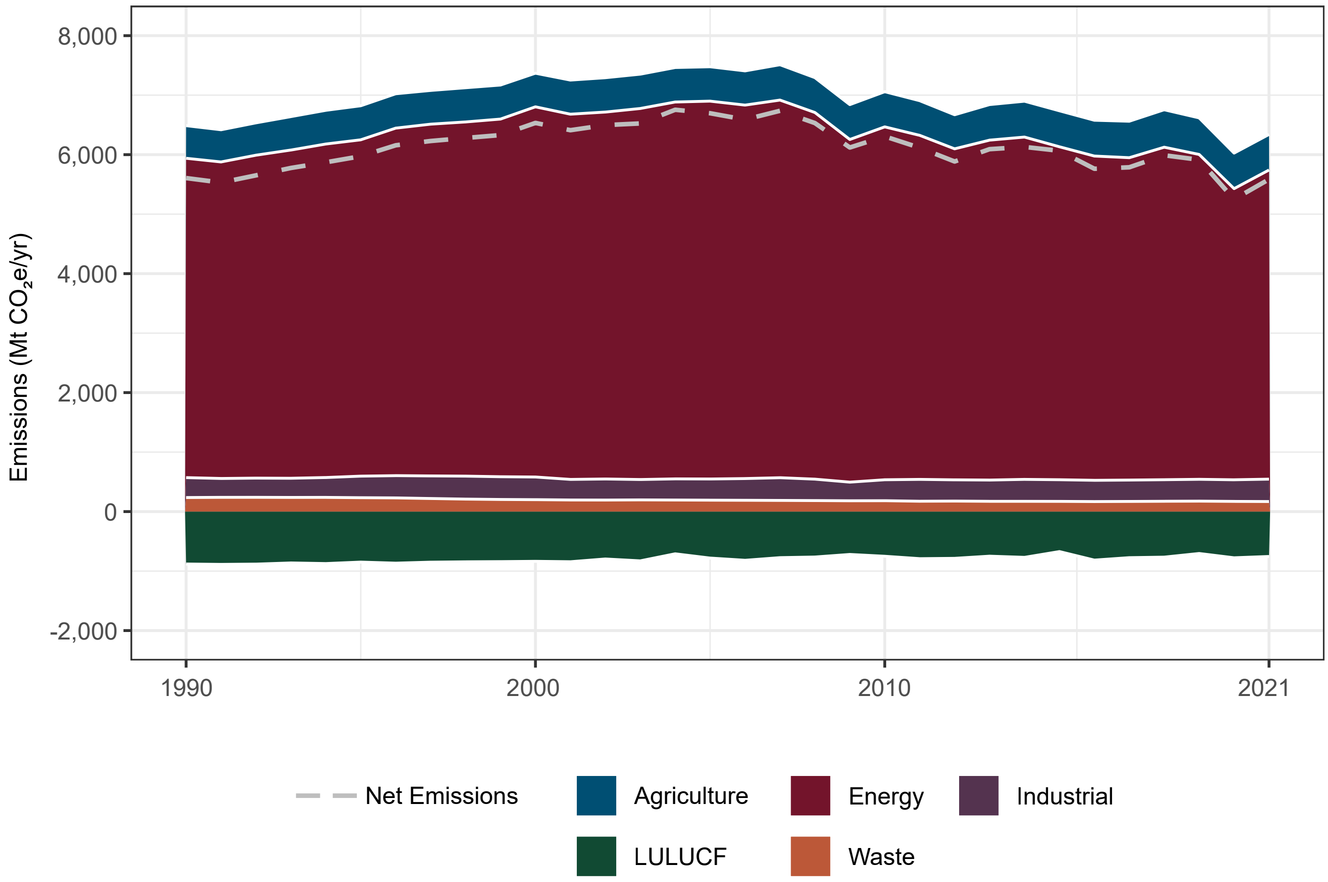
This next section of this chapter lays out the recent status of U.S. lands and related GHG emissions and provides an overview of potential GHG mitigation options. The last section further discusses the models used in the report, including a discussion about how assessments of lands-based mitigation can be done in different ways. More details on methods and data are in Chapter 2, the results are presented in Chapter 3, and discussion of the results is in Chapter 4.

Results of a controlled burn in a pine forest in Alabama.

1.2 Trends in Forest and Agriculture Land Use and GHG Emissions

This report focuses on activities and land management that occur in AFOLU, which encompass emissions and sequestration categories included in the agriculture sector as well as those in the LULUCF sector, as determined by IPCC guidelines (IPCC, 2006).

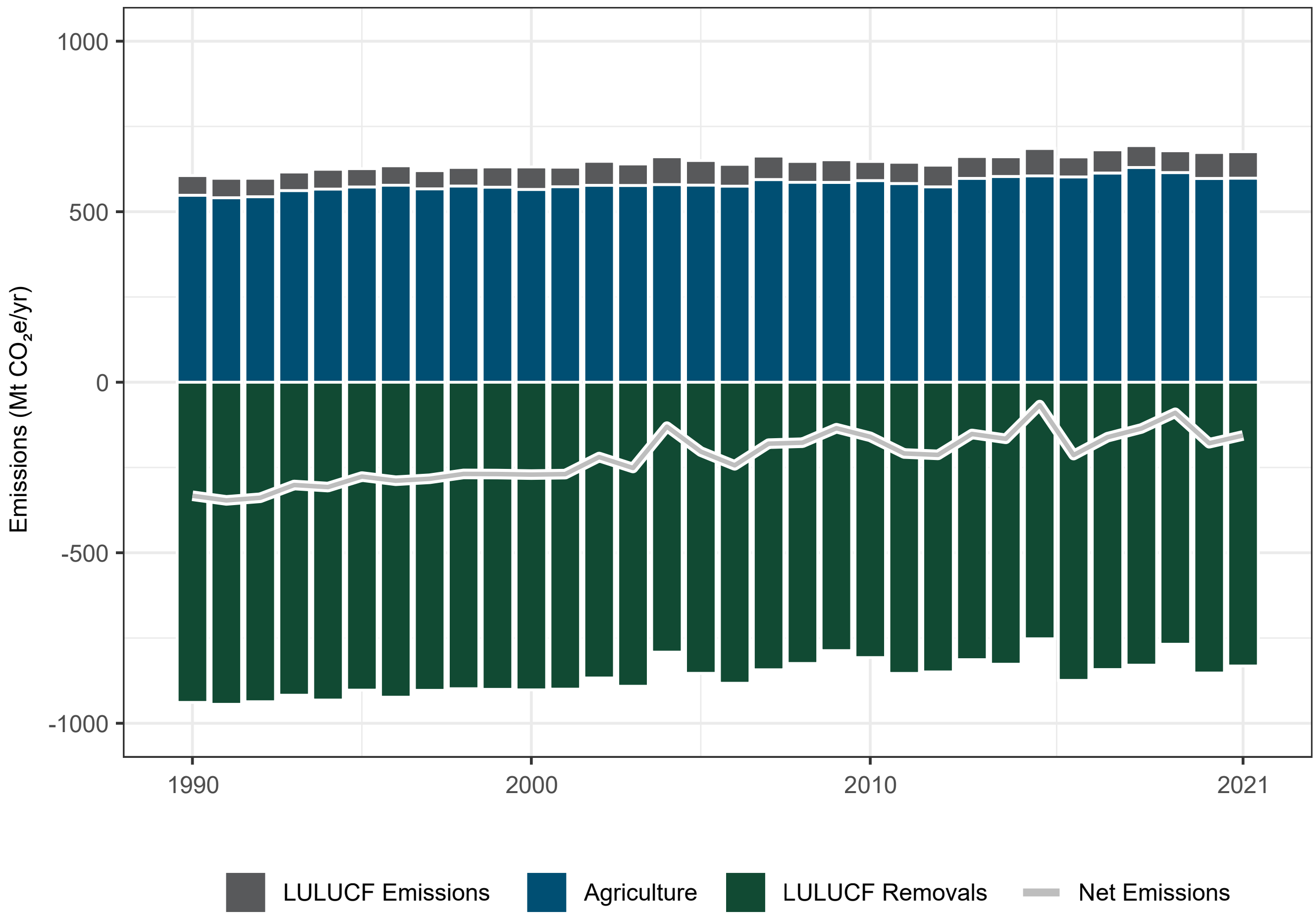
FIGURE 1-1 **U.S. greenhouse gas emissions and sinks by sector (in Mt CO_2e, 1990–2021)**



Gray line shows net emissions from all sectors. Data source: 2023 U.S. GHGI (EPA, 2023).

The U.S. landscape represented 8% of the world's forests (766 million acres) (FAO, 2020a) and 8% of global agricultural lands (including cropland and grasslands, about 988 million acres) in 2016 (FAO, 2020b). The Inventory of U.S. Greenhouse Gas Emissions and Sinks (U.S. GHGI) reported a net increase in carbon stocks (i.e., net CO_2e removals from the atmosphere) of 832 million metric tons of carbon dioxide equivalent (Mt CO_2e) in the LULUCF sector in 2021.[1] CH_4 and N_2O emissions from LULUCF activities in 2021 were 66 and 12 Mt CO_2e, respectively, and thus the overall estimated net flux from LULUCF resulted in a removal of 754 Mt CO_2e (EPA, 2023). On the other hand, emissions from the U.S. agriculture sector (crop and livestock systems) were 598 Mt CO_2e the same year. Therefore, the U.S. AFOLU sector combined constituted a net CO_2e sink of approximately 156 Mt CO_2e in 2021.

FIGURE 1-2 **U.S. greenhouse gas emissions and sinks from agriculture and LULUCF sectors (in Mt CO_2e, 1990–2021)**



[1] Per IPCC guidelines (IPCC, 2006), the LULUCF sector includes reporting of fluxes related to changes within and conversions between all land-use types including: forest land, cropland (including the soil carbon pool), grassland, wetlands, and settlements as well as other land.

Data source: 2023 U.S. GHGI (EPA, 2023).

The 2023 GHGI (EPA, 2023) indicates that while the AFOLU sector currently is a net sink, the estimated net sink over time has been getting smaller.

Carbon fluxes associated with forested lands make up most of the LULUCF net removals; in 2021, 793 Mt CO_2e was stored in forests of which 695 Mt CO_2e came from existing forests and 98 Mt CO_2e from lands converted to forests. However, since 1990 the net sink from forests has decreased by 126 Mt CO_2e. As forested land area has stayed relatively constant in the last 30 years (in 2021, the United States had 692 million acres of managed forest land, which is less than a 1% decrease compared to 1990), the decline in the sink was primarily driven by a reduction in the rate of net carbon accumulation in forests (EPA, 2023). This slowing rate of carbon accumulation has multiple drivers, including the age of U.S. forests (Wear & Coulston, 2015) and the increase in natural disturbances (EPA, 2023). In the future, possible increased levels of natural disturbances—such as fires, insects, diseases, droughts, and storms largely due to climate change—could potentially reduce the net forest carbon sink even further (Seidl et al., 2017). These trends may be counterbalanced by increasing timber demand and/or emerging demand for new forest-based products and bioenergy that will encourage continued and new investments in forested lands and restoration activities (Tian et al., 2018; Wade et al., 2022). Also, mounting evidence of CO_2 fertilization effects (the phenomenon that higher atmospheric levels of CO_2 can enhance tree growth) can in some regions boost tree growth and increase corresponding carbon sequestration per hectare of forests (Baker et al., 2023; Davis et al., 2022; Mendelsohn et al., 2016; Norby & Zak, 2011). These countervailing drivers make the possible future of U.S. forest carbon levels uncertain. Some studies and modeling tools estimate that U.S. forests may become a net source of emissions in the next 10–40 years (Coulston et al., 2015; U.S. Department of Agriculture Forest Service, 2012; Wear & Coulston, 2015), whereas other studies estimate that the net forest carbon sink may be maintained or even increase in the coming decades (Favero et al., 2021; Tian et al., 2018; U.S. Department of State, 2014, 2022), and still others point out that forests could either increase or decrease their future carbon storage (Ryan et al., 2012). Differences driven by things such as different research goals, modeling approaches, study design, and data inputs are discussed in general below and for specific studies in Chapter 4.

The agriculture sector emits GHGs through various activities including livestock management (generally to include enteric fermentation and manure management), rice cultivation, liming, urea application, field burning of agricultural residues, and agricultural soil management.[2] Total agricultural GHG emissions (from both crop production and livestock practices) were 598 Mt CO_2e (9% of total U.S. GHG emissions) in 2021 (EPA, 2023), a 51 Mt CO_2e increase since 1990. Compared to economy-wide emissions that decreased by 2% from 1990 to 2021, emissions from the agriculture sector increased by 7% over the same timeframe. In 2021, enteric fermentation was the largest anthropogenic source of CH_4 emissions, accounting for 195 Mt CO_2e (about 27% of total CH_4 emissions). This level represents a 6% increase since 1990, largely due to increasing cattle populations (EPA, 2023). Manure management emissions increased 62% between 1990 and 2021 (from almost 50 Mt CO_2e to about 80 Mt CO_2e) due to rising populations of key livestock species and intensification of livestock production. Agricultural soil management activities were the largest contributors to U.S. N_2O emissions in 2021 (accounting for 74%), and these levels have been relatively constant since 1990. In the future, as the population and economy continue to grow, the national and international demand for agricultural commodities is expected to increase which could drive more land to be converted to cropland and/or subjected to intensified production. These changes in land use and land management are expected to increase GHG emissions over the next several decades under business-as-usual practices (Wade et al., 2022).

[2] Per IPCC reporting guidelines, the U.S. GHGI includes soil carbon stock changes on agricultural lands as part of the LULUCF sector.

1.3 Overview of Mitigation Opportunities

A broad range of different potential mitigation actions currently exist—some have been employed for decades, whereas others are still in research and development stages.

These activities generally focus on preserving and enhancing existing carbon pools and GHG-rich landscapes, and on increasing active sequestration via removals from the atmosphere and directly reducing GHG emissions.

Table 1-1 includes key examples of land-based mitigation options sourced from different studies (starting with practices that are widely deployed followed by lower-adoption and/or emerging options). Not all the options listed in the table are included in this report but they are included here for comprehensiveness (for many emerging mitigation options, there are not yet sufficiently comprehensive datasets for such practices applied in the United States).

Estimated magnitudes of different mitigation options from different studies are highlighted in Figure 1-3 and are discussed in more detail in comparison with the results of this study in Chapter 4.

TABLE 1-1 Land-based mitigation options, as defined in the literature

Land-based mitigation options	Description	References	Included in this report	Level of adoption
Afforestation and reforestation	Increase in above and below ground carbon sequestration from conversion of land to forest that either historically has not contained forests (afforestation) or has recently contained forests (reforestation).	Busch et al. (2019)	Yes	High
Reduce deforestation/ reduce forest conversion[a]	Increase in above and below ground carbon sequestration from actions that avoid the conversion of forest to non-forest. While deforestation still occurs globally, it mainly occurs in the tropics.[b]	Austin et al. (2020); Busch et al. (2019)	Yes (but in the United States, it includes only reduced conversion because widespread deforestation is not expected to occur in the country in the future)	High
Improved forest management	Increase in above and below ground carbon sequestration from improved forest management strategies which include extending timber harvest rotations and increasing the productivity of forests through thinning diseased and suppressed trees, decreasing competition by removing brush and short-lived trees, increasing stock levels in understocked areas, and maintaining stocks at high levels.[c]	Austin et al. (2020); Sohngen & Brown (2008); Van Winkle et al. (2017)	Yes	High
Forest CO_2 products	Carbon storage via production of long-lived wood products; substitution of wood products for carbon-intensive materials like cement in buildings.	Griscom et al. (2017); Sohngen & Brown (2008)	Yes (substitution of carbon-intensive materials is not included)	High

Land-based mitigation options	Description	References	Included in this report	Level of adoption
Forest CO_2 soil	Enhance soil organic carbon sequestration in forests.	Jiang & Koo (2013)	Yes	High
Cropland non-CO_2	Management activities to reduce/avoid N_2O and CH_4 emissions associated with nitrogen application and through nutrient management, residue management, water management, dry seeding and combinations of these activities; avoided N_2O from reducing total fertilizer application.	Beach, Creason, et al. (2015); EPA (2019a, 2019b)	Yes	High
Cropland CO_2	Reduce CO_2 emissions from fossil fuel use for agriculture production.	Wade et al. (2022)	Yes	High
Agricultural CO_2 soils	Enhance soil organic carbon sequestration in croplands by shifting from, for example, current management to no-till management, changes in residues management and crop mixes	Pape et al. (2016); Roe et al. (2021)	Yes	High
Livestock non-CO_2	Management activities to reduce/avoid CH_4 emissions from ruminant livestock enteric fermentation (e.g., changing diets, feed additives), and CH_4 and N_2O emissions from improved manure management practices (e.g., adoption of improved anaerobic digesters).	Archibeque et al. (2012); Beach, Zhang, et al. (2015); EPA (2019a); Hristov et al. (2013)	Yes	High
Pasture and rangelands management	Retain carbon stocks (e.g., in soils, root systems) by avoiding LUC and improving grazing practices.	Baker et al. (2020); Bogaerts et al. (2017); Claassen et al. (2018); Jones & O'Hara (2023)	Yes	High
Improved resilience to natural disturbances	Avoided emissions from natural disturbances (e.g., fires) via practices such as hazardous fuel removals.	Griscom et al. (2017)	No (emerging option)	Low
Bioenergy with carbon capture and storage (BECCS)	Carbon sequestration from electricity generation derived by combusting crop-based or forest-based biomass and combined with carbon capture and storage (CCS).	Hanssen et al. (2020)	No (emerging option with high uncertainty of future demand)	Low
Reduce land degradation and restore natural lands	Avoided emissions from degradation and/or loss of carbon stocks in mangrove ecosystems, wetlands, and degradation of peatlands (emerging options).	Griscom et al. (2017); Humpenöder et al. (2020); The White House (2016)	No (emerging option)	Low
Other practices	Alternative solutions such as increased adoption of riparian buffers, solid separators, agroforestry practices, application of biochar, and enhanced weathering.	Pape et al. (2016)	No (emerging options)	Low

[a] This category does not include forestland managed through periodic harvesting for timber production.

[b] The IPCC *Special Report: on Climate Change and Land* defined deforestation as the conversion of forest land to non-forest land (IPCC, 2019a).

[c] Improved forest management could also increase forests' adaptability to climate change, making them less susceptible to future wildfire, drought, and pests (as shown in Anderegg et al., 2020).

1.4 Assessment Approach

> Insight into future potential trends in forest and agriculture GHG emissions fluxes, and the environmental and economic conditions that drive those trends, is necessary for the design of effective mitigation programs and policies, as these trends can influence the magnitude and costs of various GHG abatement activities (Baker et al., 2017; IPCC, 2019b; Van Winkle et al., 2017).

This report is intended to establish a foundation for evaluating the broad potential of AFOLU mitigation across the United States and as such must incorporate market feedback effects. To achieve this end, this study focuses on application of economic simulation models, which integrate detailed land use and biophysical processes with land management responses to market drivers and costs under various scenarios of future conditions to explore the relationships between policies and other drivers on decisions related to agricultural production activities, forestry management, and other related land use and land use changes.

The three models simulate baseline and alternative scenario projections of U.S land use activities and characteristics including land use management, land use change, demand and supply of commodities produced, associated costs and GHG fluxes. These projections were constructed using historical ecological data (e.g., detailed land GHG information from process models such as DAYCENT), economic parameters (e.g., cost data pertaining to specific forest management activities) and specified future economic and technological conditions. These future conditions include socioeconomic elements that can significantly influence how land resources are used and managed, such as future GDP and population growth and assumptions on technological innovations impacting agricultural productivity. Future socioeconomic assumptions are harmonized across models and unchanged under policy scenarios. Finally, mitigation scenarios are explored in the models in forms of payments for GHG abatement and carbon sequestration activities. The inclusion of fiscal incentives like these payments modifies business-as-usual trends and allows for evaluating how those incentives change the U.S. land use activities and characteristics and associated GHG fluxes relative to the baseline.

Moreover, all three models explicitly capture important feedbacks that occur when market changes influence the opportunity costs of investing in land use sector mitigation, and hence affect the resulting potential magnitude and cost of different GHG mitigation activities over time.

1.4.1 Different Approaches for Estimating Mitigation Potential

The development of projections of future GHG fluxes in the forest and agriculture sectors is particularly challenging due to spatial and temporal variability in land carbon stocks and GHG flux processes, dynamic and interconnected global markets for forestry and agricultural commodities (Forest2Market, 2018; Latta et al., 2016; Ohrel, 2019; Schmitz et al., 2014), diversity among land owners and their management responses to market signals (Håbesland et al., 2016; Sohngen & Mendelsohn, 2003), and uncertainty regarding the effects of policies that influence land use and commodity markets directly and indirectly (e.g., bioenergy policies) (Favero et al., 2020; Guo et al., 2019; Latta et al., 2013; Wise et al., 2014).

Different models are designed to address these challenges in various ways, and with different levels of complexity, spatial and temporal detail, input data, model structure and specification, sectoral coverage, macroeconomic assumptions, and analytical objectives (e.g., Latta et al., 2018; Sjølie et al., 2015; van Meijl et al., 2018; Wade et al., 2019). Because modeling tools are often developed in different ways and for different purposes, they can produce divergent estimates of mitigation potential (Ohrel, 2019; U.S. Department of State, 2014; U.S. Department of State & the U.S. Executive Office of the President, 2021).

Various approaches and modeling tools have been used in the literature to simulate future trends in forest and agriculture GHG fluxes and assess mitigation potential of land, including biophysical or ecological process models (Law et al. 2021; Law et al. 2018), techno-economic approaches (Cook-Patton et al., 2021; Eagle et al., 2022; Fargione et al., 2018), econometric models (Lubowski et al., 2006), PE models (Baker et al., 2013; EPA, 2005), computable general equilibrium (CGE) models and integrated assessment models (IAMs) (Calvin et al. 2019; Golub et al. 2009).

Ecological models are used to consider future biophysical characteristics and potential GHG profiles of, for example, forests and they provide useful information to assess biophysical parameters such as maximum yields, forest ecosystem dynamics, and climate change impacts on forests. This methodology usually does not include human-induced changes in forest productivity via changes in management activities driven by policies and/or market signals (e.g., demand shifts); therefore, their findings might provide only a partial perspective of the mitigation potential of land.

A reseeded forest managed plot in Shasta County, California, in the northeastern section of the state.

In AFOLU applications, techno-economic (or bottom-up) approaches generally aggregate individual marginal abatement costs from different sources to provide the cumulative abatement available from the land sector. This approach usually lacks a representation of resource competition across sectors or mitigation options, which may yield outcomes that overestimate the potential GHG mitigation from the resource or underestimate the cost of abatement activities. Other studies provide a static representation of mitigation opportunities by measuring the maximum technical and economic mitigation potential under specific engineering assumptions (e.g., EPA, 2019a).

Econometric models are used to estimate carbon sequestration potential by simulating the effects of carbon subsidies on land rent and land abatement activities and corresponding changes in carbon sequestration. Sampling-based and simulation approaches such as the one devised by Jiang and Koo (2013) use current census data and producer preferences to simulate future mitigation potential of land. Usually, both of these methodologies can assess mitigation costs at the regional level, but they make implicit assumptions about land availability with simplified representations of biophysical constraints.

PE models, such as the three used for this report (FASOMGHG, GLOBIOM, and GTM) equate supply and demand in one or more markets such that prices stabilize at their equilibrium level. PE models tend to have a high level of detail in the land sector, but limited interactions with other sectors relative to IAMs, as discussed below.

CGE and IAM models are more comprehensive in their representation of the economy, reflecting feedback effects among all economic sectors and factors of production, such as capital and labor. CGE models are the broadest in economic scope but tend to lack detail in their physical and technological representations. IAMs are the broadest in their representation of the interactions between human (e.g., economic) and Earth (e.g., biophysical) systems but often lack detail in their representation of particular sectors (e.g., finance, labor) and technologies. For example, CGE models are designed to track resources in terms of their monetary value and require subsequent accounting methods to estimate physical quantities. On the other hand, IAMs incorporate complex market interactions, as these models typically are global and economy-wide in scope and have extensive economic representation, but often do not have the level of detailed biophysical or mitigation activity cost information needed for national and subnational analyses of land-based mitigation, especially for forestry (e.g., Calvin et al., 2019). Furthermore, these complex models provide results at the global or regional level without detailed descriptions of country-specific mitigation potential. Further discussion of general attributes related to these different approaches can be found in Ohrel (2019).

When considering tradeoffs between these methodological options, one must consider the goals of the analysis and whether cross-sectoral impacts are potentially influential on the overall results. For this specific report, the analysis primarily focused on detailed behavior within the land sector. PE models are well suited for this type of analysis as they provide a detailed representation of economic factors driving the markets of land commodities together with a sophisticated representation of biophysical characteristics of land. Moreover, the three PE models selected for this report have some important differences that allow them to portray a range of possible outcomes on the future of land mitigation in the United States and consider resource competition in their mitigation assessment across activities.

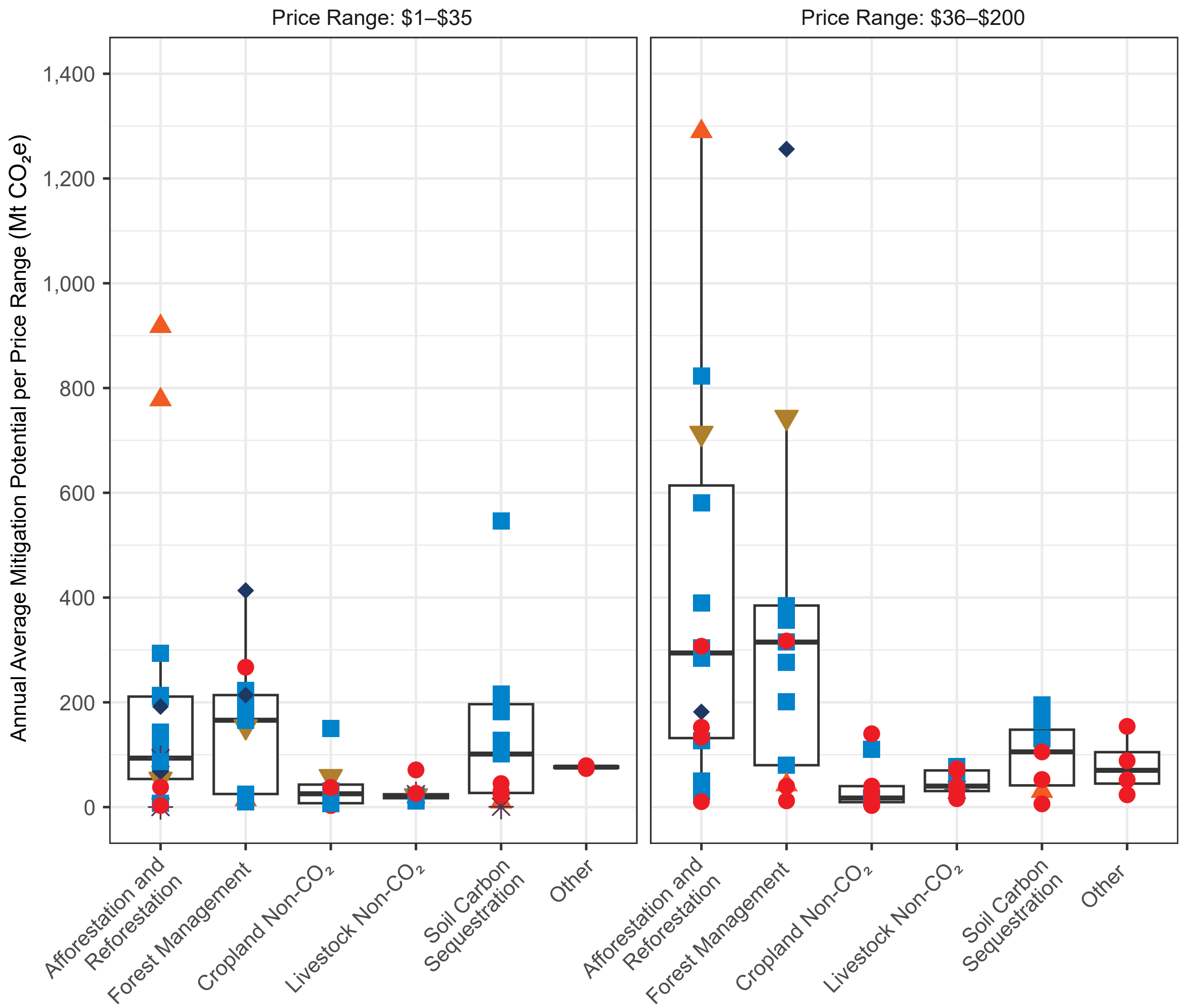
A review of peer-reviewed articles and reports from 2000 to 2022 conducted for this report identified 39 studies assessing land-based mitigation potential using six main methodologies. Because multiple methodologies have been developed to estimate abatement opportunities in the land sector, the literature presents a large range in recent studies' estimated mitigation potential for activities in the forestry and agriculture sectors, driven largely by model type and different underlying scenario parameters (Figure 1-3). For example, estimates of mitigation potential from improved forest management in the United States differ by a factor of ten due to variations in macroeconomic assumptions, abatement policy formulations, and economic modeling approaches (Van Winkle et al., 2017). Despite the differences, the studies reviewed and reflected in Figure 1-3 indicate that the average mitigation potential of forest-based activities is likely to be higher than agriculture-based activities, but the associated degree of uncertainty also is higher. Moreover, the mitigation potential of forest-based activities is likely to be more sensitive to the assumed price incentive; for example, the average mitigation of forest management increases by 90% under the \$36–\$200/t CO_2e price range relative to the lower price range.

1.4.2 Modeling Approach Used in this Report

Historic U.S. land use and land use management changes and related levels of GHG fluxes were shaped over time by a variety of environmental, social, and economic conditions, and thus simulation of future trends in this arena should be informed by these key elements. U.S. lands are heterogeneous, and the commodities and markets related to lands are as well, making it crucial that tools applied to assess GHGs associated with U.S. lands reflect these varied biophysical and economic aspects. Exploring the dynamic roles that forest and agricultural lands can play in U.S. mitigation efforts requires tools that 1) include both biophysical and economic capabilities (meaning competition between resources is reflected), 2) are based on historical data, and 3) can simulate baseline trends as well as project potential impacts of different future market, social-economic, environmental, and technical conditions, including mitigation policies and incentives.

This analysis applies three detailed economic models that simulate future potential GHG fluxes, land cover change, and commodity production in the forestry and agriculture sectors using detailed regional biophysical and economic land input data. The three models incorporate the capabilities and detailed attributes necessary to generate projected outcomes that consider the important interactions among managed natural resources, markets, and other key socioeconomic and biophysical components. Of particular importance in the selection of these tools is the ability to

FIGURE 1-3 **Average mitigation potential per price range (\$1–\$35/Mt CO_2e and \$36–\$200/Mt CO_2e) across land-based activities in the United States**



Averages were calculated using data from Van Winkle et al., (2017) and original sources listed in Appendix B. Many studies report mitigation potential in 2030 while other studies (e.g., Cook-Patton, Gopalakrishnaet al., 2020; Roe et al., 2021) do not explicitly mention the time horizon assumed in their analyses.

The category “Other” includes the following mitigation activities: peatland restoration, reducing conversion of mangroves, coastal wetland (mangrove) restoration (tropics), agroforestry, biochar, BECCS, food waste, altered diets, cover crops, windbreaks, avoided grassland conversion, alley cropping, grassland restoration, grazing optimization, legumes in pastures, fire management, urban reforestation, avoided seagrass loss, and seagrass restoration.

incorporate competitive market interactions, which means that projections of mitigation potential and associated costs from these tools can provide additional insight beyond what is provided via purely biophysical or techno-economic assessments. The models used in this report include data from a variety of sources (discussed further in Chapter 2), including biophysical or process models.[3]

The models simulate both a future without new or additional land-based mitigation policies in place (baseline scenario) and multiple scenarios that can emulate different levels of mitigation incentives or other policy incentives. GHG mitigation strategies in this study are represented in each model as GHG price incentives under different initial values and growth rates. By including alternative future mitigation scenarios, the report presents a future range of land abatement potential driven by the price level associated with GHG emissions.

By including the same GHG price pathways in three different well-recognized models, the report presents the effects of the underlying models' parameters, assumptions, scale, and scope on the mitigation potential estimates. In this way, multiple levels of uncertainty are explored and considered to present a most likely (if possible) outcome of the future mitigation potential of the land sector. Moreover, each model is uniquely suited to provide different perspectives and insights related to key drivers of land-based mitigation activities in the United States—global market competition (GLOBIOM), cross-sector interactions (FASOMGHG), and forestry investments (GTM), all of which have particular importance for assessment of this sector.

Finally, because the baseline does not incorporate recent and proposed policies, the results could be used to estimate the effects of different policies on land use and land management. Moreover, price incentive scenarios could be used to emulate alternative programs and their results could be used to assess the potential effects of the program on land use and land mitigation potential.

1.4.3 Multi-Model Comparison

It is critical that the forest and agriculture modeling communities continue to evaluate the performance of their models both independently and as part of larger model comparison efforts (Daigneault et al., 2022; Fujimori et al., 2019; Rosenzweig et al., 2014). The analysis in this report compares three independently developed models built on observed (and modeled) economic and biophysical data. Comparing multiple models allows for more robust evaluation of different potential outcomes, reduces potential bias inherent in single-model projections, and provides a deeper understanding of model results' sensitivity to input data, structural features, and underlying assumptions. This multi-model approach allows for more transparent representation of uncertainties and more robust understanding of the directionality and magnitude of mitigation potential and costs than a one-model approach. Identifying results that are consistent and robust across different models and assumptions can build confidence in projections (e.g., Schmitz et al., 2014; Waldhoff et al., 2015).

The multi-model approach applied in this report provides insight into the variability in projected baseline pathways together with the projected portfolio of abatement opportunities and associated costs across models under different levels of incentive. The variability is driven by the individual attributes of each model framework despite some key data and parameters being harmonized across models. Moreover, the multi-model approach can elucidate the potential role of globally integrated markets and global availability of mitigation opportunities on U.S. domestic mitigation quantities and costs (see van Meijl et al., 2018, for a similar example). Finally, this approach allows for a direct comparison between domestic and global frameworks to understand the relative impacts of policies implemented domestically versus those implemented globally and supports evaluation of the role of international trade dynamics on domestic mitigation cost estimates.

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[3] For example, the FASOMGHG model uses data from the DayCent model to inform its crop analysis. DayCent is a biogeochemical model that tracks soil processes in daily time steps to allow scheduling of management practices (IPCC Tier 3 method). To initialize levels of soil organic matter pools, DayCent estimates pre-settlement vegetation and historical cropping practices from 1900-to the present (Del Grosso et al., 2012). Whereas process models often require data from previous decades to establish initial or equilibrium conditions, economic-based future simulation models do not rely on and therefore do not include decades of historic data. Relatedly, validation exercises for these types of models are often conducted via sensitivity tests as opposed to validation via comparison of measured historic data with projected results for historic time periods (Canova, 1995; Ohrel, 2019).

Box 1

FOCUS: Representation of resource competition in partial equilibrium models

PE models, like those used in this report, endogenously account for market opportunity costs as commodity market adjustments occur in response to mitigation investments. Conversely, techno-economic estimates of marginal abatement costs taken in isolation do not account for market opportunity costs and could thus represent an overly optimistic perspective on mitigation potential at a given price incentive. Some studies (such as Fargione et al., 2018), may directly compare or add together results from a variety of studies (e.g., a mix of biophysical and technical potential analyses and competitive market potential estimates) to estimate maximum mitigation potential. Applied in this manner, this approach may overestimate mitigation potential at a given price because it does not incorporate important resource competition, opportunity costs, and market interactions that would arise as different mitigation practices across sectors are implemented simultaneously, thus reducing mitigation potential.

Figure B1 provides a simple illustration of market opportunity costs. If commodity supply and demand (left-hand side) are explicitly linked to the total abatement from some mitigation strategy (depicted by the MACCs on the right-hand side), then the level of abatement could impact the total supply of the commodity. As a hypothetical example, N_2O emissions reduction from alternative nitrogen (N) fertilizer management strategies could induce a small yield loss in certain contexts. A traditional MACC framework will reflect the farm-level opportunity costs of this yield loss valued at the original crop price, through the corresponding increase in mitigation price (Pc) required to "break even" or keep farm revenue constant. This effect can be shown as movement along MACC1 with higher levels of abatement (A^1 to A^2 in this hypothetical example) from an increase in the mitigation price (P_c^1 to P_c^2).

In a linked model, the yield loss would also affect the market equilibrium for crops. Lower yields would result in a shift of the commodity supply function (e.g., from S^1 to S^2). This supply shift results in higher market prices overall (P_c^1 to P_c^2), and lower equilibrium production levels (Q^1 to Q^2).

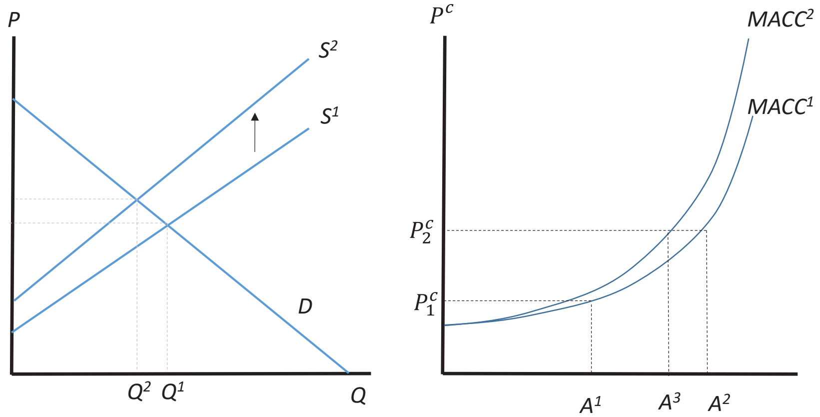
As these two mechanisms work together, the higher market prices for crops are passed back to the MACC model on the right. That is, higher market prices raise the marginal costs of abatement by increasing the opportunity costs of forgoing production. In this example, this price change results in a shift in the MACC ($MACC^1$ to $MACC^2$) to reflect higher opportunity costs of foregone commodity production, thus lowering total abatement from A^2 to A^3. In a combined model, these processes iterate until convergence is achieved.

While this simple conceptual diagram illustrates the market potential of a particular strategy by reflecting market opportunity costs, PE models can reflect market opportunity costs for multiple abatement sources and associated commodity markets simultaneously. That is, PE models can also quantify the competitive market potential of a particular abatement strategy, which acknowledges resource competition across sectors (e.g., finite land resources) and competition across different abatement strategies under a given set of market conditions and mitigation incentives.

Returning to the nitrogen fertilizer management example, consider an alternative situation where incentives are available for a second abatement strategy: afforestation. In this case, afforestation incentives could increase the competition for land resources, because as mitigation prices may induce tree planting on agricultural lands. This shift in land use pressures commodity supply (again shown as a leftward shift of the crop supply function in the left panel) and further raises the opportunity costs of reducing yields from alternative nitrogen management strategies (right panel). Thus, the competitive market potential of nitrogen management change as a mitigation strategy in conjunction with changes in afforestation could be lower than the market potential of nitrogen management considered in isolation (see Ohrel, 2019, for a more comprehensive discussion of market vs. competitive market mitigation potential).

By reflecting commodity market dynamics and resource competition, PE models provide a more comprehensive estimate of mitigation potential. Further, unlike techno-economic analyses, these models offer flexibility in simulating different policy or market frameworks and associated performance metrics. For example, PE frameworks can simulate outcomes of different policy or pricing designs, such as those that identify specific mitigation activities or those that look at the effects of regional programs targeting AFOLU strategies, as well as associated indirect consequences (e.g., leakage, as discussed in Box 4) (Fingerman et al., 2019; Latta et al., 2011).

Figure B1: Conceptual illustration of market opportunity costs for a hypothetical commodity market and MACC for an abatement strategy that generates a loss in yield or total production



The panel on the left shows a hypothetical commodity market with demand D and initial supply S. The panel on the right shows the MACC for an abatement strategy where A is abatement and P the marginal cost of A abatement (e.g., P_1^c represents the marginal costs of abating up to A^1). In this simple conceptual example, the market opportunity cost is the direct feedback between the market price change associated with a change in the mitigation quantity and the marginal costs of abatement.

1.4.4 Harmonization

Key underlying factors—such as future macroeconomic variables and underlying biophysical data like U.S. forest representation—are harmonized across the models to mitigate the degree of variability in projected GHG outcomes stemming from differences in these influential variables (see Wade et al., 2022). The goal of this analysis was not to exactly align the baseline projections across models but instead to harmonize specific data inputs and future conditions to a reasonable extent and then explore changes in emissions between the baselines and various counterfactual price scenarios. This limited harmonization approach is recognized and regularly applied in the literature as well as in numerous U.S. government official reports and submissions to, for example, the UN Framework Convention on Climate Change (U.S. Department of State, 2014, 2016, 2021, 2022).

The models are run in parallel, not in a linked or interactive manner (where outputs from one or more models are fed into another model). The conceptual framework of the applied approach here progressively zooms in on different topics across the models that highlight the strengths of each model—starting with a global model capturing global biophysical and economic interactions, followed by a domestic model offering detailed results on the U.S. agriculture and forest sector land use and market interactions, and then a global forestry model focusing on the more specific U.S. forestry and forest market dynamics and how they relate with global markets. Linking these tools in an iterative or linked fashion could offer useful insights and thus presents an opportunity for future research.

Part of this analysis's objective was to study the independent projected outcomes of the individual models selected. All three tools include a detailed representation of U.S. forest and agricultural lands and associated GHG fluxes. Although the GHG gases and GHG mitigation activities are not the same across the models, the intent is to evaluate the extent to which the outcomes across the models as they are generally applied align or differ and to understand why. In addition to offering insights into cost-effective GHG mitigation opportunities available in the United States, this aspect of the evaluation—how tools can approach mitigation assessment differently and how that affects outcomes—can also be useful to policymakers as they look to different types of modeling tools to evaluate different policy designs to address climate change.

1.4.5 Interpretation of Results

The three economic models projected the future of the land sector in terms of land cover, management, carbon stocks, and GHG emissions under specific ecological, socioeconomic and policy assumptions that represent the main drivers of land demand (e.g., GDP) and land availability and productivity (e.g., regional supplies of land-based commodities). The results are indeed estimates of potential outcomes under specific assumptions about future socioeconomic, environmental, technology, and policy conditions. They are intended not to serve as predictions of the future but rather to offer insights into what might occur given a certain set of conditions. Although these types of models are simplifications or abstractions of reality, they provide valuable insights to policymakers designing and implementing policies that affect forestry and land use about the potential directionality and magnitude of policy outcomes given certain conditions, assumptions, and constraints while acknowledging related uncertainties.

In the report, results are presented in different forms:

- Absolute values such as GHG emissions (in Mt CO_2e), land area (in million acres), timber harvest (in million metric tons), and crop and livestock production (in million tons).
- Average annual change from the baseline scenario. In the report, land mitigation potential and abatement potential are interchangeable terms used to describe the change or "delta" in emissions between the baseline scenario without GHG price scenarios and the GHG price scenarios. Other key results such as changes in forest area, pastureland, and cropland from the baseline scenario are presented in the report.
- Relative change from a base year. Projected changes in GHG emissions aligned to a specific year.
- Distribution of mitigation activities by regions and by sectors under specific GHG price scenarios.

- In addition, MACCs are calculated by combining the projected abatement with the GHG price driving that level of abatement in each reference year across GHG price scenarios. Annual observations are interpolated using a polynomial function that represents the curve. MACCs for subsectors and for each GHG are also presented in the report and they represent the potential abatement achieved by specific activities under each GHG price scenario.

The results from each model should be viewed as complementary to one another as they can provide different perspectives on outcomes generated using common scenarios. Each set of results provides a valuable source of information on GHG abatement trends that can inform detailed policy or research applications. This complementarity is important, for example, in cases where end users are developing regionally focused climate strategies or investment decisions, which may require spatially disaggregated results from the domestic model; or in the case of practitioners in the global climate finance community, who may need results that capture trade impacts from the global models.

Finally, the results presented in the report can offer useful insights to different stakeholders. The results can, for example, help identify opportunities for landowners to participate in offset markets or other conservation initiatives to boost rural economic development and save money by reducing fertilizer applications or improving soil health. The report also provides further guidance on the interpretation of results from each model and suggests key considerations for determining the most appropriate set or range of mitigation results for a given policy or research application.

1.5 Report Organization

The remainder of this report is structured as follows:

- **Chapter 2: Methods and Scenario Design** introduces the models and details the scenario design used in this analysis.
- **Chapter 3: Baseline and Mitigation Scenario Results** presents information on key baseline trends, reviews mitigation cost estimates and abatement portfolios at the national and subnational levels in the United States and over time, and provides the multi-model comparison of mitigation outputs.
- **Chapter 4: Discussion and Future Research** offers key takeaways from this analysis, caveats and limitations, results from sensitivity analyses, and general guidance on the practical use of mitigation estimates from this report. It also compares results from this analysis to those from previous studies, including the 2005 EPA report, which also presented estimates of mitigation potential in U.S. forest and agriculture sectors. This chapter also discusses limitations of the report and future research needs.
- **Supplemental appendices** offer more detailed information on the three specific modeling frameworks applied and models' outputs.

Twelve boxes provide either stand-alone analyses (FOCUS) or sensitivity tests of models' assumptions and the results (SENSITIVITY).

2 Methods and Scenario Design

This chapter describes the models, methods, and scenarios used in this technical report to estimate GHG mitigation potential and costs in the U.S. forest and agriculture sector.

The first section describes the models used in this report and provides key details on those models. The next section discusses how certain elements have been harmonized between the selected models. Lastly, the chapter discusses the scenarios applied in the analysis.

2.1 Background Information on Models Applied and Modeling Approach

This report uses three well-recognized land use models that include detailed economic and biophysical sectoral coverage: FASOMGHG, GLOBIOM, and GTM.

The report uses three models—FASOMGHG, GTM, and GLOBIOM—that include detailed economic and biophysical sectoral coverage, detailed spatial data, and temporal range. Each of these models has been extensively applied in the literature for a variety of objectives, including projecting land management, market, and environmental changes across different policy, environmental, and macroeconomic scenarios. They have also been used in various official government modeling applications. For example, FASOMGHG and GTM were used to evaluate land-based mitigation potential in legislative policy proposals (EPA, 2009) and LULUCF projections in several U.S. government reports (e.g., U.S. Department of State, 2022; U.S. Department of State & the U.S. Executive Office of the President, 2021). GLOBIOM has been used by the European Commission to build the EU Reference Scenario 2020, the policy scenarios for delivering the European Green Deal, the EU Climate Target Plan impact assessment, and the in-depth analysis of the EU Long-Term Strategy (European Commission, 2018, 2020; European Commission Directorate-General for Energy, n.d.).

This section discusses the models considered in the report: FASOMGHG, GLOBIOM, and GTM. A summary of each of these models is provided, including their history, sectoral representation, spatial coverage and resolution, temporal representation, and GHG emissions representation. Links to detailed documentation and discussion of previous applications for each of the models are provided. As previous versions of each model have been thoroughly documented through past technical reports and academic manuscripts, model characteristics discussed here are limited to recent model updates and attributes most pertinent to this analysis. Section 2.5, provides an overview

The Pacific coast of California with farmland close to the cities of Salinas and Monterey.

Each of the three land use models used in the report has been extensively applied in the literature for a variety of objectives, including projecting land management, market, and environmental changes across different policy, environmental, and macroeconomic scenarios. They have also been used in various official government modeling applications.

of similarities and differences across models, including more details on the models' attributes, and highlights model elements that were harmonized for this analysis. Section 2.6 provides information on how the models were aligned under baseline scenarios. Section 2.7 presents background on the mitigation scenarios implemented in each model. Finally, Section 2.8 introduces stand-alone analyses that were implemented in each model to further take advantage of each model's unique capabilities.

2.2 Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOMGHG)

FASOMGHG is a U.S.-only, intertemporal optimization economic model of the agricultural and forestry sectors.

2.2.1 History and Model Applications

FASOMGHG is a dynamic non-linear optimization model of the forestry and agriculture sectors in the United States, developed initially by Dr. Bruce McCarl at Texas A&M University, Dr. Darius Adams at Oregon State University, and Dr. Ralph Alig at the U.S. Forest Service (USFS) (Adams et al., 2005; Adams et al., 1996; Beach et al., 2010) in collaboration with researchers at RTI International, EPA, North Carolina State University, University of Idaho, and Texas A&M for the version used in this study.

Since the use of FASOMGHG in the 2005 EPA report, the model has been substantially updated to reflect new data and technologies as well as improve applicability to emerging environmental and policy issues. In-depth documentation reports of model updates include Adams et al. (2005) and Beach et al. (2010), with additional supporting documentation on intermediate updates presented in Jones et al. (2019) and Wade et al. (2022).

Since 2010, FASOMGHG has undergone extensive development to update its forest sector representation. The FASOMGHG forestry side is based on spatially and temporally aggregated inputs from the spatially detailed Land Use and Resource Allocation (LURA) modeling system, described in Latta et al. (2018). The LURA framework includes a spatially explicit supply-side representation of the U.S. forest resource system based on 2015 USFS Forest Inventory and Analysis (FIA) National Program inventory data and new empirically estimated yield growth curves that vary by region, site class, forest type, ownership, and management intensity. Plot-level information from the LURA model is aggregated to FASOMGHG regions to maintain a consistent inventory and age-class distribution of different forest types by site class (Latta et al., 2018). Additional information on the LURA-to-FASOMGHG development process, plus other relevant updates to agricultural sector data and inclusion of new mitigation technologies, can be found in Jones et al. (2019).

Moreover, Wade et al. (2022) updated FASOMGHG to include alternative baseline assumptions for each of the five Shared Socioeconomic Pathways (SSP) (Riahi et al., 2017). This update included revised parameters for urbanization expansion, using projected urbanization rates from each SSP coupled with historical rates of land conversion to development based on the 2015 National Resources Inventory (U.S. Department of Agriculture Natural Resources Conservation Service, 2017). Exogenous demands for agricultural products in FASOMGHG were adjusted according to the different levels of GDP per capita and dietary assumptions in each SSP. Finally, differences across SSPs in the forest sector were reflected as changes in domestic demand for harvested wood products (HWP), shifts in biomass for energy demand based on Annual Energy Outlook (AEO) 2022 projections (EIA, 2022), and changes to forest product exports based on Daigneault and Favero (2021).

In terms of policy applications, FASOMGHG has been used to assess adaptation to environmental change by Beach et al. (2015) and Zhang et al. (2014), GHG mitigation potential of and associated economic impacts of mitigation and renewable energy policies (Alig et al., 2010; Baker et al., 2010; Latta et al., 2013; Ogle et al., 2016), and biofuel policy analysis with global systems models (Mosnier et al., 2013). Different versions of the model have been used to support federal policy and research efforts, including for the Renewable Fuels Standard (RFS2) Regulatory Impact Analysis (Beach and McCarl, 2010) and illustrative case studies published in EPA's draft biogenic CO_2 assessment framework report (EPA, 2014). The latter relied on improved model representation of biopower generation and costs from alternative agriculture and forestry feedstocks, including regional boiler capacity constraints and co-firing options from Latta et al. (2013). Moreover, Galik et al. (2019) uses the version of the model presented in Latta et al. (2013) to evaluate a range of federal incentives designed to reduce emissions from agriculture and forestry. Cai et al. (2018) incorporate new supply curves for afforestation and compare mitigation outcomes across cost specifications. Jones et al. (2019) present emissions projections and policy analysis using the updated version of the model with a redesigned forest sector, and Wade et al. (2022) evaluate mitigation potential across a range of socioeconomic scenarios.

2.2.2 Economic and Biophysical Features

This model is a detailed dynamic non-linear intertemporal optimization model of the U.S. forestry and agriculture sectors with representations of regional production processes, land management potential, and commodity market feedbacks, along with spatial heterogeneity in forestry and agriculture activity productivity and production costs.

FASOMGHG uses 63 subregions for agriculture, 11 market regions for forestry and bioenergy (Appendix A, Figure A-1), and a limited representation of bilateral trade with specific regions outside of the United States. The dynamic nature of the FASOMGHG model yields multi-period equilibrium on a 5-year time-step basis over a period of 85 years in this study,[4] resulting in dynamic simulation of prices, production, consumption, management, and GHG implications in

A large industrial crane at a logging mill lumberyard along the Yaquina River near the Oregon coast.

[4] FASOMGHG was run for a period between 2015 and 2100, while results included in this report are for the period 2020–2070 to limit the potential impacts of terminal conditions.

the forest and agriculture sectors. Historical production, consumption, and prices for both agricultural and forestry commodities are used to calibrate the initial year (2015) to observed levels. Additionally, land areas are aligned with the National Resources Inventory and USFS FIA (Jones et al., 2019).

The model maximizes the total present value of consumer and producer surplus (net welfare) in the land sector (forestry and agriculture) over dynamic intervals. The model solves all time periods simultaneously via intertemporal optimization. This model function allows actors within the model (farmers and timberland managers) to have what is called "perfect foresight" on expected future environmental, economic, and policy conditions. Intertemporal optimization is an important model attribute, particularly for the forestry sector, because forestry investments are made today with expected returns in the future, often decades out. Investments in the forest resource base are an attempt to neither overinvest nor underinvest based on the current period's expectations of the future. Furthermore, intertemporal dynamics play a role in agricultural management since the two sectors are linked via competition for land resources and soil carbon management in agriculture follows a dynamic process.

2.2.3 Land Sector in the Model

In FASOMGHG, there are six major land cover types: cropland, cropland pasture, pasture, forest, lands enrolled in the Conservation Reserve Program (CRP), and developed land.

FASOMGHG represents both privately managed and public timberlands, though public harvest levels are held fixed and exogenous, as management decisions regarding public lands are less driven by and responsive to markets than those regarding private lands. Forestry in FASOMGHG is represented using FIA plot-level data, aggregated to each of the 11 regions included in the model. Characteristics of forests included in the FIA data, such as age class, cite class, forest type, and management level, are all retained to accurately represent the domestic forest base.

Agricultural land uses represented in the model include cropland (supports the production of traditional crops and dedicated biofuel crops), pasture (medium-productivity grassland systems that are passively managed), cropland pasture (managed land suitable for crop production but currently being used as pasture land; for this reason, cropland pasture and pasture are combined when presenting pasture results), and rangeland (typically lower-productivity grassland and rangeland in the Western United States).

The model allocates land between alternative uses (cropland, forestry, pasture, and cropland pasture) to produce primary and secondary agricultural commodities and forest products, and to meet biomass demand, when applicable. The model also includes a bioenergy sector with first- and second-generation biofuels and biomass power plants. Bioenergy products include ethanol, cellulosic ethanol, biodiesel, and bioelectricity from agricultural and forestry feedstocks. More details can be found in Section 2.5.

2.2.4 Greenhouse Gas Emissions

Comprehensive GHG accounting for AFOLU is implemented in the model, including carbon stored in above- and belowground biomass and other pools for forests, CO_2 emissions from energy-intensive input use in agriculture, carbon fluxes related to soil management, and non-CO_2 emissions from crop and livestock production systems, as detailed below.

2.2.5 Land-based Mitigation Strategies

Mitigation incentives in FASOMGHG are implemented via a symmetric price on GHG emissions. The model responds to the price by abating emissions and increasing carbon sequestration through different activities across the country, up to the point in which the cost of reducing the additional ton of emission is equal to the GHG price. This approach is further described in Baker et al. (2010), Alig et al. (2010), and Ogle et al. (2016).

2.3 Global Biosphere Management Model (GLOBIOM)

GLOBIOM is a global, recursive dynamic economic model of the agricultural and forestry sectors.

2.3.1 History and Model Applications

The GLOBIOM model is a spatially disaggregated, recursive dynamic, PE model developed and applied by the International Institute for Applied Systems Analysis (IIASA). The model was developed in the late 2000s based on FASOMGHG to assess the impact of climate change mitigation policies of biofuels and other land-based efforts at the global level. There are several model versions of GLOBIOM available for different applications and contexts. More detailed descriptions of the GLOBIOM model structure and key parameters, including additional references to recent publications, are provided in Havlík et al. (2011), Valin et al. (2014), Havlík et al. (2014), Baker et al. (2018), and Janssens et al. (2020). A sample of GLOBIOM code is available to the public, and an open-source version is under development.[5]

A farm in the hillsides of the Green Mountains, Vermont.

The GLOBIOM modeling framework has been applied extensively to evaluate GHG mitigation potential from the land use sectors. Recent mitigation-focused analyses with the model include Frank et al. (2018; 2021), which looked at agricultural non-CO_2 and AFOLU wide GHG mitigation potentials; Hasegawa et al. (2018) and Fujimori et al. (2022), which each looked at food security under climate change mitigation scenarios; Lauri et al. (2019) and Daigneault et al. (2022), which analyzed the role of the forest sector under mitigation policies; and Frank et al. (2019) and Wu et al. (2023), which looked at the impact of diet changes on GHG emissions. The model has also been incorporated into multi-model assessments of climate stabilization futures, including by Riahi et al. (2017), to assess the impacts to the global land use sector under alternative socioeconomic futures.

2.3.2 Economic and Biophysical Features

GLOBIOM is a detailed PE model that integrates the agricultural, bioenergy, and forestry sectors with the aim of simulating commodity trade flow patterns between spatially separated supply and demand markets (Havlík et al., 2011). GLOBIOM represents the world partitioned into 37 economic regions (Appendix A, Figure A-2), in which a representative regional consumer optimizes their consumption, depending on income, preferences, and product prices in a 10-year time step framework. The model manages land in a recursive dynamic fashion across simulation decades, with each modeled time step being influenced by the previous time-step's solution, but without considering future price projections (in contrast to FASOMGHG and GTM). The model solution reveals an optimal combination of measures and land allocation across regions. In every period, GLOBIOM finds market equilibrium that maximizes the sum of producer and consumer surplus subject to resource, technological, demand, and policy constraints. Producer surplus is defined as the difference between market prices at a regional

[5] See GLOBIOM, "Model Code," https://iiasa.github.io/GLOBIOM/model_code.html.

level and the product's supply curve. The supply curve accounts for labor, land, capital, and other purchased input. Consumer surplus is based on the level of consumption of each market and is arrived at by integrating the difference between the demand function of a good and its market price. The model uses linear programming to solve, although it also contains some non-linear functions that have been linearized using stepwise approximation (IIASA, 2023). The first three periods (2000, 2010, and 2020) are used as a calibration step where parameters such as production, land use, and emissions are aligned at the regional level based on global datasets such as the Food and Agriculture Organization (FAO) Global Forest Resources Assessment, and country-level reporting to the United Nations Framework Convention on Climate Change (UNFCCC).

2.3.3 Land Sector in the Model

There are nine land cover types in GLOBIOM, and six of these are modeled dynamically: cropland, grassland, short rotation plantations, managed forests, unmanaged forests, and other natural vegetation land. The other three land cover categories are represented in the model but kept constant; they include other agricultural land, wetlands, and not relevant (ice, waterbodies, etc.).

The detailed grid cell-level spatial coverage for GLOBIOM includes more than 10,000 spatial units worldwide. The model represents 18 crops globally using FAOSTAT, FAO's statistical database of food and agriculture data, as the primary database for crop statistics. Crop modeling includes differentiation in management systems and multi-cropping.

GLOBIOM also features highly detailed livestock representation, based on FAOSTAT data. The model includes seven animal products, which can be produced in differentiated production systems. For ruminants, there are eight production system possibilities, including grazing systems in different climatic locations such as arid and humid, mixed crop-livestock systems, and others. Pigs and poultry are classified under either small-holder or industrial systems. Based on the production system, animal species, and region, GLOBIOM differentiates diets, yields, and GHG emissions. For instance, dairy and meat herds are modeled separately, and their diets are differentiated. Poultry in industrial systems is split into laying hens and broilers, again with different dietary needs. For ruminants, livestock production is modeled spatially in GLOBIOM's gridded cell structure. At the cell level, animal yields for bovine and small ruminants are estimated using the GLOBIOM module, RUMINANT. RUMINANT calculates a production yield that matches plausible feed ratios and checks this against regional-level data of livestock production. Feed for animals is also differentiated in the RUMINANT model and can be composed of feed crops, grass, stover, and other feed. Monogastric productivities are calculated based on FAOSTAT and assumptions of potential productivities of both small holders and industrial livestock systems. Livestock production is allowed to intensify or extensify, thereby altering the amount of feed or grass consumed.[6] Because for ruminants this is modeled spatially, any changes in grassland consumed due to changes in production systems, animal type, yield, and GHGs are captured in the spatially relevant areas. Each final livestock product is considered a homogeneous good with its own specific market (apart from bovine and small ruminant milk).

Forestry in GLOBIOM is captured through the Global Forest Model (G4M) module (Gusti, 2010; Kindermann et al., 2013) and includes detailed representation of the sector and its supply chain and a differentiation between managed and unmanaged forest areas (Shchepashchenko and Kindermann, 2023). GLOBIOM includes bilateral trade for agricultural and wood products. These products are assumed to be homogeneous and traded based on the least expensive production costs, though transportation costs and tariffs are also included.

The model also includes a bioenergy sector with first- and second-generation biofuels and biomass power plants. Perennial crops and short-rotation coppice are included as inputs to the bioenergy sector. GLOBIOM represents biofuel coproducts including distillers grains and oilseed meals.

[6] Intensifying involves increasing livestock output without expanding the area of pastureland by grazing more livestock per area of land, increasing feed relative to grazing, or using feedlots. Extensifying involves expanding pasture area in order to increase livestock production.

These coproducts can be traded either in their processed or whole forms. Coproducts that can be used for livestock feed are incorporated into the livestock RUMINANT module and can substitute other forms of feed depending on protein and metabolizable energy content (Valin, Sands, et al., 2014).

2.3.4 Greenhouse Gas Emissions

GHG emission coverage includes 12 sources of emissions that cover crop cultivation, livestock, above- and belowground biomass, soil organic carbon, and peatland. Although GLOBIOM does not track terrestrial carbon stocks dynamically, carbon fluxes from LUC are calculated with equations, following IPCC guidelines, that estimate changes over time and allocate the average annual emissions to the period in which the LUC occurs.

2.3.5 Land-based Mitigation Strategies

Comprehensive GHG accounting for AFOLU is implemented in the model, and mitigation incentives are implemented via price mechanisms. For modeling GHG mitigation potentials from the full AFOLU sector, GLOBIOM is coupled with the G4M model to explicitly simulate forest management, afforestation (including reforestation) and deforestation activities, and GHG implications. Specifically, mitigation incentives in GLOBIOM are introduced as a direct payment on land-related emissions and carbon sequestration activities.

For agriculture, GLOBIOM represents a set of structural and technological non-CO_2 mitigation options as well as changes in consumption levels in response to a mitigation policy. Structural options are represented through different livestock and crop production systems that vary in GHG intensity. The model can choose to move to more GHG-efficient management practices on site, reallocate production to more productive areas within a region, or reallocate through international trade across regions. In addition, technological mitigation options such as anaerobic digesters, animal feed supplements, and others are represented based on the EPA mitigation option database (Beach, Creason, et al., 2015).

For forestry, G4M models the reduction of deforestation area, increase of afforestation area, change of rotation length of existing managed forests in different locations, change of the ratio of thinning versus final fellings, change of harvest intensity (amount of biomass extracted in thinning and final felling activity), and change of harvest locations (Gusti, 2010). The introduction of a GHG price gives an additional value to the forest through the carbon stored and accumulated in it. In general, an introduction of a price incentive tends to decrease deforestation and increase afforestation and reforestation. However, this might not happen at the same intensity across all locations and all activities, and market interactions can result in negative feedbacks. For example, a reduction in deforestation increases land scarcity and might therefore decrease afforestation relative to the baseline scenario. The existing forest under a GHG price is managed with longer rotations of productive forests and shifting harvest to less productive forest. Where possible, the model increases the area of forests used for wood production, meaning a relatively larger area is managed relatively less intensively. This modeling approach also implies changes of the thinning versus final felling ratio toward more thinning (which affects the carbon balance less than final fellings). Forest management activities can influence emissions from deforestation by increasing or decreasing the average biomass in forests prior to their being deforested. They also influence rates of biomass accumulation in newly planted forests, depending on whether these forests are used for production or not.

Land use in GLOBIOM allows for both intensification and extensification. When land is converted, this is endogenously determined in the model based on conversion costs, and the profitability of primary products, coproducts, and final products. Costs increase as the area converted expands. Additionally, there are biophysical land suitability and production potential restrictions. LUC is determined at the grid cell level. There is a land transition matrix that sets the options for land conversion for each cell and is based on land conversion patterns specific to that region and conversion costs depending on the type of land converted.

2.4 Global Timber Model (GTM)

GTM is a global, intertemporal optimization economic model of the forest sector.

2.4.1 History and Model Applications

GTM is an intertemporal economic optimization model of the global forest sector, based on the dynamic approach described in Sedjo and Lyon (1990), Binkley et al. (1987), and Sohngen and Sedjo (1998).

GTM is a well-known global forest sector model that has been applied to a variety of different applications in numerous peer-reviewed publications and many scenarios reviewed by the IPCC. The GTM framework has been applied extensively to evaluate GHG mitigation potential from forests. GTM has been used to assess climate change impacts in the forest sector (see Sohngen et al., 1999, 2001; Tian et al., 2016); forest sector carbon sequestration potential under climate change mitigation incentives (Baker et al., 2019; Kindermann et al., 2008; Sohngen and Mendelsohn, 2003, 2007); GHG emissions under alternative market and environmental change scenarios (Tian et al., 2018); forest bioenergy policy analysis (Daigneault et al., 2012; Kim et al., 2017); forest carbon sequestration and woody bioenergy in comprehensive economy-wide analysis of climate change mitigation and stabilization scenarios via links with an IAM model (Favero and Mendelsohn, 2014; Favero et al., 2017; The White House, 2016); and the effects of forest-based mitigation activities on surface albedo (Favero, Sohngen, et al., 2018). Baker et al. (2017) conducted a U.S.-focused assessment of GHG mitigation potential, while Baker et al. (2018) and Favero et al. (2020) addressed policy complementarity between carbon sequestration and bioenergy policies and Austin et al. (2020) quantified economic costs of carbon sequestration.

Tug boat moving logs in Juno, Alaska.

2.4.2 Economic and Biophysical Features

GTM generates projections of future timber resource and market conditions, and related carbon implications, using detailed biophysical and economic forestry data for different countries and regions, including the United States. Specifically, GTM is a dynamic PE model that maximizes total welfare in timber markets over time across approximately 350 world timber supply regions by managing forest stand ages, compositions, management intensity, and acreage given production and land rental costs over 200 years. Land classes in the model were linked to vegetation types represented in biophysical models such as LPX-Bern (Favero, Mendelsohn, et al., 2018; Favero et al., 2021) and MC2 (Kim et al., 2017; Tian et al., 2016). Though the version of GTM used for this report does not include climate change impacts that could vary under different GHG emissions pathways, the model does incorporate historical climate change, as the yield functions for the land classes in the model are consistent with current climatic conditions. Moreover, the model incorporates overall land limits on areas derived from the ecological models, such that only land that is capable of naturally supporting forests can be used for timber production. Finally, the model is calibrated to regional forest inventory to the extent possible, and recent analysis indicates that future market and land use projections are robust to parametric uncertainty related to forest growth and land supply parameters (Sohngen et al., 2019). Another GTM paper provides a historical calibration exercise with the model performing a simulation of a historical time to illustrate the important contributions of management to the evolution of terrestrial carbon stocks historically (Mendelsohn & Sohngen, 2019).

GTM provides a long-term view of forest resource use and product supply under assumed future market, policy, and environmental conditions. The model optimizes the net market surplus of the timber sector by selecting the optimal levels of timber harvests, timber investments, and land use over time. When forests are harvested, forest owners have the option to allow land to regenerate naturally or convert to a more intensively managed/planted system depending on the future market expectation (e.g., higher timber prices). Like FASOMGHG, the model relies on forward-looking behavior and solves all time periods at the same time via intertemporal optimization. This dynamic optimization approach means that landowners incorporate future market expectations into land use and forest management decisions today to reflect future expectations (i.e., decisions anticipate future potential net returns). The model is global in scale, with 16 individual regions represented (including the United States) (Appendix A, Figure A-3). GTM has more than 150 disaggregated U.S. forest types and over 200 forests and management types globally. Recent developments have added heterogeneous forest product demand to explicitly represent pulpwood and sawtimber demand. The model has a 150- to 200-year time horizon to account for the long time intervals between harvest and regeneration in many of the world's forests.

Aerial photograph of logging clear cuts in the forest near Yachats in Lincoln County, Oregon.

2.4.3 Land Sector in the Model

Like FASOMGHG, GTM maximizes the net present value of consumers' and producers' surplus (net welfare) in the forestry sector. Consumers' surplus for timber markets is derived from inverse timber demand functions calculated from timber prices and consumption quantities that are endogenous to the model solution. Producers' surplus is composed of the gross returns to timber harvests minus the costs of managing and holding timberland. The costs of managing timberland include the costs of replanting timber, the costs of harvesting, accessing, and transporting timber, and the opportunity cost of maintaining land in forests rather than switching to agriculture for crop cultivation and livestock grazing.

The model solution determines how much to harvest in each age class and period, how many hectares to regenerate in each forest type in each period, how intensively to regenerate the hectares when they are planted, and how many new hectares of high-value plantations to establish. As a dynamic intertemporal economic optimization model, GTM relies on forward-looking behavior and solves all time periods at the same time.

GTM is a detailed model of the global forest sector that does not explicitly model agricultural production and commodity demand systems, but it considers the competition of forestland with farmland using a rental supply function for land. In the model, the rental functions are shifted exogenously over time to simulate rising demand for land to be used in agriculture, resulting in land use change. The parameters used to model land rents have been calibrated to past land use change and reflect assumptions about future demand for agricultural products by world regions (Austin et al. 2020). The rental supply functions are restricted to agricultural land that is naturally suitable for forests, and an assumption is made that the least productive crop- and pastureland will be converted first and that rental rates increase as more land is converted and thus becomes scarcer. That is, as more farmland is devoted to forestland, the opportunity costs of converting an additional acre of land into forests rise to reflect the underlying inelastic price of food. The total amount of forestland in GTM is therefore endogenous and driven by the demand for timber products, GHG price incentives, opportunity cost of land, and management costs.

2.4.4 Greenhouse Gas Emissions

In GTM, forest carbon stock is measured as the sum of carbon stock in four different carbon pools: above, soil, market, and slash carbon.

Aboveground carbon accounts for the carbon in all tree components, including stem, stump, branches, bark, seeds, and foliage, as well as carbon in the forest understory and the forest floor. Aboveground carbon in the GTM framework does not include dead organic matter such as from slash, which is contained in a separate pool. Market carbon pool is the GTM classification for carbon stored in HWP under assumed rates of product turnover in markets and resulting oxidization and decay. GTM classification of market carbon is consistent with the U.S. GHGI definition of HWP pools that affect "Changes in forest carbon stocks."

Soil carbon includes carbon stored in mineral and organic soils (including peat). GTM models changes in soil carbon storage from forest LUC but does not capture nuanced soil carbon dynamics associated with forest operations. Finally, slash carbon measures carbon stored in slash that remains on site, resulting from timber harvesting operations.

2.4.5 Land-based Mitigation Strategies

Mitigation policies are included in GTM as carbon rental payments and direct subsidies to carbon sequestration. Specifically, forest owners receive carbon payments (subsidies equal to the GHG price) for the carbon permanently stored in wood products and are compensated by annual rent[7] for providing annual carbon sequestration in forests. The change in soil carbon when land switches between forests and agriculture is also valued at the GHG price. Mitigation options available in the model include lengthening timber harvest rotation, increasing forest management intensity, avoiding forest conversion, converting agricultural lands to forest, and increasing carbon stored in wood products.

[7] In GTM, carbon rent R_c at time t is related to carbon price P_c as follows: $R_c(t) = P_c(t) - P_c(t+1)/(1+r)$, where r is the discount rate equal to 5%.

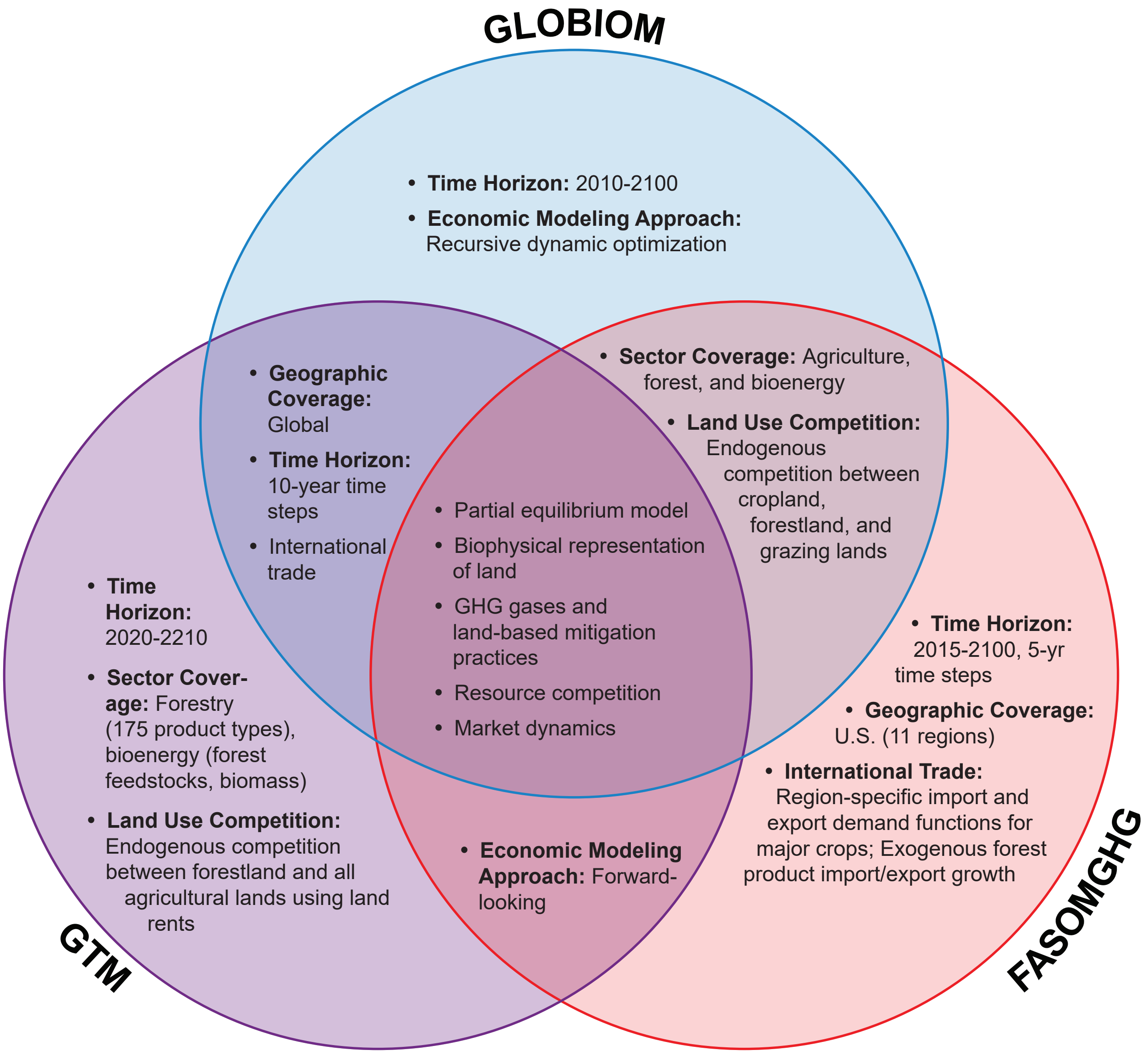
2.5 Similarities and Differences in Models' Attributes

> Each model has specific characteristics that make it a comprehensive and valuable tool for this study, and their individual frameworks complement each other.

The three models selected for this assessment include specific economic and environmental attributes that make them uniquely positioned to provide robust projections of potential future baseline and GHG mitigation quantities and associated costs under alternative policy scenarios. Each model has specific characteristics that make it a suitable tool for this study, and their individual frameworks complement each other. Specifically, GLOBIOM captures global interactions within the land sector, FASOMGHG provides a detailed description of the U.S. agriculture and forest sector market interactions, and GTM produces a very specific representation of the U.S. and global forestry dynamics. As this approach employs different frameworks and scopes, it allows for a broader spectrum of analysis and investigation of results from different perspectives. Some specific attributes are similar across models, while others diverge significantly, as described below and shown in Figure 2-1.

First, all three models are economic models. The models are price endogenous, meaning output prices are part of the model solution and are impacted by the initial stock of resources, scenario specifications, and the competition for resources both within and across sectors. Each model has a primary objective to maximize economic surplus by choosing efficient levels of supply and consumption given other scenario-specific inputs.

FIGURE 2-1 **Primary model attributes (similarities and differences)**



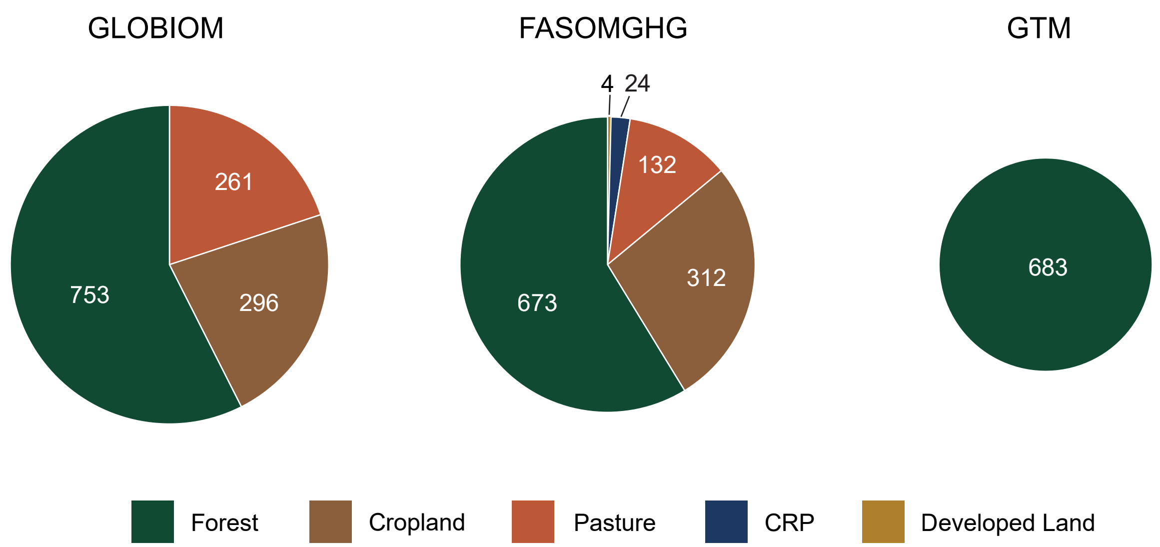
Where the circles overlap, the attributes are similar, and they are different where the circles do not overlap.

Second, the models include a detailed biophysical representation of the land sector. Specifically, they include a representation of spatial heterogeneity in biophysical and economic conditions to capture important variations in crops, species, production practices, natural resource availability, infrastructure and related costs, and markets. Moreover, forestry and agricultural production processes include spatially disaggregated information on crop yields and forest productivity by type and management regime. Each model relies on recent biophysical data and trends to the extent possible to inform future projections by including and/or being calibrated to recent publicly available forestry, agricultural, and land use statistics. All three models rely on officially published forest inventory data: FASOMGHG and GTM utilize the USFS FIA for U.S. forest characteristics such as initial forest biomass and land area, while GLOBIOM uses data published by the United Nations (UN) FAO, which is informed by USFS data. Despite this alignment, discrepancies do exist due to multiple differences across models, such as the inclusion of Alaska[8] in GLOBIOM and GTM, but not FASOMGHG, and different land categories considered in each model (Gidden et al., 2023)[9] (Figure 2-2).

[8] In the U.S. GHGI (EPA, 2023), forest remaining forest in Alaska has been estimated to range from a net sink of CO_2 of 19 Mt CO_2e yr^{-1} to a net source of 111 Mt CO_2e yr^{-1} from 1990 to 2021 compared to a national net sink of 823–611 Mt CO_2e yr^{-1} for the same pool.

[9] Note that discrepancy also exists between land models and National GHG Inventories because national inventories incorporate a wider definition of managed land (see Gidden et al. (2023) for more details).

FIGURE 2-2 **U.S. land area categories included by model (2020)**



Land categories in million acres for each model. The size of each donut represents total land area included per model. Land categories do not include grassland and wetlands. FASOMGHG forest area does not include Alaska. Source: FASOMGHG and GTM utilize the USFS FIA for U.S. forest characteristics such as initial forest biomass and land area, while GLOBIOM uses data published by the UN FAO, which is informed by USFS data.*

*Note: GLOBIOM uses country-level data published by FAO to be consistent across regions. The U.S. data submitted to FAO is from the USFS FIA.

Third, GHG gases and land-based mitigation practices are well detailed in each model as summarized in Figure 2-3. The report identifies and discusses eight GHG categories to both assess future baseline projections and future mitigation potential in the land sector. FASOMGHG reports emissions projections from all GHG categories listed in Figure 2-3. In the non-CO_2 emission categories, FASOMGHG only accounts for direct and indirect sources of N_2O emissions from crop production directly related to fertilizer use and does not include other soil N_2O fluxes (including from residue management, organic soil amendments, and mineralization and asymbiotic fixation). In the CO_2 emission categories, FASOMGHG includes on-farm CO_2 emissions (from activities such as energy-related emissions from groundwater pumping, commodity storage, and on-farm fuel use) and off-farm CO_2 emissions from fertilizer production. The model explicitly tracks U.S. soil carbon changes over time and across sectors. GLOBIOM does not include agricultural CO_2 emissions from fossil fuels, carbon stored in HWP, or soil carbon emissions or removals on agricultural land. Instead, it tracks changes in above- and belowground biomass due to conversion of natural lands to agriculture, which this report includes in the agricultural soils category (see Box 2).

All the GHG projections in Chapter 3 will be reflected in CO_2e using the global warming potential (GWP) rate of 25 for CH_4 and 298 for N_2O (IPCC, 2007).[10] The detailed representation of gases and activities allows the direct estimation of the abatement potential across technologies or land management strategies, with associated costs. These models have the ability to produce MACCs for the whole sector or for only specific practices or gases.

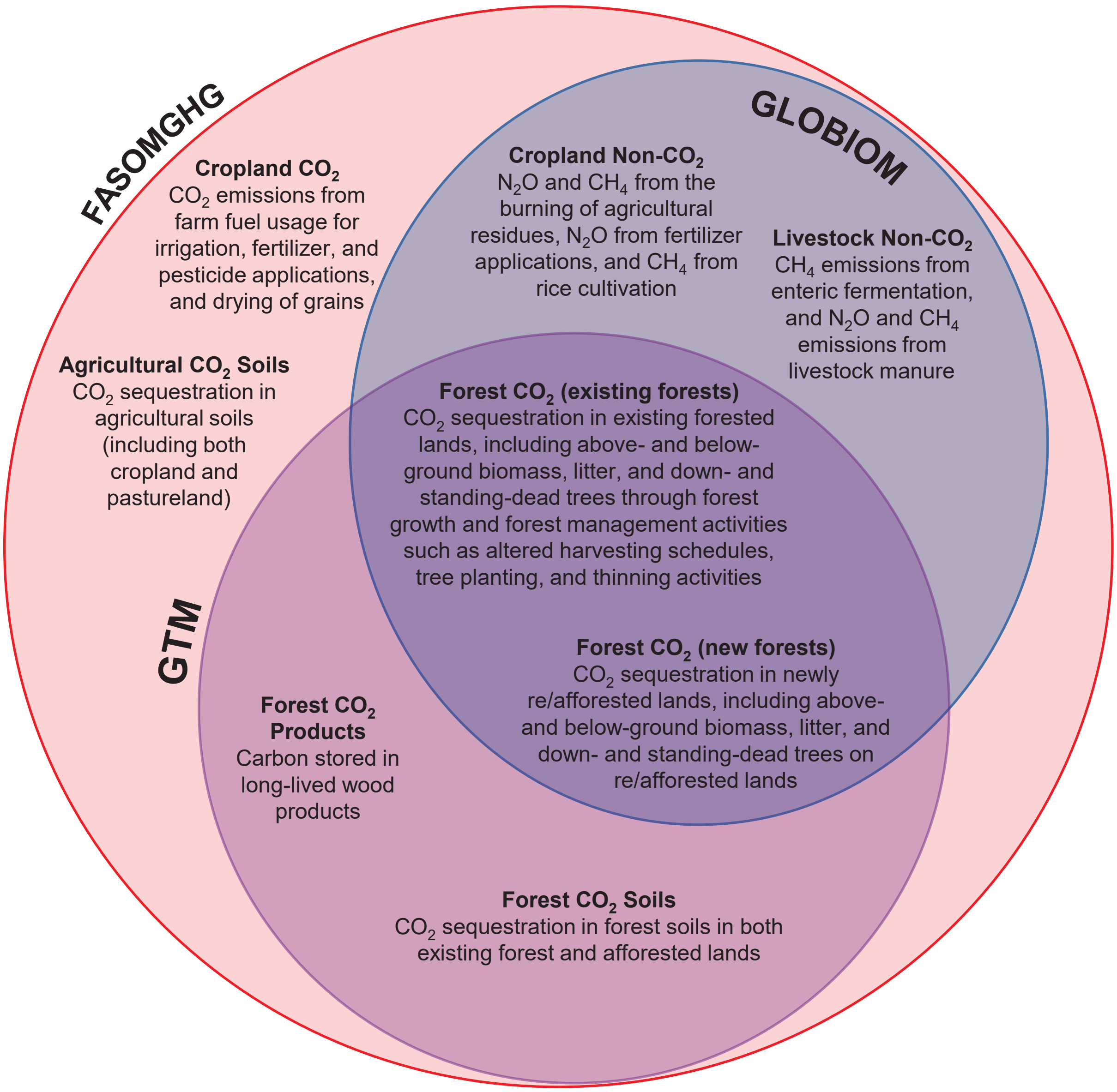
Fourth, all models consider resource competition in terms of land use competition between sectors—either directly through LUC possibilities or indirectly through economic land supply functions and parameters and land management change opportunities at the intensive margin—for example, conversion to planted or otherwise intensively managed forestry systems, and input intensity, irrigation, and crop/livestock mix changes for agriculture.

Fifth, all three models well represent market dynamics for specific sectors (agriculture and forestry) where the demand for land-based commodities must be met by the supply at any time. That is, each model includes exogenous drivers (e.g., population and GDP) for timber demand, crops demand, and livestock demand, and solves by selecting the optimal allocation of land resources to supply each demand. In this way, at any period, the land market (only forestry for GTM and both agriculture and forestry for FASOMGHG and GLOBIOM) is in equilibrium.

Finally, their economic structure allows the introduction of policy scenarios using a similar methodology introducing a common price signal on all GHG emissions. Furthermore, each model's framework allows for resource management to respond to market or policy signals at the intensive and extensive margins. Extensive margin investment in forestry and agriculture requires land use expansion (e.g., afforestation or expansion of crop production on other land uses). In forestry, an intensive margin investment could include thinning to enhance productivity, or planting forests post-harvest instead of allowing forests to naturally regenerate. In agriculture, intensive margin expansion could include more input use intensity per unit area or changes in regional crop mixes to more input-intensive systems. FASOMGHG and GLOBIOM each have the flexibility to allow for variable rates of fertilizer use, irrigation intensity, and implementation of alternative cropping patterns. While each model has some representation of the bioenergy and/or biofuels market, the analysis in this report does not incentivize additional use of bioenergy and/or biofuel as part of the mitigation scenarios. Specifically, under the mitigation scenarios developed for this study, bioenergy/biofuel demand is not changed relative to the baseline scenario to isolate only the effect of direct incentives on land-based abatement activities.

[10] For consistency, all three models used the same GWPs established by the IPCC Fourth Assessment Report (AR4) during the analysis phase of this report's development, which took place from 2020 to 2023. Use of AR4 GWPs was appropriate as it followed with reporting guidelines as defined by UNFCCC at that time. Updated guidelines will require countries including the United States to adopt the IPCC Fifth Assessment Report (AR5) (2013) 100-year GWP values for national GHG inventory reporting in 2024. More information is available at https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-annex-6-additional-information.pdf.

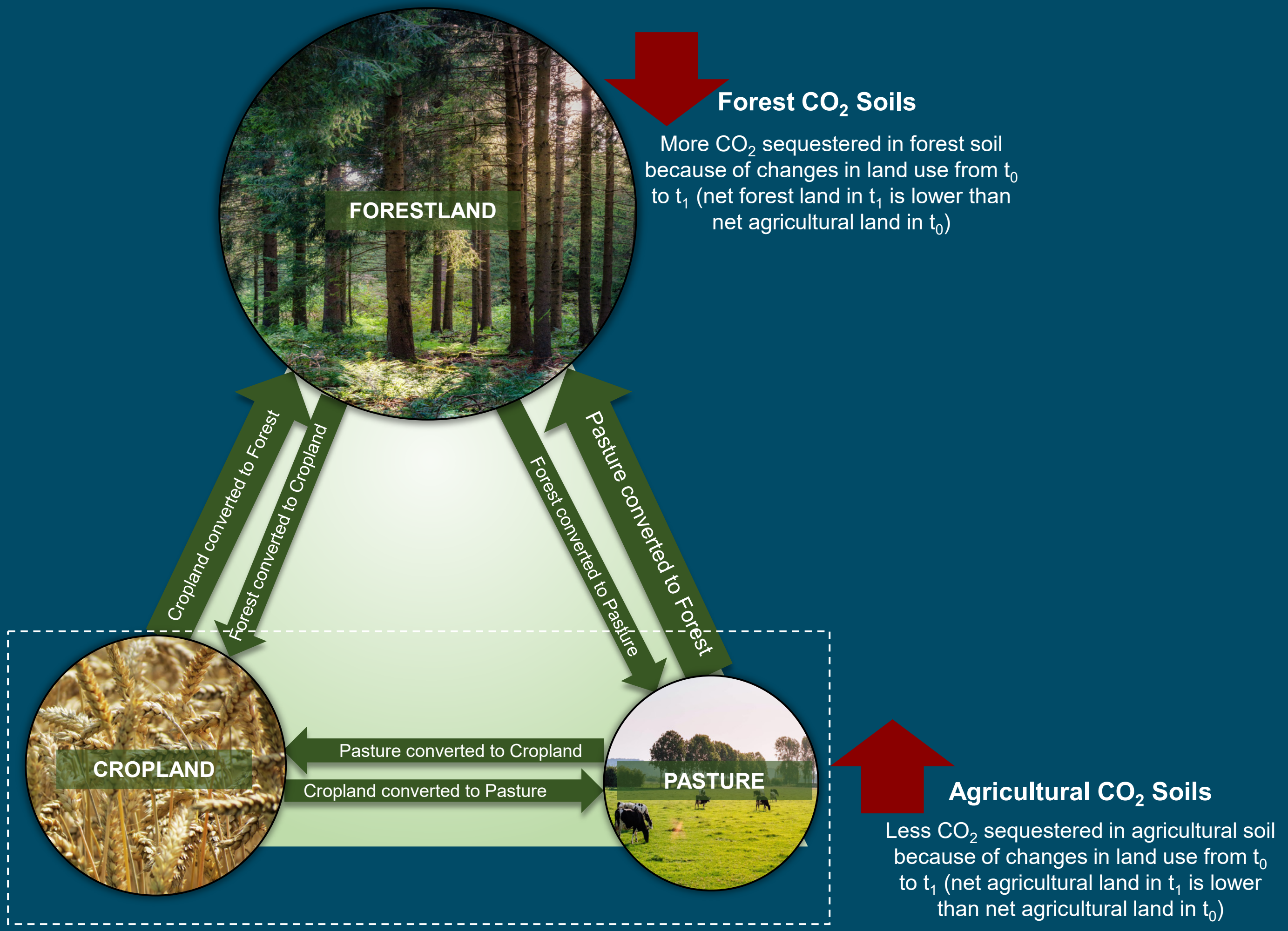
FIGURE 2-3 **Greenhouse gas categories included in each model**



FASOMGHG includes all the eight categories, while only two GHG categories are included in the three models: Forest CO_2 (existing forests) and Forest CO_2 (new forests). GLOBIOM accounts for agricultural soil carbon fluxes, but not forest soils.

Box 2

FOCUS: Representation of carbon in agriculture and forest soils



It is important to highlight how carbon sequestered and stored in soils is allocated in FASOMGHG. As the soil carbon basically "moves" with any land that transitions in and out of different land uses, this movement can cause the soil carbon pools between the various sectors in the model to appear to have large fluctuations in the estimated volumes. This outcome is due to land use changes, not large changes in the actual volumes of sequestration and storage of carbon by the soil pools. The figure above shows how FASOMGHG accounts for carbon sequestered in land soil by considering the current stock of soil carbon in each land use and the change in land uses from two different time periods (t_0 and t_1).

Agricultural CO_2 soils include both the amount of carbon sequestered in existing agriculture land soils (including both cropland and pasture) and the difference between increasing soil carbon stored due to more land converted to agriculture and decreasing soil carbon due to agriculture land converted into other uses from one period to the next period. In the case shown in the figure, net agriculture land declines, driving a contraction in agricultural CO_2 soils from t_0 to t_1.

Similarly, forest CO_2 soils include both the amount of carbon sequestered in existing forests soils and the difference between increasing soil carbon due to more land converted to forests and decreasing soil carbon due to forestland converted into other uses from one period to the next period. In the case shown in the figure, net forestland increases, driving an increase in forest CO_2 soil from t_0 to t_1.

Note that all the land categories included in the figure could be converted to other land uses (e.g., development). These changes are included in the estimated changes in soil carbon.

As there are similarities across the modeling frameworks, there are also differences. These include the economic modeling approach (including treatment of time dynamics), geographic coverage, sectoral coverage, land use categories, land use competition, international trade dynamics, and the time horizon employed.

First, all three models are optimization frameworks that can reflect long-term scenario timeframes, but there are differences in their treatment of time dynamics. FASOMGHG and GTM are intertemporal optimization (sometimes referred to as perfect foresight) models, which simultaneously optimize the entire solution period—85 years for FASOMGHG and 200 years for GTM in this analysis. Both models include a discount rate of 5%. GLOBIOM offers an alternative, recursive dynamic optimization structure (often referred to as myopic) in that it optimizes each successive period on the basis of past and current conditions as it steps through time. Both approaches are widely used in modeling applications to project future conditions and quantify the impacts of potential policy changes to inform decisions today. However, investors, land managers, and program designers have neither perfect foresight nor myopia, so it is important to understand the implications of the treatment of time dynamics on the model results. Employing these different modeling outlooks in this exercise is purposeful, as it allows for better understanding of similarities and differences between projected outcomes with tools using different temporal outlooks. Moreover, FASOMGHG and GLOBIOM run up to 2100, while GTM runs from 2020 to 2200. In forward-looking models like FASOMGHG and GTM, different terminal years of the modeling timeframe (i.e., FASOMGHG's timeframe ends in 2100 whereas GTM's ends in 2200) are likely to affect the results even in the short-term because future long-term GHG prices drive investment decisions at any period. To explore different future scenarios, this report does not harmonize the terminal year across models but rather tests the sensitivity of the results to this factor (discussed in Box 6 of Chapter 3).

Second, variations in model attributes can influence resulting mitigation projections in the United States' context in potentially different and significant ways. For example, differences in spatial scale can affect the regional distribution of mitigation action in response to an exogenous policy driver. GTM and GLOBIOM are global models, which capture general market feedbacks in a global setting as changes in global market conditions and trade flows can change the opportunity costs of pursuing mitigation opportunities. For example, if all countries face similar policy incentives to reduce emissions or increase carbon sequestration, countries with a comparative advantage (meaning lower opportunity costs) in GHG mitigation activities relative to traditional commodity production could see increased relative investments to reduce emissions, and supply could shift dramatically. Countries such as the United States, with large amounts of productive lands and highly developed technologies, could maintain a strong comparative advantage in both mitigation and traditional agricultural and forest product supplies, so mitigation potential in the United States could be heavily influenced by global market conditions and shifting trade patterns. Global models are needed to assess these potential international market interactions (Baker et al., 2018).

On the other hand, FASOMGHG is a domestic (U.S.-only) model that does not explicitly capture market and policy feedback with the rest of the world. The model does include global trade flows between the United States and other regions with the use of endogenous supply functions in the agricultural sector and constant supply functions from other regions in the forestry sector; hence, trade adjustments can be introduced exogenously under different market and policy conditions (Jones et al., 2019). The advantage of a domestic model like FASOMGHG is that it provides additional detail on the production processes and offers a more activity-scale disaggregation, including a wider range of product markets, than global models. Furthermore, domestic models typically capture greater levels of spatial heterogeneity in cost structures and production activities. Reflecting more detailed domestic markets and land use production processes, as well as capturing intra-regional interactions and spillovers, domestic models offer the capability of evaluating policy-induced changes in mitigation costs and portfolios over time and across domestic regions. Ultimately, the selection of models with different geographic scales allows for evaluation of how projected outcomes are affected by that variable.

Third, sectoral coverage also varies across models and can impact net mitigation outcomes. GTM, for example, offers highly disaggregated detail of the global forestry system and markets for pulpwood and sawtimber, which allows for more detailed assessment of global forest market interactions and related land use and forest carbon outcomes than with the other two models used in this study. However, competition for agriculture in this model is only represented indirectly through land rental functions and land supply elasticity parameters (Kim et al., 2017; Sohngen et al., 2019). While GTM's focus on forestry reflects the rising opportunity cost of bringing additional land into forestry at the expense of agriculture, the model's lack of direct resource competition with crop and livestock production systems results in mitigation portfolios that ignore endogenous market responses in agriculture to climate policies (e.g., impacts on changes in agriculture practices and demand for land). Conversely, FASOMGHG and GLOBIOM explicitly represent agricultural components and therefore provide a more comprehensive description of land use and related market competition between sectors but offer less detail within the global forestry sector than GTM.

Finally, each model uses a slightly different approach for incentivizing GHG emissions reduction relative to the baseline. GTM includes a carbon rental payment (Favero et al., 2020; Sohngen & Mendelsohn, 2003). The rental payment approach pays forest owners an annual rental rate for carbon sequestered on standing stocks and the GHG price for storage in HWP. If forested land is converted to non-forest use, that benefit (positive rental payment in the objective function) is lost in perpetuity. If forests are simply harvested, then it takes time to rebuild the carbon stock and accompanied carbon rents, though the rental payment can influence management changes, such as longer rotations and management intensification (including forest planting or interventions that boost productivity). GLOBIOM treats this price incentive as a direct payment from landowners for GHG emissions released. Similarly, but within an intertemporal optimization framework, FASOMGHG uses a symmetric GHG mitigation price incentive that rewards emissions reductions relative to the baseline with a welfare payment and penalizes emissions above baseline levels.

2.5.1 Mitigation Opportunities Across Models

The models used for this analysis have been selected to evaluate aggregate mitigation potential at large scales, which requires addressing market feedbacks, as well as considering an idealized and comprehensive implementation approach (a GHG price applied to all land emissions). Moreover, this analysis does not restrict the models to only consider options that are present across all the models but leverages models' specific attributes to present a comprehensive assessment of direct land mitigation in the United States. Each model has specific mitigation activities

Planting soybeans into corn residue and wild mustard using a no-till planter on a farm in Vincennes, Indiana, on May 13, 2021. (Indiana Natural Resources Conservation Service photo by Brandon O'Connor) available across the eight GHG categories and responds to the price incentive by finding its specific mix of abatement options for any period. A total of 24 mitigation activities have been identified across the three models: from 5 in GTM focusing only on the forestry sector to 21 in FASOMGHG that account for the largest number of abatement options available. GLOBIOM has 20 abatement activities available to respond to the price incentive (Figure 2-4).

In the forestry sector, five activities can be implemented in response to the GHG price, namely avoiding forest conversion, lengthening timber harvest rotation, converting agricultural lands to new forest, increasing forest management intensity, and increasing production of wood products to increase carbon sequestered in long-lived wood timber products. Management intensification in U.S. forestry is an important factor for developing long-term carbon projections (Jones et al., 2019; Tian et al., 2018; Wade et al., 2022), which is endogenously captured in all three models. However, GLOBIOM does not represent all forest management intensification options consistent with current management patterns in the United States, such as plantation forestry, but it does allow for changing of rotation lengths, change of the ratio of thinning versus final fellings, change of harvest intensity, and change of harvest location. Finally, all models account for emissions at the time of harvesting as foregone carbon sequestered in forests. FASOMGHG and GTM assume that some carbon will be tied up in wood products for a number of years. Specifically, carbon in timber products may be released to the atmosphere many years in the future as products decompose; the decomposition rate varies depending on the products (e.g., short-lived or long-lived) and models (see Winjum et al. 1998 for estimates used in GTM and Skog 2008 for estimates used in FASOMGHG). GLOBIOM does not include the HWP carbon pool over time but reports these as emissions from forest management at the time of harvesting.

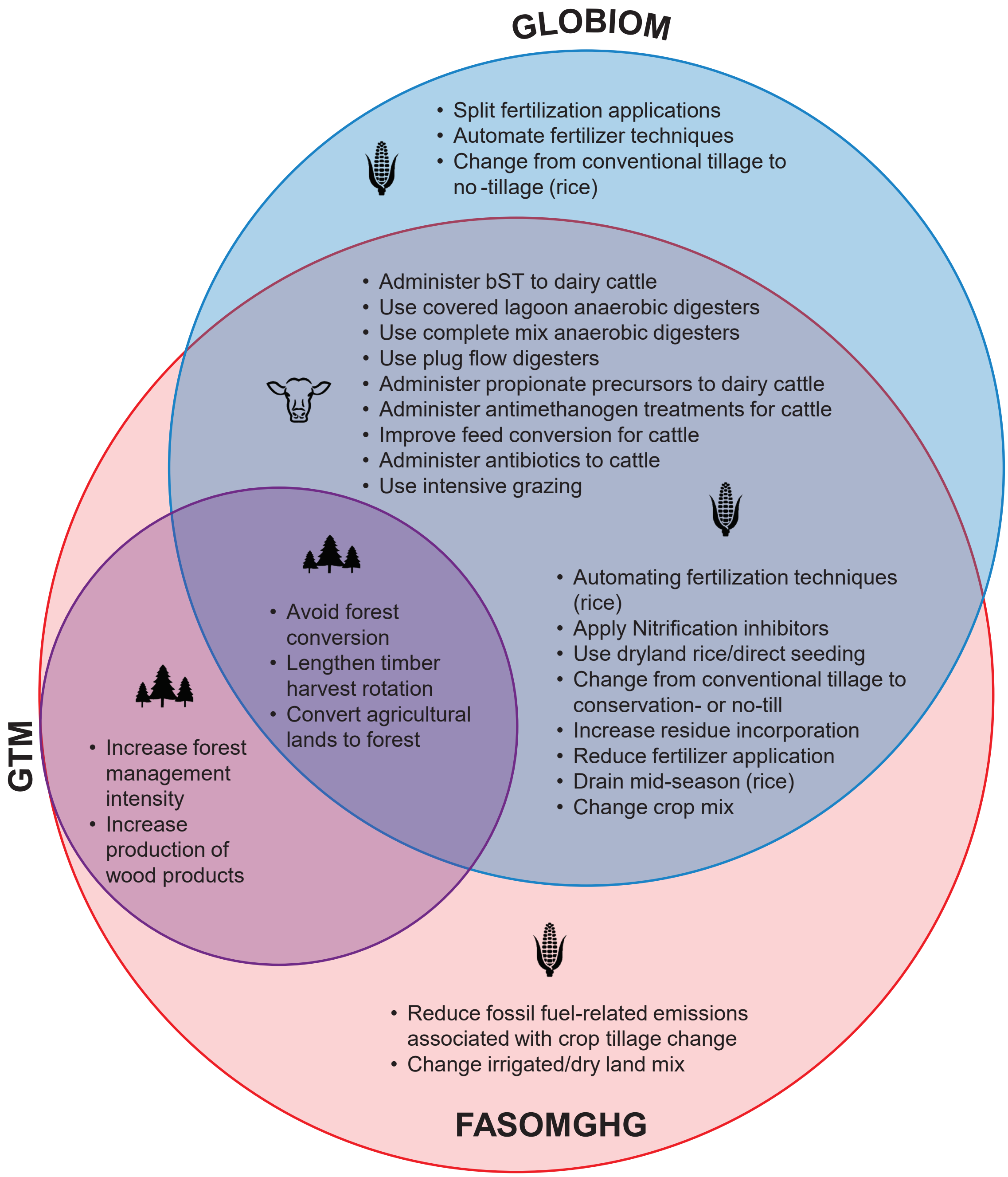
In the agriculture sector, mitigation activities are divided into cropland-based activities and livestock-based activities for CO_2, N_2O, and CH_4. In both FASOMGHG and GLOBIOM the following mitigation activities are included: adoption of automatic fertilization systems for rice production,

Brush management practice has opened the rangeland for cattle to better graze and improved the land near Sauerbier Ranches LLC, in southwest Montana (August 27, 2019). (USDA Photo by Lance Cheung)

the application of nitrification inhibitors, the usage of dryland rice production and direct seeding, implementing conservation and no-till practices, increased crop residue incorporation into soils, reduced fertilizer application, and mid-season draining of rice. Additionally, FASOMGHG allows for reduced on-farm fossil fuel emission and changes to irrigation intensity, while GLOBIOM includes split fertilization applications, automated fertilizer techniques on other crops[11] in addition to rice, and no-till on rice. For livestock, both models include the usage of plug flow, covered lagoon anaerobic, and complete-mix digesters; the administration of bovine somatotropin (bST) to dairy cattle; the administration of propionate precursors to dairy cattle; the administration of antimethanogen treatment for cattle; improved feed conversion; changes to antibiotics administered to cattle; and changes to grazing activities. Both FASOMGHG and GLOBIOM include spatially explicit, crop-, and livestock-specific emissions reductions for these activities to account

11 Auto-fertilization refers to advanced methods of soil analysis to determine the optimal quantity of fertilizer to maximize crop yields. Soil pH or plant characteristics can be analyzed to determine the nutrient quality of soils and determine the timing and quantity of fertilizer application. Precision fertilization can reduce input fertilizer costs for farmers in the case of overfertilization in addition to increasing yields (Oberoi et al., 2017).

FIGURE 2-4 **Mitigation technologies and management strategies available in each model**



Each circle includes the list of activities for each model; circles overlap where models have the same activities included.

for heterogeneity across space and agricultural systems. Across both models, alternative input mixes, which may be utilized to reduce emissions, will influence crop yields. For example, in FASOMGHG, reducing nitrogen input by 15% on corn fields has a median yield decrease of 14%. At the same time, changing tillage practices can result in either an increase or decrease in corn yields depending on location, nitrogen input, and irrigation levels.

In addition to model-specific abatement activities, each model has the flexibility to change where activities such as crop planting, livestock grazing, afforestation, and forest harvesting occur to maximize the net benefit from both agricultural and forestry products entering markets, and from incentives placed on GHG mitigation outcomes. In this analysis, all mitigation categories are treated in each model without consideration of their level of risks related to permanence, additionality, and leakage (see Box 4 in Chapter 3 for a specific example of the potential effects of leakage on the results presented in this report).

Finally, all models include bioenergy, but the GHG price does not apply to bioenergy supply; therefore, it does not receive any incentive/disincentive in the GHG price scenarios relative to the baseline case. This scenario design was selected to focus the report on direct mitigation from the land sector without considering future demand for land and changes in land management driven by decarbonization activities from other sectors (e.g., energy sector). Moreover, there is uncertainty in modeling future demand for bioenergy and biofuels as a GHG reduction strategy, uncertainty of adoption of dedicated energy crops such as switchgrass, and ongoing policy changes in renewable fuel programs that would increase the degree of uncertainty in the direct estimates of land-based mitigation potential. Other direct land mitigation options (such as agroforestry) are not represented in the models, largely due to a lack of adoption to date domestically, which means no comprehensive historic data on environmental outcomes and costs, plus a lack of GHG reporting guidelines (i.e., no established guidelines for reporting this activity in IPCC GHG reporting guidelines).

2.6 Model Input Harmonization and Baseline Scenario

In each model, pertinent exogenous parameters and input data have been harmonized.

To evaluate net mitigation potential for different GHG categories (or specific activities) in the land sector, model-specific baseline simulations are run using harmonized parameters and input data, as described below, to facilitate comparison among model outputs. In each model, baseline scenarios reflect no mitigation policies (e.g., GHG incentives, state-level renewable standards) in place, and market and biophysical conditions drive future land use and land management decisions. Moreover, climate change impacts on land are not included in the assessment.

This analysis does not attempt to align the baseline projections across the models exactly but instead to harmonize data inputs and model parameters for key drivers to a reasonable extent and to then explore changes in emissions between the baselines and various counterfactual GHG price scenarios. This limited harmonization approach is regularly applied in the literature, including numerous U.S. government reports and official submissions to the UNFCCC (e.g., Biennial Reports, U.S. Department of State, 2014, 2016, 2021, 2022). Aligning all underlying parameters to achieve similar baseline projections would not support the goal of this analysis, which is to evaluate the estimated magnitude and directionality of projected GHG mitigation versus a baseline—the “delta” between the simulated policy case and business-as-usual baseline. As applied, this harmonization effort narrows the primary focus to comparing differences in modeled emissions projections between baseline and GHG mitigation scenario pathways, and discussion of variability in results driven by key structural or data-oriented differences between the models.

Specifically, this effort harmonizes overarching macroeconomic drivers, such as U.S. population and GDP, that can materially affect projected outcomes (Riahi et al., 2017), as well as key biophysical inputs such as U.S. forest data. Specifically for this report, initial conditions in each model were aligned to age-class distribution from the 2015 U.S. Forest Inventory and Analysis dataset to reflect recent U.S. forest resource conditions (USFS, 2017).

For the macroeconomic drivers, each model aligns with U.S. population and GDP growth rates from the AEO Reference Case scenario, as these factors drive total demand growth for agricultural and forestry commodities (EIA, 2022). All three models use AEO 2022 projections of U.S. GDP and population until 2050. For other regions of the world, GLOBIOM and GTM apply population and GDP growth rates from the SSP2 scenario (Riahi et al., 2017). In FASOMGHG, growth rates for the United States after 2050 follow the SSP2 macroeconomic growth rates, and trade projections are calibrated to SSP2 growth projections for the rest of the world. This SSP2 scenario generally considered a "middle of the road" case, in which macroeconomic trends follow their historical patterns and population and economic growth is moderate through 2100, which has implications for agriculture and forest product demand and the land use sector broadly (Daigneault et al., 2019; Popp et al., 2017; Riahi et al., 2017).

By harmonizing socioeconomic and technological specifications across models using SSP2, this report does not test the effects of those specifications on future mitigation potential of land. However, each model has been tested under different SSP scenarios and Box 3 provides a summary of the main findings for each of them.

Aside from the harmonized elements specifically discussed here, the models are applied using parameters and other specifications as generally applied by the modeling teams (meaning that there was no further harmonization for elements such as estimated future CRP enrollment or future RFS volume mandate updates).

Finally, the harmonization process does not align 2020 values across models because initial values in each model differ due to varying GHG pools included in each model, as discussed above, such as FASOMGHG including emissions from on-farm fuel consumption, which GLOBIOM does not. Additionally, GTM and GLOBIOM include representation of Alaska, while FASOMGHG does not. Moreover, some models start in 2015 (FASOMGHG), while GTM begins in 2020, and GLOBIOM begins in 2000, creating possible discrepancies in 2020 results.

2.7 Mitigation Scenarios

> To assess land mitigation potential, 10 alternative GHG price scenarios, ranging from \$5 to \$100/t CO_2e in 2020 and reaching \$7 to \$281/t CO_2e in 2050, have been applied to each model.

To evaluate net mitigation potential of land, a set of consistently defined GHG price scenarios is run within each model, and the results of the baseline runs are compared to the mitigation scenario runs to estimate the change in GHG emissions and sequestration driven by the price path.

To incentivize mitigation, each model applies 10 alternative GHG price path scenarios (as all GHGs evaluated in the report are reflected as CO_2e, the GHG prices are shown in \$/t CO_2e). These scenarios include five initial prices beginning in the year 2020—\$5, \$20, \$35, \$50, and \$100/t CO_2e—in combination with two real price growth rate scenarios of 1% and 3% annually. The growth rates of 1% and 3% were selected to be consistent with the average economic growth rate presented in the AEO 2022 (EIA, 2022) and SSP2 (Riahi et al., 2017) and were used to simulate future socioeconomic pathways in this report. Moreover, these rates are in line with the average 2020–2100 growth rate of the prices in the Integrated Assessment Modeling Consortium (IAMC) 1.5 °C Scenario Explorer and data hosted by IIASA (Huppmann et al., 2019).

Box 3

FOCUS: Models' results under alternative socioeconomic scenarios

Socioeconomic and technology specifications about future conditions substantially influence projected levels of land use sector mitigation potential. The three models used for this report have been tested under multiple socioeconomic pathways, and the results are presented in Wade et al. (2022) for FASOMGHG and Daigneault et al. (2022) for GTM and GLOBIOM.

Each SSP scenario reflects different assumptions of GDP, population growth, urban development, demand growth for agricultural and forest commodities due to changes in population, dietary preferences, trade, and shifts in agricultural productivity growth.

Below is a summary of the main takeaways of the effects of the SSPs in each model.

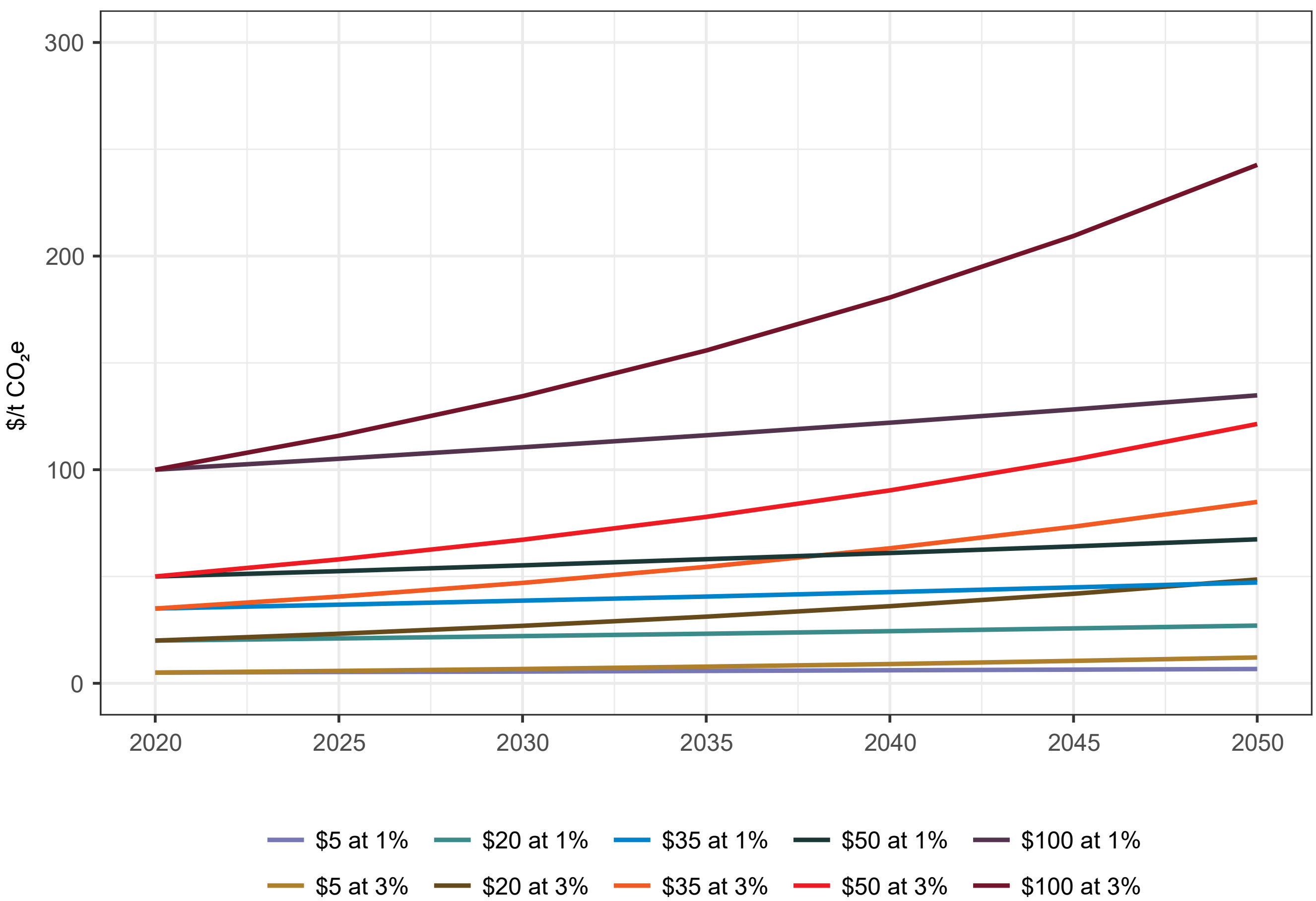
- **Income and demand growth are positively related to GHG emissions from agriculture, (FASOMGHG and GLOBIOM) and to carbon sequestration from forestry (FASOMGHG GLOBIOM, and GTM).**
- **The models select a different portfolio of mitigation activities across sectors depending on socioeconomic conditions.**
- **Under scenarios with a high population and economic growth scenario (as in SSP5 or SSP3), it is likely that agriculture sector mitigation will be a relatively more important component of a domestic climate strategy (FASOMGHG and GLOBIOM); whereas under scenarios with lower growth and reduced agricultural and forest product trade (as in SSP1 or SSP4), forest sector mitigation is likely to be more cost-effective (FASOMGHG and GLOBIOM).**
- **Across all SSPs, forest area increases under climate change mitigation scenarios from the baseline (FASOMGHG, GLOBIOM, and GTM).**
- **Across all SSPs, forest management provides the greatest source of mitigation across all SSPs within the forest sector (FASOMGHG, GLOBIOM, and GTM).**
- **Variation in agricultural sector mitigation potential is driven primarily by the differences in baseline demand for agriculture products across the scenarios. Low baseline demand for agricultural products projects higher mitigation from agriculture because of lower marginal abatement costs (FASOMGHG and GLOBIOM).**

Figure 2-5 and Appendix A, Table A-1 present the GHG price paths over time. The lower bound corresponds to the recent global average carbon credit price in the voluntary carbon market of around \$7/t CO_2e, and nature-based credits have a value of around \$5/t CO_2e (World Bank, 2023). On the other hand, the higher bound is in line with the new central estimated social cost of carbon between \$61 and \$168/t CO_2e (Rennert et al., 2022) and mimics current carbon excises of about \$130/t CO_2e in Switzerland, Uruguay, and Sweden (World Bank, 2023).

Each model treats GHG prices as direct fees for landowners for the GHG emissions resulting from land use and land management activities and direct payments to landowners for carbon stored through sequestration activities. This function translates to monetary incentives to reduce emissions and to increase sequestration relative to the baseline without GHG prices. Note that while GLOBIOM and FASOMGHG include one-time direct payments for all forest-based sequestration activities, GTM uses a carbon rent approach to "reward" aboveground carbon stock in forest annually.

By using different mitigation price paths, the study can represent likely bounds on the magnitude of overall GHG mitigation and gauge how different levels of incentives and growth rates influence the projected mix of mitigation activities. Dynamic economic models are particularly impacted by applied growth rates for mitigation incentives. Therefore, by including different growth rates, this study can

FIGURE 2-5 **GHG prices in \$/t CO_2e applied to each model in the mitigation scenarios (2020–2050)**



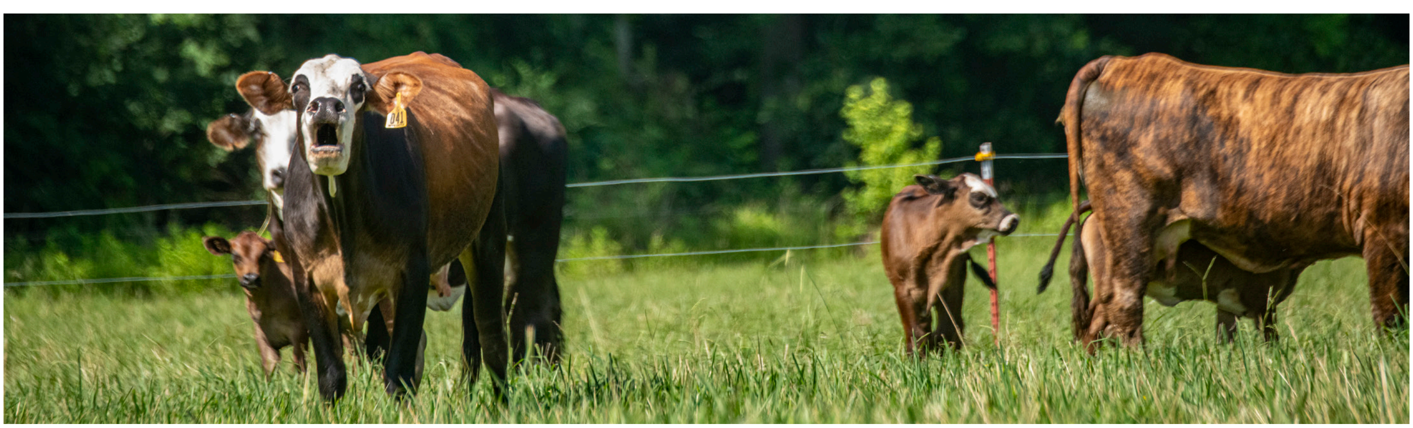
GHG prices in \$/t CO_2e applied to each model in the mitigation scenarios, 2025–2050.

analyze the influence of mitigation price growth on potential delay or anticipatory mitigation action in the land use system (Baker et al., 2018; Baker et al., 2017).

Estimated mitigation potential and related total costs are calculated by comparing projected model-specific baseline emissions, sequestration with emissions, or sequestration under each price scenario at any time. Both projected changes in cumulative emissions and annual flux changes are compared against the baseline. Costs are calculated for each simulation step (5-year or decadal increment, depending on the model), and over time. These results are then presented as MACCs, which represent the annual GHG mitigation (in CO_2e) associated with each GHG price incentive across different scenarios in each model, and are then compared across models. MACCs show the corresponding abatement under a selected GHG price or the required GHG price to meet a defined level of emissions reduction. The results, including MACCs, are presented in Chapter 3.

Baseline trends are an important factor in determining the estimated magnitude of net mitigation potential. For instance, a projected baseline with relatively high expansion in one sector (e.g., forestry) or specific management activity (e.g., afforestation) would face a different set of opportunity costs when pursuing mitigation strategies (e.g., larger foregone forestry rents) or possibly lower levels of future potential mitigation from that activity (e.g., less projected afforestation in response to policy incentive). The variability in estimated future baseline conditions can impact mitigation costs and abatement portfolios even for a single model (e.g., different SSP pathways applied in one model, as seen in Wade et al. [2022] and Daigneault et al. [2019]). Aside from the harmonized macroeconomic drivers, mitigation activities will be driven primarily by the suite of available abatement options and technologies and associated costs in each model. That is, the estimated mitigation potential from each model is the cost-effective quantity of net GHG emission reductions achievable by a specific set of mitigation options and related costs relative to a specified baseline. If mitigation options are restricted (i.e., a smaller set of mitigating options are incentivized), the relative costs and mitigation levels of the remaining mitigation options are likely to change (e.g., Latta et al., 2013; Tian et al., 2018).

Note that the baseline and future scenario projections presented in this report are illustrative and are not intended to replicate any specific policy or program. They do not explicitly seek to address or evaluate other topics, such as the interplay of GHG mitigation policies with biodiversity preservation or how to achieve socio-economically equitable policy outcomes or future environmental conditions, such as climate change impacts. It is also important to note that historic climate change impacts are captured implicitly within the data inputs used in the models (e.g., climate change impacts such as changes in natural disturbance, like increased incidences of pests and wildfires). Expanding this analysis to include other issues, including specific radiative forcing scenarios, collectively across this suite of models (as they have been applied individually in previous studies [Favero, Sohngen, et al., 2018]) is an area of future potential research. Other limitations and areas of future research are highlighted in Chapter 4.



Prescribed grazing and forage and biomass planting of pastures in Sheridan, Arizona, on June 27, 2019. (USDA Photo by Lance Cheung)

2.8 Stand-Alone Analyses

Model results have been validated through five sensitivity tests.

In addition to the mitigation scenarios applied across all three models, a set of sensitivity scenarios was conducted with individual models to examine how estimated future abatement portfolios and mitigation costs might change when specific analytic parameters or variables are modified. Specifically, this approach allows for gauging how sensitive the model and model results are to changes in key variables and scenario design parameters. Sensitivity analysis is regularly practiced in modeling exercises to observe how uncertainty in model outputs relates to input uncertainty to better evaluate the robustness of results.

The report presents and briefly discusses estimated results under five sensitivity tests presented in separate boxes in Chapter 3, many of which will be pursued in more depth in future research endeavors based on this report. These sensitivity tests were carried out with individual models based on each's ability to reflect the target scenario. Box 4 uses GLOBIOM to observe what happens when global versus national emissions reduction policies are implemented. Box 5 adds additional runs from GTM to assess how inclusion of future climate scenarios and CO_2 concentrations in the atmosphere can affect estimated GHG mitigation outcomes. Box 6 shows how altering parameters around land use conversion and the effects of holding GHG prices steady after the end of the century are investigated in GTM, with the latter assessing the role that a longer, running model may have on overall mitigation results. Box 7 illustrates how outcomes are sensitive to implementation of a mitigation program that involves full participation versus one with lower participation rates, including potential leakage effects in FASOMGHG. Box 8 offers a snapshot of how specific activity eligibility constraints can affect results by restricting the geographic location of eligible mitigation activities in FASOMGHG. Specifically, it looks at what happens when there is no financial incentive for re/afforestation in the Corn Belt region (emulating a policy intent to ensure food security or landowner decisions to not adopt that mitigation practice in that region). Finally, three additional boxes in Chapter 3 provide some additional in-depth analyses by comparing the technical mitigation potential of livestock and the economic potential measured in the report (Box 9), providing an overview of long-term mitigation potential of the land sector beyond 2050 (Box 10), and discussing a hypothetical application of the models' results at specific investment levels (Box 11).

3 Baseline and Mitigation Scenario Results

This chapter provides an evaluation of U.S. land sector GHG mitigation potential by presenting the projected GHG emissions under the baseline and alternative mitigation scenarios across the three models included in this report: FASOMGHG, GTM and GLOBIOM.

For simplicity, all GHG emissions estimates (e.g., livestock non-CO_2) are presented in CO_2e emissions. The results presented largely focus on the year 2050, though Box 10 looks at some key results through 2070. As discussed in Chapter 2, key parameters have been harmonized across the three models. However, the goal of this analysis was not to align every initial parameter across the models, but rather to assess the directionality and magnitude of the estimated mitigation potential by looking at the delta between the alternative scenarios' results and the baselines of each respective model. The chapter presents results from each model to allow for the extraction of specific insights the different models provide given their relative strengths to inform the evaluation of the final results. Therefore, the results from each model are presented separately but discussed jointly to provide a comprehensive framework of the future mitigation potential of land in the United States. In the next chapter, the results will be discussed in relation to the U.S. GHGI, compared to other literature projecting emissions and mitigation from the land sector, and further discussed in terms of how these findings can be applied in real-world contexts.

The chapter is divided into five sections.

- **Section 3.1** presents estimated baseline emissions and sequestration for each model with discussion of the factors driving the differences in the future projections across models.
- **Section 3.2** discusses the MACCs for the entire land sector first and then decomposes them by GHG (CO_2, CH_4 and N_2O) across models and time.
- **Section 3.3** provides a detailed description of the MACCs by sector (forestry and agriculture) and activity across models and time.
- **Section 3.4** presents the mitigation potential of land across each activity and compares the results across models and mitigation scenarios.
- **Section 3.5** assesses the required investments needed to drive specific levels of abatement across models and time.

In this chapter, eight stand-alone analyses are presented as separate boxes. Five boxes test either the sensitivity of the MACCs and mitigation potential to some specific variables (e.g., physical parameters, model specifications) or the sensitivity of the results to the policy design and provide some practical applications. The boxes are not intended to be exhaustive studies but instead serve to assess how sensitive the results are to certain parameters and/or assumptions in the main study, highlight areas of uncertainty, determine the directionality of impacts under varied parameters, and spur future research endeavors.

An aerial view of a forest being cleared using the slash and burn method, Hendersonville, North Carolina.

Though the U.S. land sector is projected to remain a net sink through midcentury, land use GHG emissions are estimated to increase over time under the baseline scenarios.

3.1 Future Baseline Projections

Though the U.S. land sector is projected to remain a net sink through midcentury, land use GHG emissions are estimated to increase over time under the baseline scenarios.

3.1.1 Baseline Emissions from the Land Use Sector Across Models

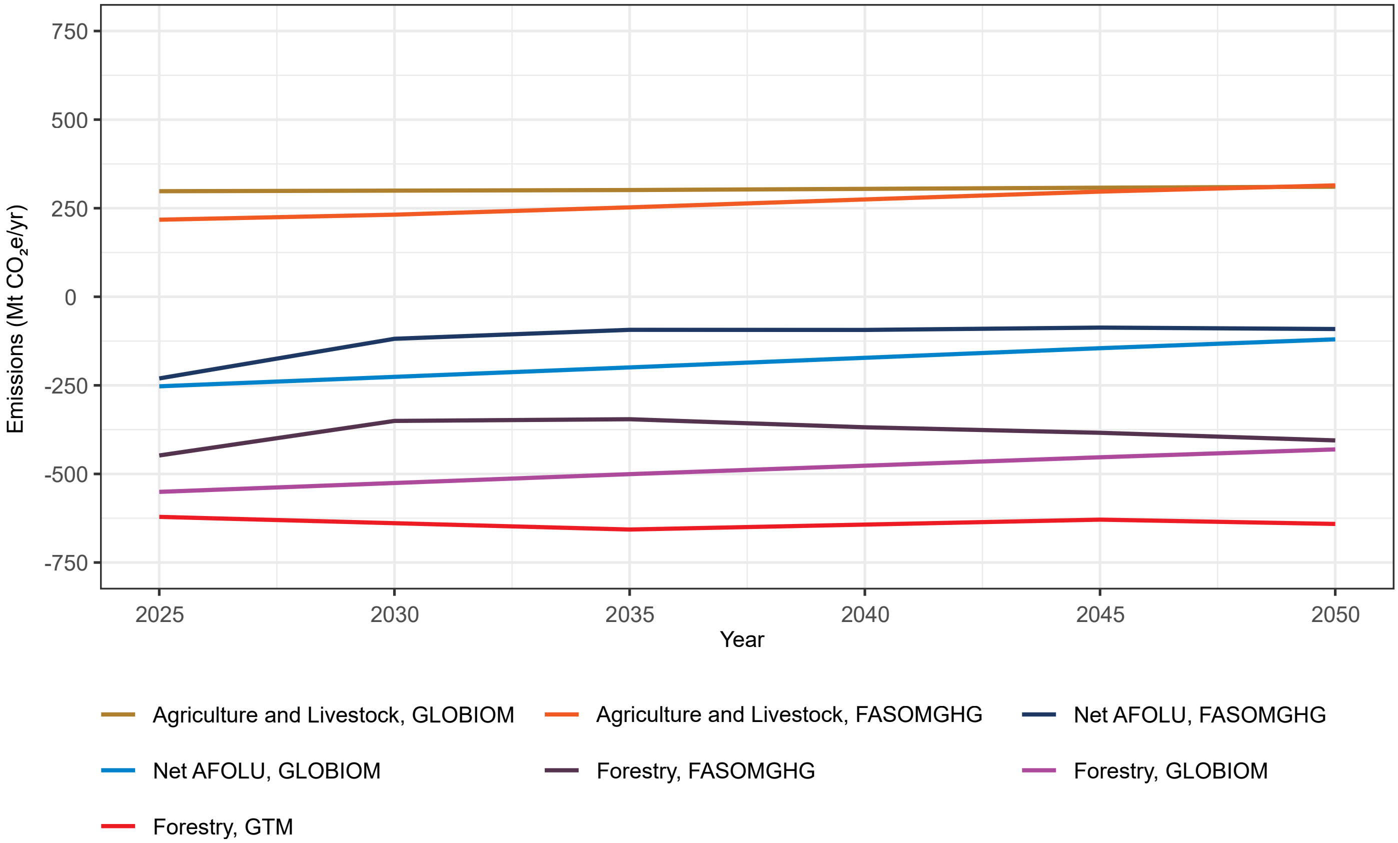
The AFOLU sector is expected to sustain a net GHG emissions reduction of between 90 and 120 Mt $CO_2e\ yr^{-1}$ in both FASOMGHG and GLOBIOM in 2050 under the baseline scenario (Figure 3-1).

FASOMGHG projects that activities such as existing forest management and afforestation/reforestation efforts will lead to a continued stable net sink from the U.S. forestry sector through 2050, though emissions from cropland and livestock production increase slightly over time and thus the overall magnitude of the net sink decreases over time. Under the GLOBIOM baseline scenario, the U.S. land sector remains a net sink, but the net sink declines by 2050 and trends toward becoming a net source of GHG as agricultural emissions rise to meet growing demand and the forestry sink declines, due to limited investment in replanting and afforestation/reforestation activities over the projection timeframe (driven by the recursive dynamic nature of GLOBIOM) and forest aging (as older tree inventories absorb less carbon) (He et al., 2012).

In the forestry sector, the three models project that the net carbon sink will remain relatively constant or decline slightly over time as unmanaged or natural forests age and harvesting activities in managed forests grow, driven by an increase in population and corresponding demand for forest-based products (Figure 3-1). The expected average annual carbon sequestration rate in 2050 is 405 Mt $CO_2\ yr^{-1}$ in FASOMGHG, 431 Mt $CO_2\ yr^{-1}$ in GLOBIOM, and 641 Mt $CO_2\ yr^{-1}$ in GTM. Both FASOMGHG and GTM project increases in plantation forest establishment at the baseline as a response to growing demands for forest products. Responsiveness to this growing demand helps the forest sector remain at a relatively constant annual sink in both models, countering slowing sequestration rates on older, mature stands. Additionally, global trade impacts each model's decision on investment levels in forestry activities differently, which will be discussed further in the next section.

A small herd of cows grazing in the fog as the sun sets in the hills of Virginia.

FIGURE 3-1 **GHG emissions by model under baseline scenario (in $MtCO_2e\ yr^{-1}$, 2025–2050)**



Emissions from agriculture and livestock, forestry, and net AFOLU. Net AFOLU emissions are calculated as the sum of emissions from agriculture and livestock and forestry. Results are presented in terms of atmospheric accounting. Therefore, positive flux equates with emissions; negative flux represents sequestration. Initial values in each model differ due to varying GHG pools included in each model as discussed in Chapter 2, such as FASOMGHG including emissions from on-farm fuel consumption, which GLOBIOM does not. Additionally, GTM and GLOBIOM include representation of Alaska, while FASOMGHG does not.

FASOMGHG projects a relatively stable sink in existing forests, with fluctuations over time driven by spatial and temporal patterns in forest growth, aging, and harvests. Further, shifting land use and production patterns in and between segments of the forestry and agriculture sector result in changes to the forest carbon sink over time. For instance, in future decades afforestation/reforestation increases the net carbon sink as forestland expands, but this increase in the sink diminishes in later periods as afforested stands, predominately plantations, experience higher harvest levels (Figure 3-2). This increase in afforestation/reforestation is driven by a growing demand for forestry products over time as population and GDP increase. At the same time, agricultural productivity is increasing, which results in the relative rental rate of forestland to be higher than that of cropland over time. Forestland transitioning into agricultural or developed uses results in declines in biomass carbon as well as soil carbon stocks as lands leave forests, thus resulting in a net emission from forest soils before midcentury (after that the rate of conversion of forestland to developed land declines). Specifically, an exogenous shift of 10 million acres of forestland is converted to developed land in FASOMGHG by 2050, based on historical LUC measures from the National Resources Inventory (U.S. Department of Agriculture Natural Resources Conservation Service, 2017) and projected expansion of built-up areas (Riahi et al., 2017). Ultimately, carbon sequestration rates of U.S. forests (existing and newly forested lands) remain relatively constant across the time horizon, resulting in the forest sector remaining a net sink past midcentury.

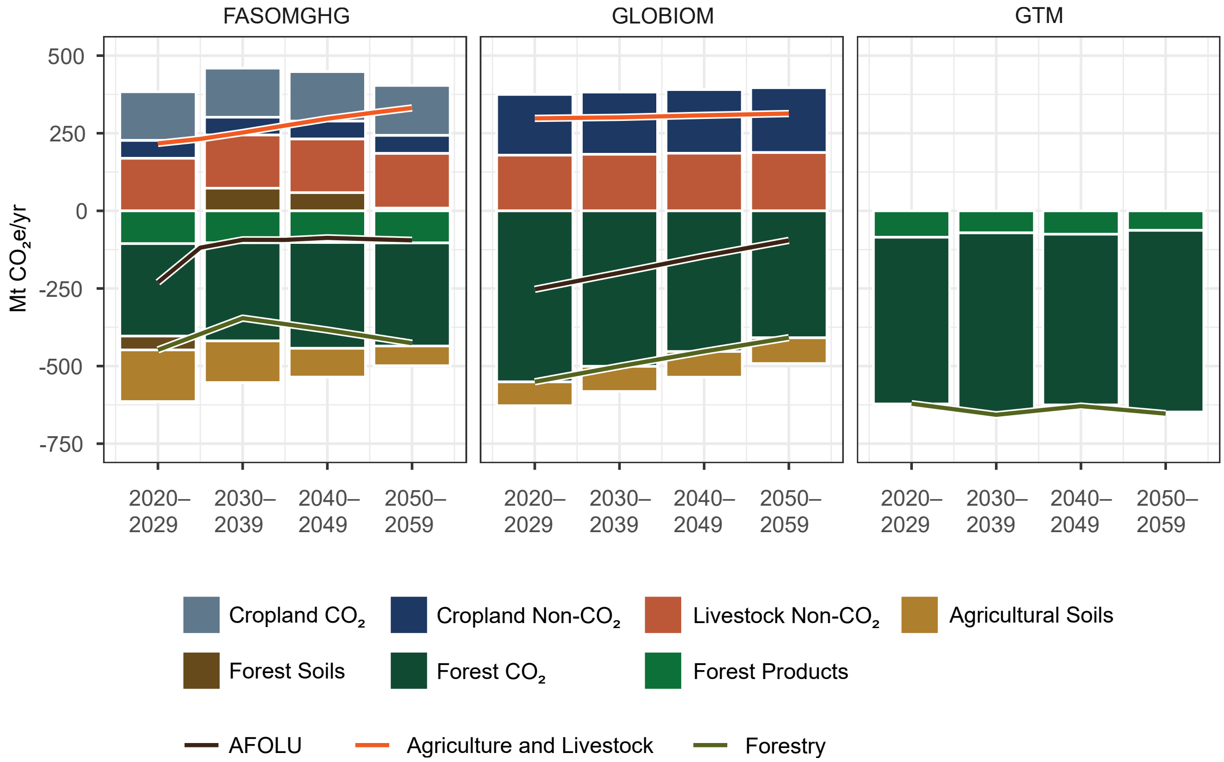
GLOBIOM projects that the U.S. forestry sector will diminish its carbon sink over the next several decades, with average annual flux from forestry declining from 551 Mt CO_2e yr^{-1} in 2025 to 431 Mt CO_2e yr^{-1} in 2050 (Figure 3-2). This outcome results from a slowing of annual carbon storage as current forest stands age, coupled with afforestation/reforestation and re-establishment of harvested forests activities that occur at a relatively low rate. GLOBIOM limits investment in forest management and afforestation/reforestation activities while increasing harvesting slightly over time, resulting in a declining annual flux.

GTM projects that the carbon sequestration from the U.S. forestry sector will remain stable at around 621 to 641 Mt CO_2 yr^{-1} from 2025 to 2050, driven by improved management activities on managed forests counteracting slowing sequestration rates from aging unmanaged forests as well as a growing forest land base (Figure 3-2). Moreover, carbon stored in HWP is expected to remain constant at around 69 Mt CO_2 yr^{-1} as new long-lived timber products enter the market driven by increasing consumption per capita despite the decay of carbon stored in existing wood products (Figure 3-2).

In the agricultural sector, which includes crops and livestock production, both FASOMGHG and GLOBIOM project an increase in GHG emissions over time despite projected increases in crop yields as rising populations and GDP lead to increases in demand for agricultural commodities both domestically and outside the United States (Figure 3-1). Specifically, FASOMGHG projects emissions from the agricultural sector to rise from about 217 Mt CO_2e yr^{-1} in 2025 to 314 Mt CO_2e yr^{-1} in 2050 while GLOBIOM shows an increase from 298 Mt CO_2e yr^{-1} in 2025 to 311 Mt CO_2e yr^{-1} in 2050. Despite the overall similarity in estimated baseline emissions outcomes, FASOMGHG and GLOBIOM rely on slightly different mechanisms to reach these levels, as explained below.

In FASOMGHG, the change over time in baseline crop and livestock emissions is driven by several factors. First, the initial stock of carbon stored in cropland soils is affected by several variables such as conversion to other land uses (including from cropland and pasture to exogenously determined development and endogenously determined conversion of cropland to pastureland and vice versa), some continued use of conventional tillage practices resulting in diminished soil organic carbon, and changes in crop mix (with residues from some crops and cover crops contributing to the soil sequestration totals), which on net diminish soil carbon stock over time. The baseline scenario in FASOMGHG reflects continued adoption of conservation and no-till techniques, which accumulates carbon for a time until additional sequestration capacity saturates (Stewart et al., 2008). Additionally, consistent with recently observed trends in the United States (Baker et al., 2020; Kuck & Schnitkey, 2021), pastureland in FASOMGHG increases slightly over time to meet growing demand for meat products. Moreover, similar to the forestry sector, FASOMGHG reflects cropland and pastureland conversion to developed land as populations continue to rise (driven in part by macroeconomic parameters in AEO 2022 and SSP2; further details are presented in Wade et al., 2022). This approach differs from GLOBIOM and GTM, which do not reflect changes in development area, and thus total natural and working land area remains constant in those models. Finally, livestock sector emissions in FASOMGHG are projected to increase slightly over time as demand growth for livestock products is driven by increasing population and income (Figure 3-2). This demand shift requires more livestock on the landscape, yielding higher emissions from enteric fermentation and manure management practices. In FASOMGHG, total agricultural input usage and production levels remain relatively constant as technological improvements increase yields over time, thus relaxing extensification pressure on agricultural land use. This increase in productivity allows the model to utilize crop inputs such as fertilizer, pesticides, and irrigation at relatively constant rates over time, which limits the increase in non-CO_2 cropland emissions.

FIGURE 3-2 **Baseline U.S. average annual carbon-equivalent flux within each decade by GHG category by model (in Mt CO_2e, 2020–2059)**



Results are presented in terms of atmospheric accounting. Therefore, positive flux equates with emissions; negative flux represents sequestration. Lines show total emissions and sequestration from the combined AFOLU (*middle lines*), agriculture and livestock (*top lines*) and forestry (*bottom lines*) sectors as reported in Figure 3-1 for each model. Initial values in each model differ due to varying GHG pools included, as discussed in Chapter 2, such as FASOMGHG including emissions from on-farm fuel consumption, which GLOBIOM does not. Additionally, GTM and GLOBIOM include representation of Alaska, while FASOMGHG does not. Between 2030 and 2050, FASOMGHG projects that emissions from LUC between forestry and agricultural lands will lead to net emissions from existing forest soils. This outcome is due to how emissions from LUC activities are modeled in FASOMGHG as described in Box 2. Emissions from land use conversions (i.e., forestland converted to agricultural land) occur in the period that the land conversion occurs. However, for land conversions that result in higher levels of stored carbon in soils (i.e., cropland converted to forestland), the accumulation of additional soil carbon occurs over a 100-year time horizon. In the mitigation scenarios presented later in this chapter, mitigation from afforestation and improved forest management are presented separately for GTM; however, in its current format, this differentiation is not possible in the baseline GTM runs.

In contrast, the factors driving the rise of baseline agricultural emissions in GLOBIOM reflect the global prominence of U.S. agriculture. First, the United States maintains a strong role in both crop and livestock commodity production relative to other regions, so production expands to meet global demand[12] (U.S. Department of Agriculture, n.d.) relative to the model's assumed increase in technologically driven yield growth[13] (Figure 3-2).

Similarly, total livestock populations and emissions grow slightly over time, as underlying model parameters from the SSP2 scenario (Riahi et al., 2017) project populations and wealth across the world will increase, driving up demand for meat products (Figure 3-2). Further, GLOBIOM livestock sector emissions are approximately 33% higher than those in FASOMGHG across the full time horizon due to higher livestock sector production levels in the baseline.

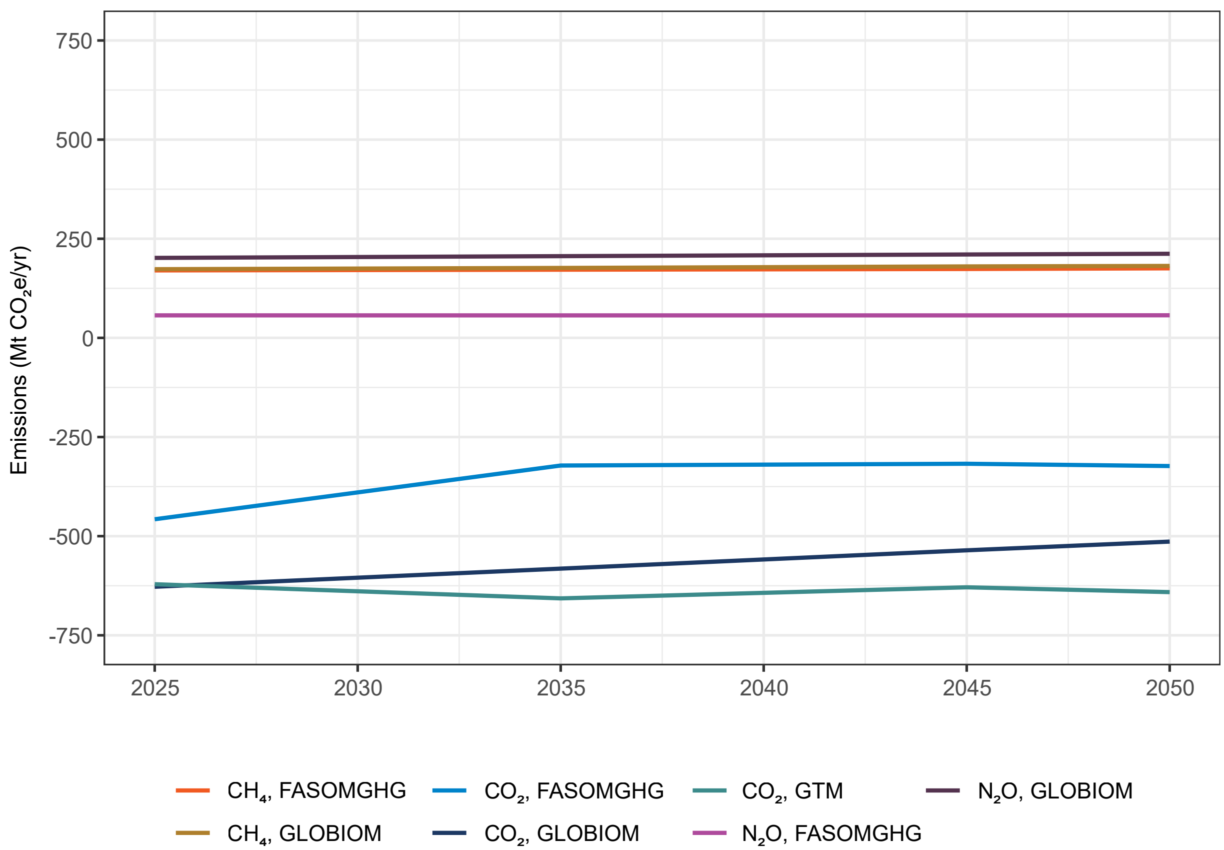
[12] Note that by the United States increasing its role as a global agricultural producer, there is the potential to lower global emissions because other regions that may use less efficient production systems can reduce output.

[13] In GLOBIOM, exogenous yield growth requires that a level of input use intensification accompanies yield gains..

Figure 3-3 shows the projected baseline trends in land emissions divided by gas. In both FASOMGHG and GLOBIOM, CH_4 and N_2O emissions are projected to increase slightly over time, as agricultural production increases to meet growing demands. FASOMGHG projects that by 2050, CH_4 emissions will have increased by 3% relative to 2025 levels (increasing from 170 Mt CO_2e yr^{-1} in 2025 to 175 Mt CO_2e yr^{-1} in 2050). GLOBIOM projects similar rates of growth in CH_4 emissions with 2050 emissions 5% higher (181 Mt CO_2e yr^{-1}) than 2025 (173 Mt CO_2e yr^{-1}). Both models include CH_4 emissions from rice cultivation, manure, and enteric fermentation from livestock, and burning of agricultural residuals. FASOMGHG and GLOBIOM also project similar growth over time for N_2O emissions from the agricultural sector. FASOMGHG projects that 2050 emissions will be less than 1% higher than 2025; GLOBIOM projects an increase of 5% in the same period.

FASOMGHG tracks N_2O emissions from volatilization and leaching from nitrogen applied to soils, fertilizer applications, pasture and manure for livestock production, draining of agricultural soils, and burning of agricultural

FIGURE 3-3 **Annual emissions, by GHG (CO_2, CH_4 and N_2O), under the baseline scenario (in Mt CO_2e, 2020–2059)**



Results are presented in terms of atmospheric accounting. Therefore, positive flux equates with emissions; negative flux represents sequestration. Initial values in each model differ due to varying GHG pools included in each model as discussed in Chapter 2, such as FASOMGHG including emissions from on-farm fuel consumption, which GLOBIOM does not. Additionally, GTM and GLOBIOM include representation of Alaska, while FASOMGHG does not. CO_2 values represented here are net estimates.

residues. GLOBIOM includes N_2O emissions from fertilizer applications, pasture and manure for livestock production, and burning of grassland and agricultural biomass. Under the baseline, FASOMGHG projections for the magnitude of N_2O emissions are lower than GLOBIOM due to GLOBIOM including more sources of emissions from soil management activities including synthetic fertilizer application, manure applied to soils, organic soils, and crop residues, while FASOMGHG accounts for N_2O emissions from residue burning, fertilizer applications, histosols, leaching, manure, pasture, and volatilization. For CO_2, both FASOMGHG and GLOBIOM project that the AFOLU sector will remain a net sink through 2050, while similarly, GTM projects that the forest sector will continue to be a net sink from 2025 to 2050. FASOMGHG and GLOBIOM estimate the net CO_2 sink will have declined by 29% (134 Mt CO_2) and 18% (114 Mt CO_2) by 2050 respectively. On the other hand, GTM projects that the forest sector will slightly increase as a net sink, with sequestration increasing by 3% in 2050 relative to 2025.

Loblolly pines grown as a commerical crop in northern Florida.

3.1.2 Baseline Land Projections and Market Dynamics Across Models

GHG emissions dynamics in the three models incorporate estimated changes in land use, land management, and expected demand for land-based products. The following sections summarize the results for land use and commodity production for forestry, cropland, and livestock across models under the baseline scenario.

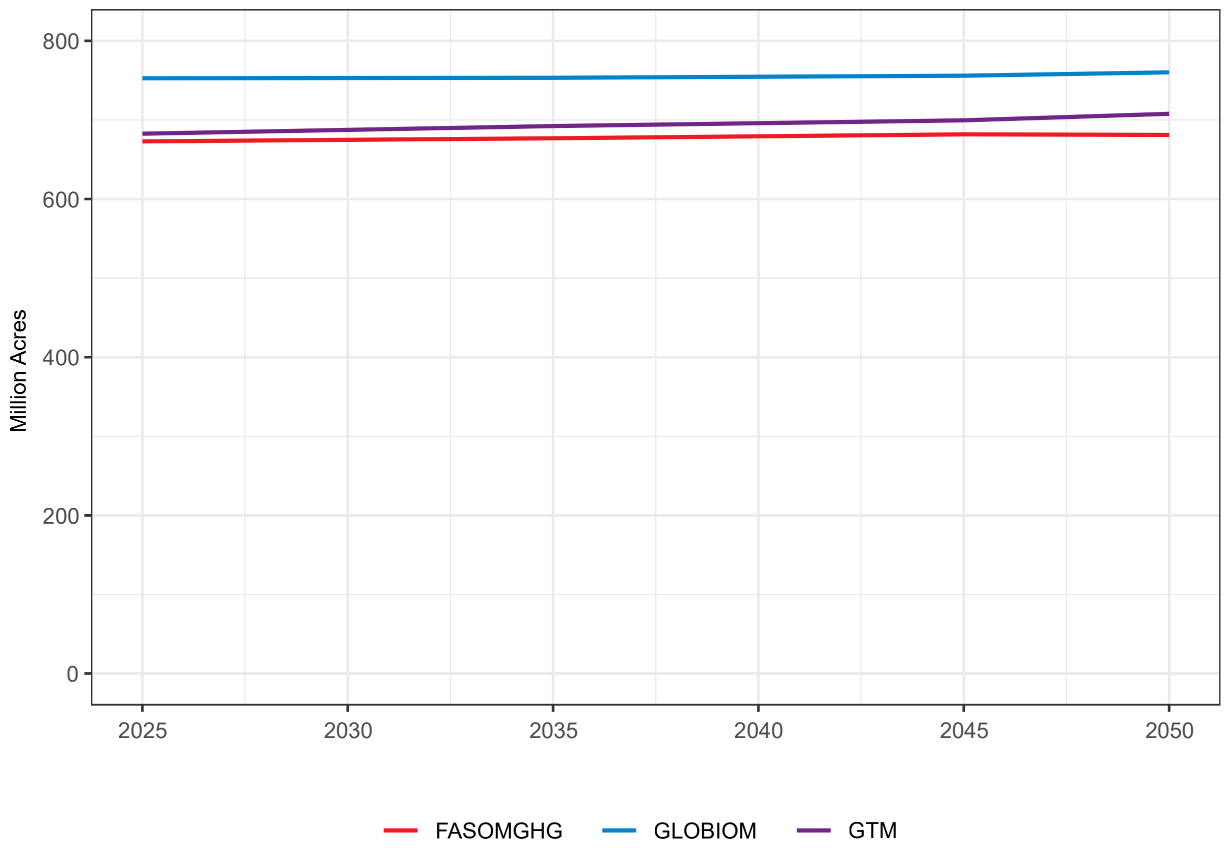
3.1.2.1 Forestry

All three models project that forest area will either remain unchanged or expand in the U.S. baseline from 2025 to 2050 and beyond to meet growing national and global demands for HWP driven by population growth and increasing consumption per capita in the future. FASOMGHG projects 10 million acres and GLOBIOM projects 5 million acres of net forest land expansion in the baseline by 2050, while GTM projects that nearly 19 million acres of net afforestation/reforestation occurs during the same period (Figure 3-4). Note that the initial forest area varies across models as they rely on different underlying datasets (FASOMGHG and GTM utilize FIA, GLOBIOM uses values presented by UN FAO) and the inclusion of Alaska in GLOBIOM and GTM, but not in FASOMGHG.

In FASOMGHG, plantation forest area increases by about 1 million acres per year from 2025 to 2050 (increasing from about 76 million acres to 106 million acres). GTM projects less expansion of plantation forests, with plantation forest area growing from 56 to 67 million acres from 2025 to 2050 (Appendix Table A-2).

Despite the varying amounts of intensification and extensification in the forestry sector across each model, overall harvest (both sawtimber and pulpwood) is consistent across the models, with gradual increases in harvest levels in FASOMGHG and GLOBIOM, and a relatively constant rate of harvesting in GTM. In 2025 the models project harvest levels of 361 million metric tons (mmt) in FASOMGHG, 369 mmt in GLOBIOM, and 392 mmt in GTM. In 2050, harvest levels equal 399 mmt in FASOMGHG, 414 mmt in GLOBIOM, and 363 mmt in GTM (Appendix Table A-3). The slight increase in harvest levels in FASOMGHG and GLOBIOM is mainly driven by high income elasticity combined with the

FIGURE 3-4 U.S. forest area under baseline scenario (in million acres, 2025–2050)

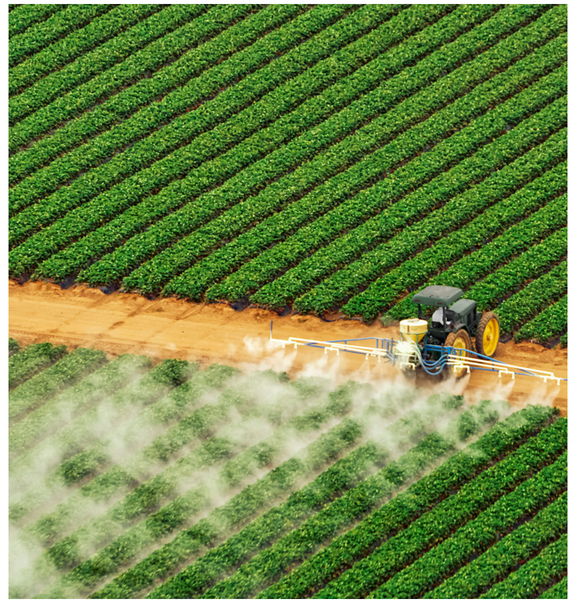


Initial values in each model differ due to varying types of forest areas included in the initial data sources: GLOBIOM is based on FAO data while FASOMGHG and GTM are based on FIA data. Additionally, GTM and GLOBIOM include representation of Alaska, while FASOMGHG does not.

income growth parameters that translate into increasing demand for things such as housing leading to expansion of (domestic or global) timber production. In GTM, global demand for timber increases in the future while the U.S. market share remains relatively constant.

Trade parameters for timber products vary across the models, affecting respective GHG emissions results. FASOMGHG has constant exogenous trade levels for forest products based on work by Daigneault and Favero (2021). GLOBIOM includes endogenous global trade, with bilateral trade represented as well. GTM does not explicitly model trade, but instead includes a global demand for timber products that each region meets according to its domestic supply. All three models project that global demand will increase for forest commodities over time largely driven by the harmonized global consumption per capita, and in response, the domestic production in the United States changes, with FASOMGHG and GLOBIOM projecting an increase while GTM shows a decline by 2050 relative to current levels. As domestic wood products demand increases, GLOBIOM projects also that the United States will increase imports over time. Imports for wood products including plywood and sawnwood increase by about 29% (1.1 million m^3) and 53% (16.7 million m^3) from 2025 to 2050 respectively, while the slight increase in forest harvest levels is mainly attributed to energy uses. These increases in domestic demand and imported harvest wood products contribute to a declining carbon sink from the U.S. forestry sector in GLOBIOM, as investments in reforestation do not outweigh the increase in harvesting activities and aging of forests.

To meet the rising demand (global or domestic), GTM and FASOMGHG project new investments in expanding forest area and in increasing highly productive plantation forests.[14] Some of these plantation investments are made post-harvest to convert formerly naturally regenerating (and slower growing) forests into plantations, consistent with forest planting trends observed in the United States since the 1950s (McEwan et al., 2020; Wade et al., 2019). On the other hand, GLOBIOM does not significantly increase management investments or change forest type in response to economic market signals of timber products, largely because in a single time step the model only incurs the upfront costs from these activities, while the future benefits are not considered given its recursive modeling framework (see Daigneault et al., 2022 for a comprehensive discussion on differences between GTM and GLOBIOM).



Aerial view of a tractor spraying fertilizer on plants in an agricultural field, California.

3.1.2.2 Cropland

Future cropland area projections in FASOMGHG and GLOBIOM are driven by different yield growth parameters and endogenously determined crop mixes, as well as by how each model responds to global markets. Specifically, FASOMGHG uses higher yield growth rates, based on higher expectations of technological improvements over time, than GLOBIOM. This difference will lead to a different demand for cropland under the same socioeconomic scenario. For instance, for the same projected food demand growth, a model with low agriculture productivity will project a higher increase in land requirements for food production than a model with a high productivity rate. As the demand for cropland increases over time, the cost of converting land into forests increases.

In FASOMGHG, technologically driven yield growth is based on USDA National Agricultural Statistical Service national data of crop and livestock yields from 1960 to 2009 and projected into the future (for additional information see Baker et al., 2013). From 2025 to 2050, FASOMGHG projects that cropland area will decline by about 30 million acres, or about 1 million acres annually (Figure 3-5). In GLOBIOM, yield growth rates are econometrically estimated using historical data from 1980 to 2010 and then projected using GDP per capita from SSP2 (as seen in Fricko et al., 2017). The yield growth rates in GLOBIOM are lower than FASOMGHG which drives a lower decline in the U.S. cropland than FASOMGHG. GLOBIOM projects that between 2025 and 2050, about 5 million acres (or about 200,000 acres annually) of cropland will convert to other uses, which results in a slight increase in crop-related non-CO_2 emissions due to increased usage of agricultural inputs such as fertilizer (Figure 3-5).

Finally, GTM does not explicitly model cropland, but it does include rental supply functions. For example, if global timber prices rise relative to farmland values, GTM projects that timber owners will rent suitable farmland for at least one rotation (increasing total forestland). Similarly, if global timber prices fall relative to farmland values, forestland will be converted back to farmland upon harvest. This approach reflects that the least productive crop- and pastureland will be converted first and that rental rates increase as more land is converted and thus becomes scarcer in the future.

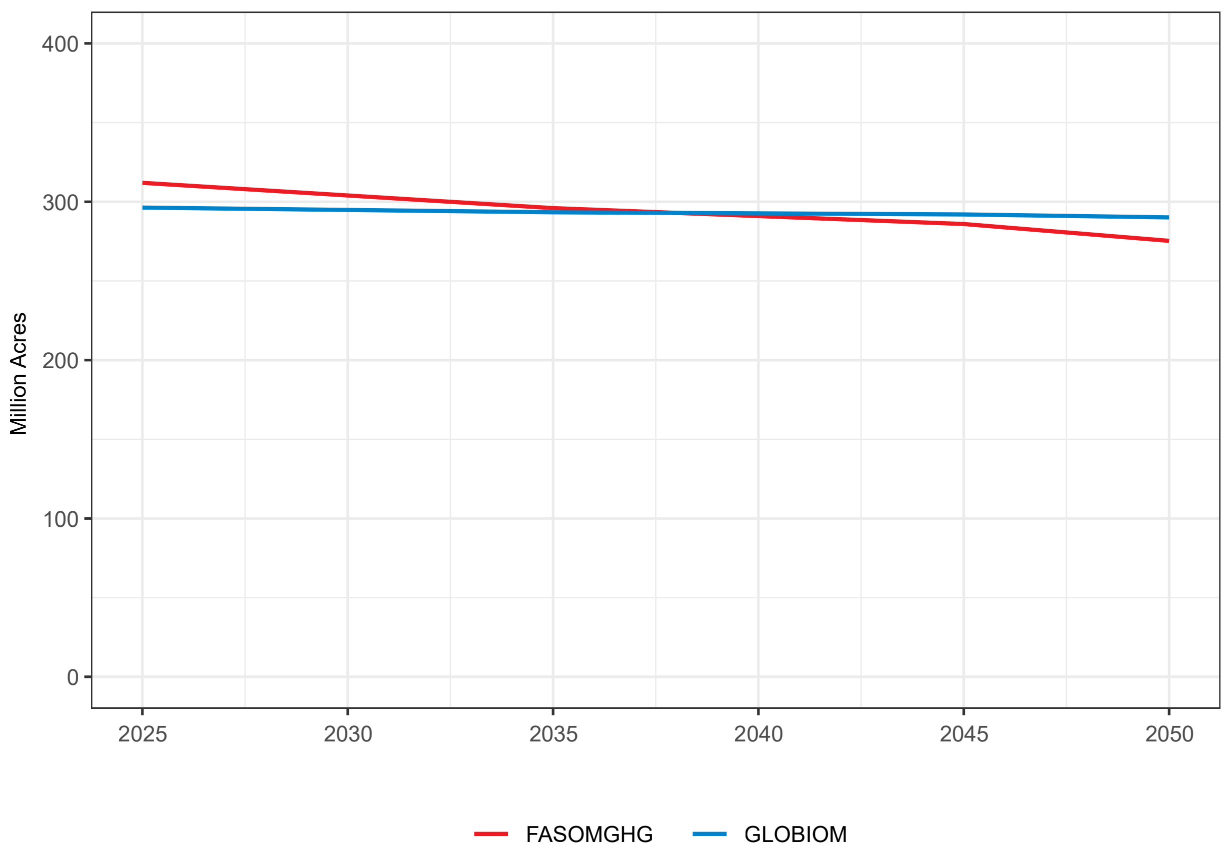
Projected crop mixes in 2050 between the two models vary, with shifts in global demand patterns represented in GLOBIOM leading to a shifting crop mix in the United States over time, while FASOMGHG has a relatively stable crop mix from 2025 to 2050 (Appendix Table A-4). For instance, in 2050, FASOMGHG projects that about 25% of cropland

[14] GTM increases plantation forest area to meet future global demand post 2050. In the medium term, domestic harvest rates decline relative to 2020 levels, with domestic demand being met through increased imports.

area is devoted to both corn and wheat, 20% to soybeans, and about 15% to hay. GLOBIOM projects a higher level of specialization in corn and soybean production in the United States with about 35% of total cropland area dedicated to each crop, while wheat production covers only about 10% of cropland area, and cotton covers about 7% (Appendix Figure A-4). In GLOBIOM, wheat production declines in the United States over time. Shifts in crop production within each model also impact livestock production due to changes in feed market dynamics, as discussed further in the following section.

Finally, global demand for crop commodities impacts the baseline in both FASOMGHG and GLOBIOM. In FASOMGHG, major U.S. export products, such as corn and soybeans, are projected to remain at relatively consistent levels of exports relative to 2025, with changes being within ±5% of today's values from 2025 to 2050. GLOBIOM projects that the United States will expand its role as a net exporter of soybeans with annual exports increasing by about 1% annually from 2025 to 2050. At the same time, corn exports are expected to drop, with levels 20% lower than today in 2050.

FIGURE 3-5 **U.S. cropland area under baseline scenario (in million acres, 2025–2050)**



Cropland is not explicitly modeled in GTM, so that model is not included. Initial values in FASOMGHG and GLOBIOM differ due to varying types of areas included in the initial inventory.

3.1.2.3 Livestock

FASOMGHG projects increased livestock production in the baseline scenario, including growth for chicken, beef, and pork driven by increasing demand through growing per capita GDP. For instance, beef production in FASOMGHG grows from about 13 million tons in 2025 to 16 million tons a year by 2050, while both chicken and pork output increase from about 17 million tons to 21 million tons (Appendix Table A-5). Additionally, FASOMGHG projects that about half of the increase in production of meat is exported from the United States, while the other half is consumed domestically. As discussed further in the mitigation section below, the increase in meat production in FASOMGHG in the baseline allows for more mitigation opportunities in the livestock sector once price incentives are implemented.

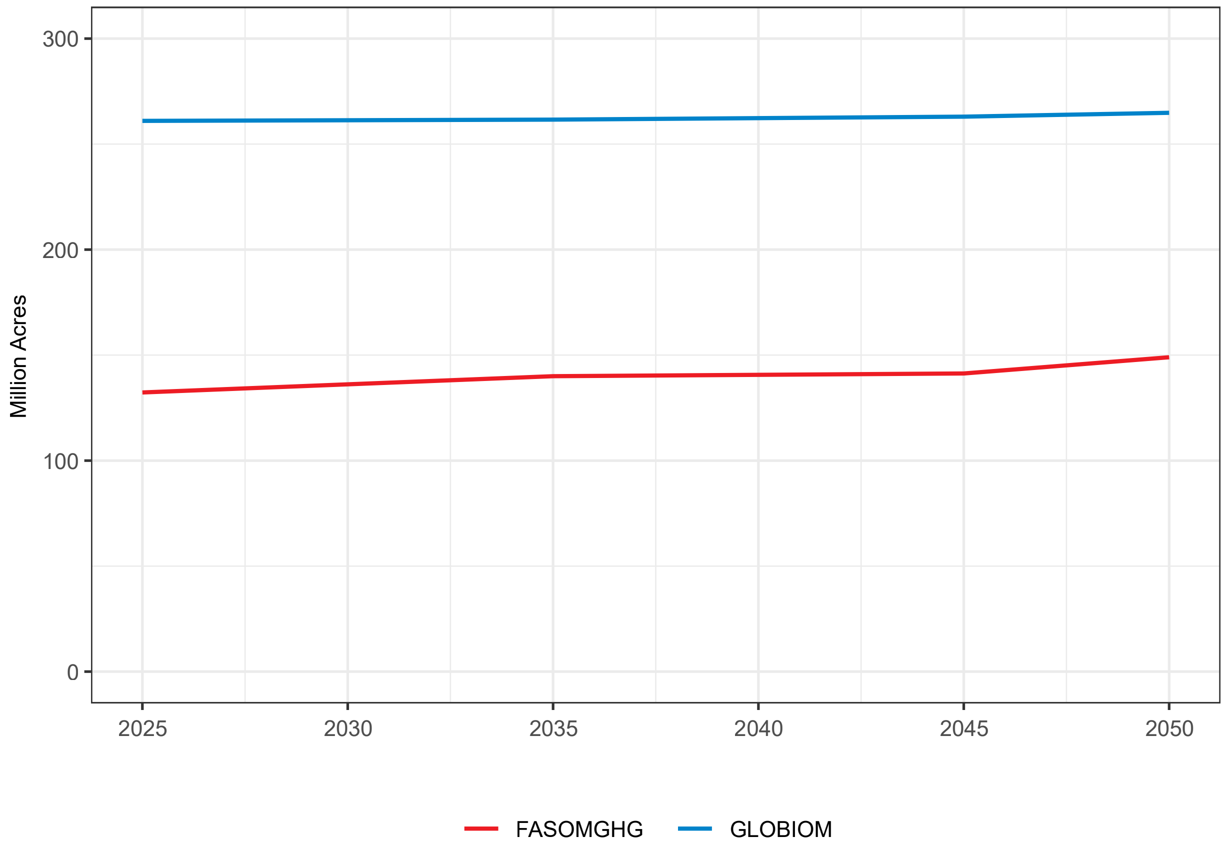
GLOBIOM differs in its demand growth rates, which results in steady levels of production for both pork and beef over the projection period (remaining at about 12 and 10 million tons from 2025 to 2050 respectively), while poultry production increases from about 20 million tons to 24 million tons annually (Appendix Table A-5). The share of total caloric intake met by meat products in the United States remains fairly constant from 2025 to 2050, with increasing overall consumption of chicken meeting the growing demand. Similar to the change in production, net trade of meat products in the United States is projected to remain relatively constant from 2025 to 2050 as increasing domestic production is used to meet increasing demand.

Both GLOBIOM and FASOMGHG project that pastureland area will increase in the baseline scenario to meet growing demands for animal products (Figure 3-6). Between 2025 and 2050, FASOMGHG projects 10 million new acres of pasture (about 400,000 acres per year) while GLOBIOM projects lower rates of conversion over the same period, with pastureland area increasing by 2 million acres by 2050 (about 60,000 acres per year) as GLOBIOM relies more on livestock production through intensive feeding operations.

FASOMGHG and GLOBIOM vary in the baseline projections of livestock commodity exports from 2025 to 2050. FASOMGHG projects that the United States will expand its export quantities of beef, chicken, and pork to satisfy a growing global demand for meat products. Conversely, GLOBIOM projects that exports of U.S. meat products will remain relatively consistent with levels of exports in 2050 being ±2% relative to 2025 levels, as other regions increase production of meat products to meet domestic demand and rely less on U.S. imports.

Aerial view of poultry houses and farm in Tennessee.

FIGURE 3-6 **U.S. pastureland area under baseline scenario (in million acres, 2025–2050)**



Initial values in FASOMGHG and GLOBIOM differ due to different land use categories included in the initial model inventory. Specifically, GLOBIOM does not differentiate between pasture and grasslands. However, the productivity of these lands varies greatly to reflect heterogeneity in ability to provide grazing opportunities. Pastureland is not explicitly modeled in GTM so it is not included.

3.2 MACCs

In 2050 at a GHG price of $100/t CO_2e, the land use sector can abate around 250–350 million t CO_2e.

This section uses the results from the multi-model assessment to estimate the cost to reduce GHG emissions across different mitigation options in the land sector and the magnitude of those projected reductions. Specifically, the analysis estimates the cost of removing an additional ton of CO_2e across different land use-based activities by creating the MACCs for the land sector from each economic model.

MACCs have been used in a variety of contexts by policymakers, investors, land managers, and economic modeling teams to inform mitigation assessments (e.g., EPA, 2009, 2019b). Moreover, model-derived projections of abatement potential that align with widely utilized macroeconomic scenarios such as the SSPs (Riahi et al., 2017) are useful in informing policy or integrated assessment modeling efforts because they directly capture economic opportunity costs of investing in alternative mitigation technologies in a competitive market (Calvin, 2016; Daigneault & Favero, 2021; Doelman et al., 2018; Wade et al., 2022; Wei et al., 2018).

Small wheeled loader moving logs around the log yard at a local sawmill in Oregon.

Furthermore, MACCs are time-dependent, and therefore can be used to assess how mitigation opportunities change for different simulation time-steps and across models. This temporal disaggregation is particularly useful in a policy context when mitigation commitments are made over different timeframes. Moreover, mitigation assessments that treat marginal abatement costs as constant over long time horizons could over- or understate mitigation potential (Fargione et al., 2018), relative to a dynamic model that cumulatively tracks opportunity costs and market feedback (Austin et al., 2020; Cai et al., 2018; Wade et al., 2023).

To build the MACCs, the analysis aggregates the projected GHG mitigation results across the 10 price incentive scenarios and two growth rate pathways presented in Section 2.7 for each model (see Appendix Table A-1). It is important to note that the price values only GHG abatement actions and does not consider possible co-benefits or side-effects such as gains or losses of biodiversity from specific land-based mitigation activities.

In the following sections, the MACCs are presented for the whole land sector and followed by a more detailed discussion of the MACCs by GHGs (CO_2, N_2O, and CH_4) and by sector (forestry, cropland, and livestock).

3.2.1 AFOLU MACCs

The AFOLU MACCs reflect the economically efficient mix of projected GHG mitigation actions across the land sector as modeled by FASOMGHG and GLOBIOM. These results therefore present a comprehensive, cost-effective mix of mitigation activities within the forestry, crop, and livestock sectors. Each model responds with its cost-effective composition of mitigation activities, which varies across GHG prices and periods. That is, while the results indicate reasonable alignment in total projected cost-effective mitigation potential across a broad range of U.S. forest and agriculture-based mitigation strategies, there are important differences between GHG mitigation opportunities utilized in each model under each price scenario, as discussed below. Furthermore, MACCs show how sensitive sector-specific abatement opportunities are to the GHG price and to if and when each abatement opportunity reaches a maximum level of mitigation capacity. Specifically, by looking at the steepness of each MACC, it is possible to measure how much an incremental increase in the value of CO_2e is likely to increase the level of abatement. For instance, a very steep MACC shows that it is very costly to abate an additional ton of CO_2e in that specific activity compared to another activity with a flatter MACC. The steep slope of the MACC in one sector relative to the other sector reflects high opportunity costs of abatement per unit area in that sector.

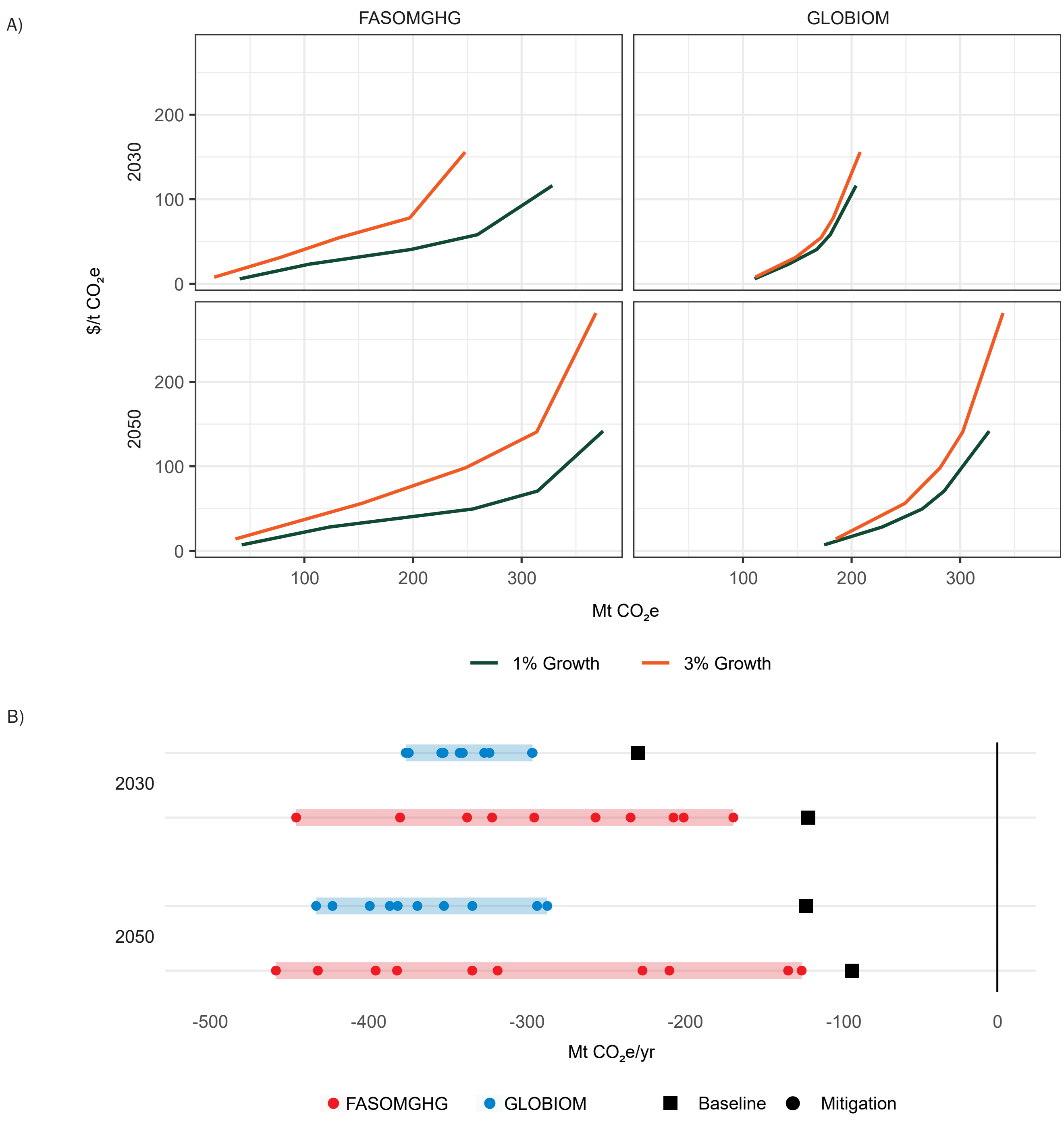
Figure 3-7 shows MACCs that aggregate all land-based (both agriculture and forestry) activities in FASOMGHG and GLOBIOM in the short- and medium-term time horizons (2030, 2050) for each price growth scenario (1% and 3%). Moreover, the figure shows the projected emissions in the sector under the baseline scenario and the GHG mitigation scenarios. Abatement presented in the MACCs is measured as the difference between emissions in the baseline and the emissions under each GHG price scenario for each model.

In the short term (2030), the mitigation scenario results show that under a GHG price of \$100/t CO_2e, the land use sector can abate about 205–300 Mt CO_2e yr^{-1} in FASOMGHG and around 195 Mt CO_2e yr^{-1} in GLOBIOM. This outcome corresponds to about doubling the net sink in GLOBIOM relative to the baseline. GLOBIOM shows potential for significant abatement even under low GHG prices with abatement above 100 Mt CO_2e yr^{-1} under a GHG price of \$5/t CO_2e. The mitigation is derived mainly from increased carbon sequestration from changes in forest management on existing stands, including changes to harvest schedules. In 2050, at a price of \$100/t CO_2e, FASOMGHG projects annual rates of mitigation of 250–350 Mt CO_2e yr^{-1} while GLOBIOM estimates 280–300 Mt CO_2e yr^{-1} of mitigation. Compared to 2030, the same price of \$100/t CO_2e in 2050 could deliver more abatement because there is more time to achieve the long-term mitigation benefits of strategies in forest management and afforestation/reforestation, given that the stock has more time to increase than in the short term.

Figure 3-7 highlights how price growth rates have different impacts in each model depending on its structure. For instance, an intertemporal optimization model like FASOMGHG selects a cost-effective mitigation portfolio

Herd of cattle grazing in a fenced-in field at sunset, Warrenton, Virginia..

FIGURE 3-7 **A) AFOLU marginal abatement cost curves; B) AFOLU absolute emissions under baseline and mitigation scenarios in 2030 and 2050**



A) MACCs are built using the abatement under each GHG price scenario starting at \$5/t CO_2e. Five observations per year are used to build each MACC. MACCs show the level of abatement in Mt CO_2e (x-axis) associated with a specific monetary value of GHG emissions in \$/t CO_2e (y-axis) for a specific reference year (2030 and 2050). GTM is not included in the figure because it does not explicitly model agriculture. B) Absolute emissions under baseline and mitigation scenarios for net emissions from agriculture, forestry, and other land use (AFOLU) in FASOMGHG and GLOBIOM. Results are presented in terms of atmospheric accounting. Therefore, positive flux equates with emissions; negative flux represents sequestration.

by considering current and future projected GHG prices. Under this specific framework, contemporaneous and future land use and land management decisions depend on the expected price growth over time. Changes in growth rates have implications even in the short term. Specifically, high growth rates (e.g., 3% in this report) have the potential effect of driving a lower adoption of mitigation actions in the short term relative to low growth rate scenarios. The model anticipates higher prices in the future and thus higher returns on mitigation actions in the future when postponed. In comparison, at the same initial price the lower growth rate (1%) yields relatively higher adoption of short-term mitigation activities because future anticipated returns are lower. For instance, under the same GHG price path in 2030, FASOMGHG projects more mitigation under the 1% growth rate when future prices are not expected to grow as fast as under the 3% case (as shown in Figure 3-7 by the gap between the 1% and 3% growth MACCs). Given the same forward-looking nature of GTM, similar effects will occur in the forest-only MACCs presented in Section 3.3.1. Conversely, mitigation potentials projected by GLOBIOM, a recursive dynamic model, are not sensitive to future expectations on key variables such as the GHG price (the gap between the two MACCs is not significant).

Across the mitigation scenarios, emissions reductions as calculated versus the baseline for the AFOLU sector are projected to be 32–364 Mt CO_2e yr^{-1} in FASOMGHG and 163–309 Mt CO_2e yr^{-1} in GLOBIOM by midcentury, meaning the two models expected a similar maximum magnitude of mitigation potential from the land sector (Appendix Figure A-5). Under the lowest price scenarios (scenarios \$5 at 1%, \$5 at 3%, \$20 at 1%, \$20 at 3%), FASOMGHG projects an average annual mitigation potential of 32–132 Mt CO_2e yr^{-1} by 2050. These scenarios correspond to a GHG price level below \$50/t CO_2e in 2050. Under the highest price scenarios (starting at \$35 at 1%), the range of abatement increases to 239–364 Mt CO_2e yr^{-1}. On the other hand, under the same high price scenarios, GLOBIOM estimates an average annual mitigation potential of 245–309 Mt CO_2e yr^{-1} in 2050 (between \$85 and \$243/t CO_2e).

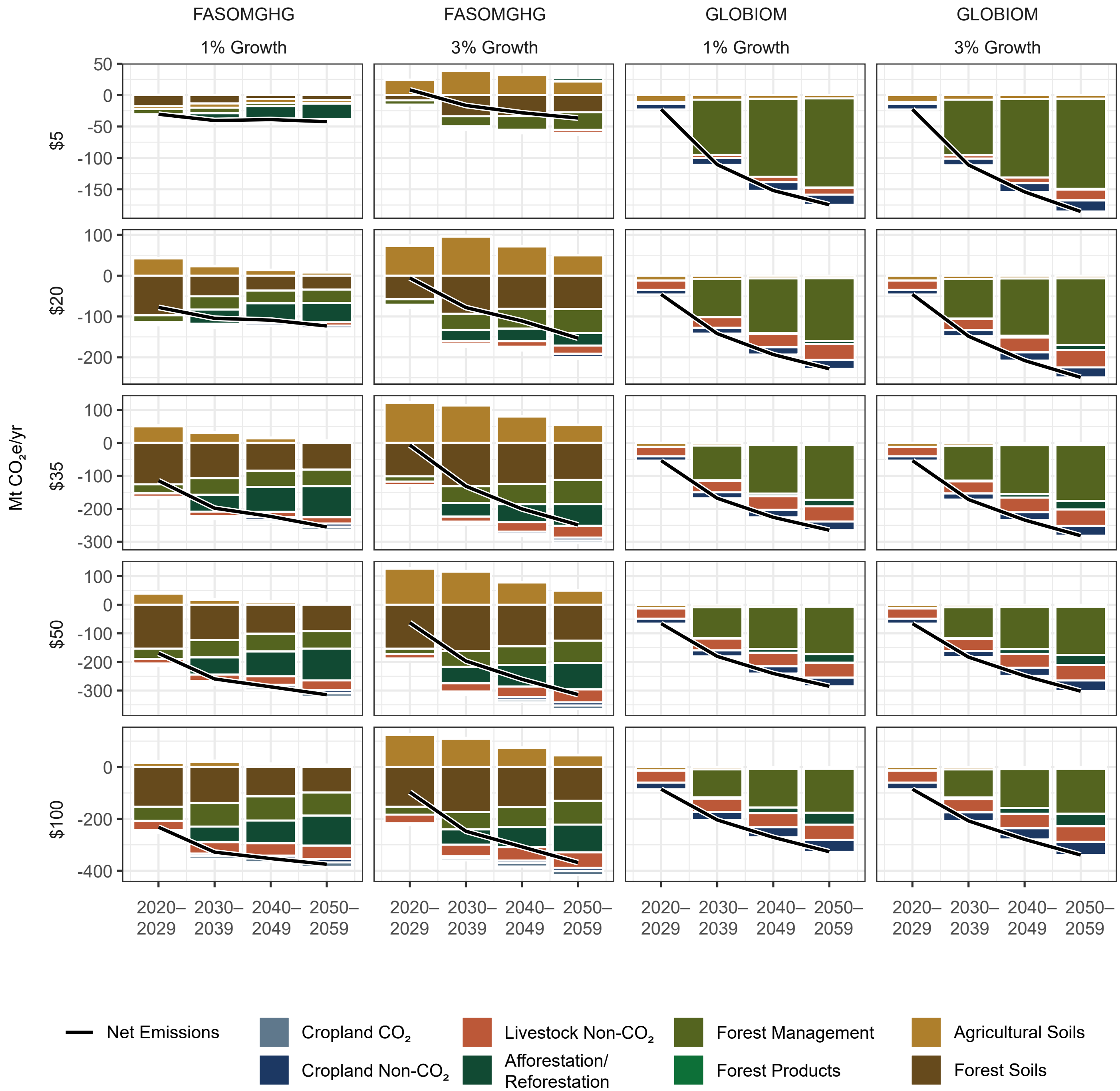
Looking at individual mitigation activities, results show that at low and moderate price scenarios, each model achieves similar mitigation levels but through different activities (Figure 3-8).

Each model chooses to implement different cost-effective land-based activities to reduce emissions or increase sequestration as a specific price response. For example, the average annual mitigation from 2025 to 2050 is projected to be 32–364 Mt CO_2e yr^{-1} in FASOMGHG and GLOBIOM, but GLOBIOM projects higher volumes of mitigation from the livestock sector and forest management compared to FASOMGHG. In FASOMGHG, the livestock sector contributes 14% of total reduction on average, while in GLOBIOM the proportion is 18%. Forest management contributes 27% in FASOMGHG and 59% in GLOBIOM. On the other hand, anticipating future returns from forestry, FASOMGHG invests in higher rates of afforestation/reforestation compared to GLOBIOM, which only looks at the current year incentives. Thus, FASOMGHG projects higher increases in both carbon sequestered in new forests and increased carbon sequestration in forest soils (afforestation and reforestation contributes 42% of total reduction on average in FASOMGHG while in GLOBIOM, the contribution is 8%).

Domestic MACCs are likely to be affected not only by internal market dynamics and land competition but also by policies, land use practices, and demand for land-based products from the rest of the world. The results presented in this chapter assume that the same GHG price incentives are applied to the land sector at the global level; thus, landowners around the world have the incentive to reduce high-emitting activities and start/increase sequestration activities. These dynamics are assessed and discussed using the specific attributes of GLOBIOM as a global model with a detailed description of the land sector in Box 4.

Log barge, Kachemak Bay, Alaska.

FIGURE 3-8 **Average annual change in GHG flux in the land sector from the baseline across mitigation scenarios and models, by GHG category (in Mt CO_2e yr^{-1}, 2025 to 2050)**



Baseline GHG emissions from the land sector by GHG category are presented in Figure 3-1. GHG categories are described in Figure 2-3. FASOMGHG includes all GHG categories, while GLOBIOM does not include forest products, forest soils, or cropland CO_2. As the results are presented in atmospheric accounting terms, negative values equal more mitigation than the baseline. GTM is not included because it does not explicitly model emissions from agriculture. Initial values differ among the models because they measure the change from baseline values and because the models respond differently to different GHG prices. Note the differences in scale across the graphics. See Box 2 for further discussion on movement of soil carbon across land use categories when land use change occurs in FASOMGHG.

Box 4

SENSITIVITY: Estimated differences in outcomes between global and domestic-only GHG emissions approaches

The MACCs presented above show the mitigation potential of the land sector in the United States under a GHG price incentive applied worldwide (for the global models used in this report). While a worldwide GHG price is the most efficient and the cheapest route to cut GHG emissions, public support for carbon pricing varies across the world and technical and political complexity limits the practicality (Haites, 2020; Pollitt, 2019; Steinebach et al., 2021). It is more likely that before a global carbon pricing scheme is agreed upon, individual countries will unilaterally continue to set policies aimed at GHG reductions. For instance, as countries aim to meet their Paris Agreement targets, many have already set carbon pricing schemes (e.g., the European Union, Japan, Australia) (World Bank, 2023). To test the effects of a more likely near-term policy scenario, a domestic set of GHG prices on land emissions in the United States is implemented in GLOBIOM and compared to the global GHG price scenarios presented in the report.

Results show that a domestic U.S.-only GHG price scenario always projects more abatement in the United States than the global GHG price scenarios in GLOBIOM. This dynamic is driven by the changes in the opportunity costs of land-based mitigation activities in the United States relative to the rest of the world when the price incentive is applied globally. Specifically, when the price is applied globally, abatement in the United States becomes relatively more expensive, therefore less domestic mitigation is reported under the same price. Under a global program, more land is projected to be converted into forests, with correspondingly less agriculture and thus higher land prices. This effect is more significant under higher GHG price scenarios and in the long term. For instance, in 2050 under the price scenario of \$50/t CO_2e, the United States sequesters 7% more than it would with the same price applied globally while under a high price level of \$135/t CO_2e, it sequesters 10% more than the global price scenario (Figure B4).

The United States reaches more abatement under the domestic GHG price scenario by converting more cropland and pasture to forest than under the global price scenarios, as well as by retiring land from agricultural production. For instance, in 2050 under a GHG price of \$50/t CO_2e, the United States converts 5 million acres of cropland, 1 million acres of pasture, and 2 million acres of other natural land to forests, while gaining 8.1 million acres of forested area relative to the global GHG price scenario. In the highest price scenario of \$100 at 3%, cropland

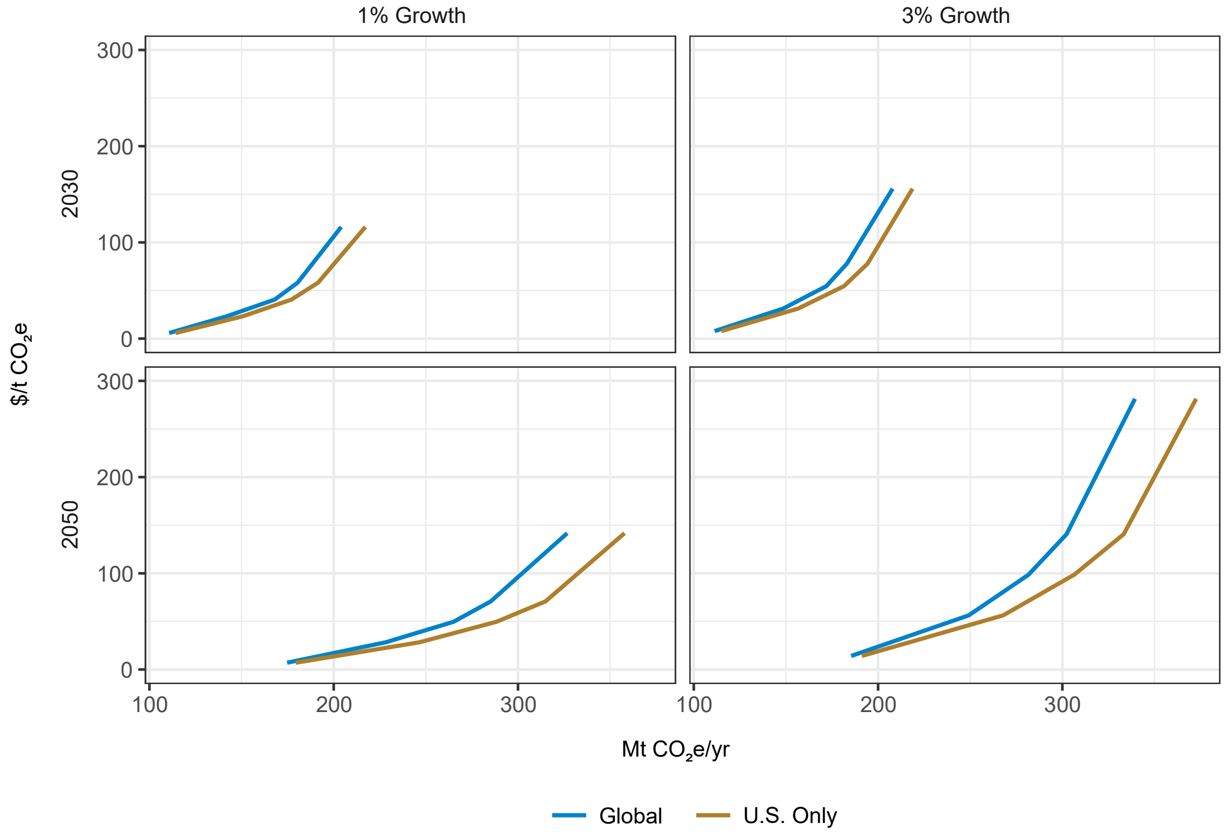
loss would be 31 million acres, pasture loss would be 12 million acres, and gains in forested area would be 7 million acres. Other natural land (undeveloped land which is not agriculture, pasture, or forestry) increases by 35 million acres, as cropland with limited tree-growing capacity is retired from agricultural production.

A unilateral GHG price is likely to indirectly affect agricultural production in the United States relative to the rest of the world, lowering the United States' competitiveness because of the additional domestic costs included in GHG-intensive production processes and goods. For instance, under the highest price scenario, the U.S. share of global agricultural production falls from 9% in the global price scenario to 7% in the U.S.-only price scenario. Further, demand for land-intensive agriculture products, such as meat and dairy, are expected to increase in the coming decades (see for example Komarek et al., 2021), and much of the supply for those products might be displaced to potentially less efficient production systems in other countries, resulting in higher meat prices and lower consumption.

Moreover, results show that a unilateral policy (like a domestic GHG price) is likely to create GHG leakage. As more domestic mitigation actions are implemented in response to the GHG price, more emissions will be produced in the rest of the world to make up for commodity supply losses caused by the management changes driven by the GHG price, possibly offsetting total cumulative abatement from the land sector globally. Table B4 shows that as much as 11% of the estimated mitigation gains achieved in the United States are erased by changes in production patterns and mitigation strategies elsewhere in the world under the U.S.-only GHG price. These results are similar to findings in a GTM analysis that quantifies U.S. forest sector mitigation potential for unilateral and global policy scenarios (Baker et al., 2017). It is important to note that the leakage effect could occur when other countries implement GHG mitigation strategies, but the United States does not.

The AFOLU sector is globally interconnected, and the model runs described here illustrate how unilateral climate policy by one country (in this case the United States) might affect LUC, likely shifting some of the country's commodity production as well as displaced emissions to other parts of the world. They also highlight the importance of accounting for global market interactions and related GHG outcomes as countries are developing national policies aimed at climate and other sustainability targets.

Figure B4: Marginal abatement costs of the U.S. land sector in 2030 and 2050 under U.S.-only GHG price scenarios and global GHG price scenarios, GLOBIOM



MACCs are built using the abatement under each GHG price scenario starting at \$5/t CO_2e. Five observations per year are used to build each MACC. MACCs show the level of abatement in Mt CO_2e (x-axis) associated with a specific monetary value of GHG emissions in \$/t CO_2e (y-axis) for a specific reference year (2030 and 2050). The global scenario applies the GHG price scenarios to all GHG emissions in the land sector at the global level while the U.S.-only scenario applies GHG price scenarios only to GHG emissions in the U.S. land sector.

Table B4: Average annual mitigation for the land sector in the United States and in the rest of world (ROW) under a global GHG price and under the U.S.-only GHG price scenario from 2025 to 2050 (Mt CO_2e yr^{-1})

	Global GHG Price Scenario		U.S.-Only GHG Price Scenario	
Average GHG Price in \$/t CO_2e (2025–2050)	**U.S. Mitigation (Mt CO_2e yr^{-1})**	**ROW Mitigation (Mt CO_2e yr^{-1})**	**U.S. Mitigation (Mt CO_2e yr^{-1})**	**ROW Mitigation (Mt CO_2e yr^{-1})**
\$5–20	175–185	2,822–3,321	179–191	(4)–(3)
\$21–40	228–249	4,653–5,085	246–268	(16)–(12)
\$41–90	265–302	5,553–6,277	288–333	(35)–(16)
\$91–165	327–339	6,544–6,724	358–373	(41)–(31)

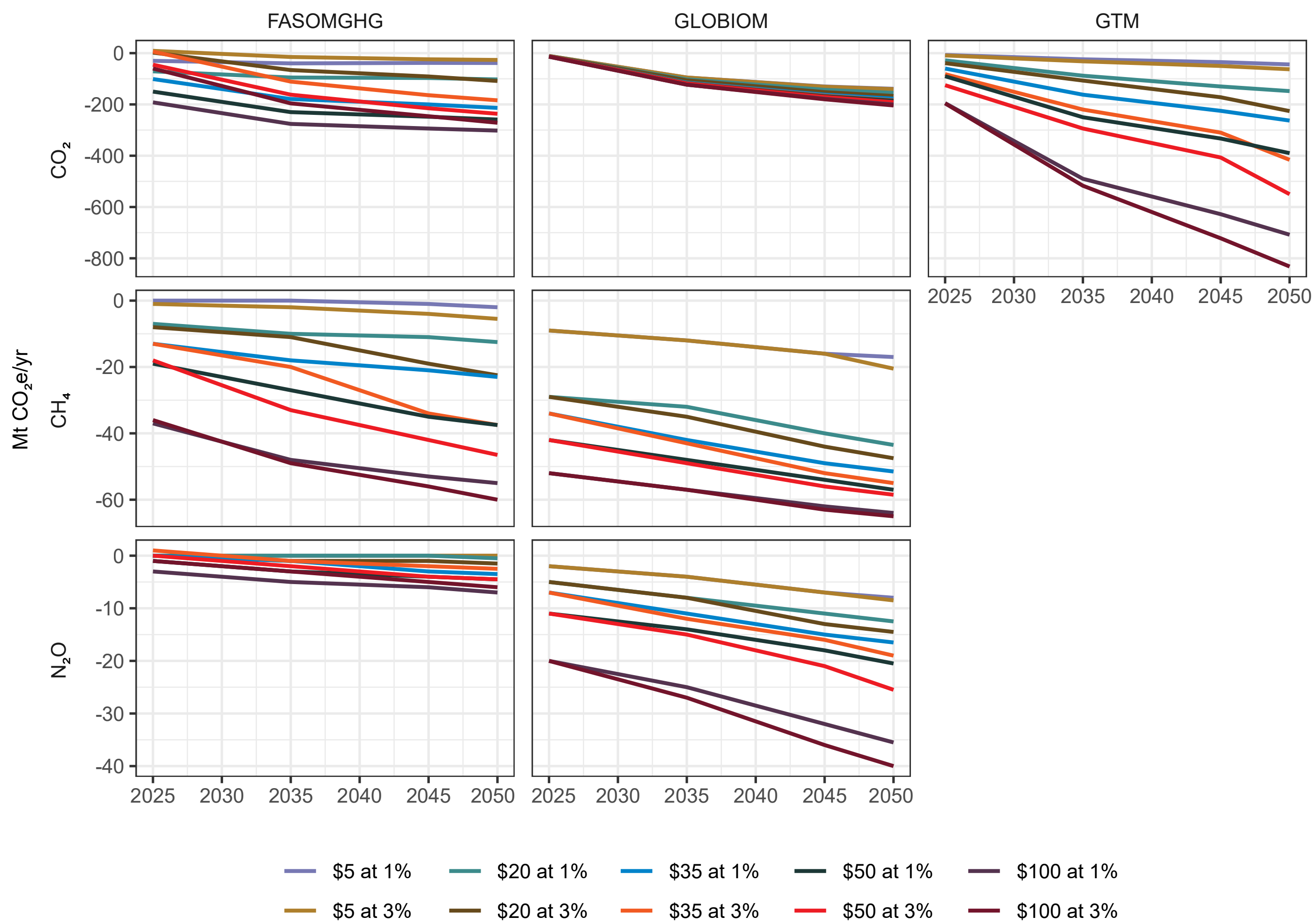
The Average GHG Price column shows the 2025–2050 average prices across the 10 mitigation scenarios. Positive mitigation values reflect net mitigation and values in parentheses represent net emissions.

3.2.2 Gas-Based MACCs

This section presents estimated mitigation opportunities in the land sector by focusing on each GHG across FASOMGHG, GLOBIOM, and GTM (CO_2 only).

Figure 3-9 shows the projected changes in emissions from each GHG (CO_2, N_2O, and CH_4) under GHG price scenarios. In 2050 under the highest GHG price scenario of $100 at 3%, the maximum CO_2-only emission reductions are expected to be 302 Mt CO_2 in FASOMGHG, 204 Mt CO_2 in GLOBIOM, and 800 Mt CO_2 in GTM (it is important to note that CO_2 is the only gas represented in GTM). Under the same scenario, CH_4 emissions are expected to decline relative to their baseline projections by 60 Mt CO_2e in FASOMGHG and 65 Mt CO_2e in GLOBIOM. Finally, for N_2O the abatement is 7 Mt CO_2e in FASOMGHG and 40 Mt CO_2e in GLOBIOM.

FIGURE 3-9 **Average annual change in GHG flux in the land sector by GHG from the baseline across scenarios and models (in Mt CO_2e yr^{-1}, 2025 to 2050)**



Baseline GHG emissions from the land sector by GHG are presented in Figure 3-1. Because the results are presented in atmospheric accounting terms, negative values equal more mitigation than at the baseline. GTM models only CO_2 in the forestry sector. Initial values are different because they measure the change from baseline values, because the models respond differently to different GHG prices, and because the models include different mitigation strategies across GHGs. Note the differences in scale across the graphics.

Figure 3-10 presents the MACCs for each gas in the short and medium term.

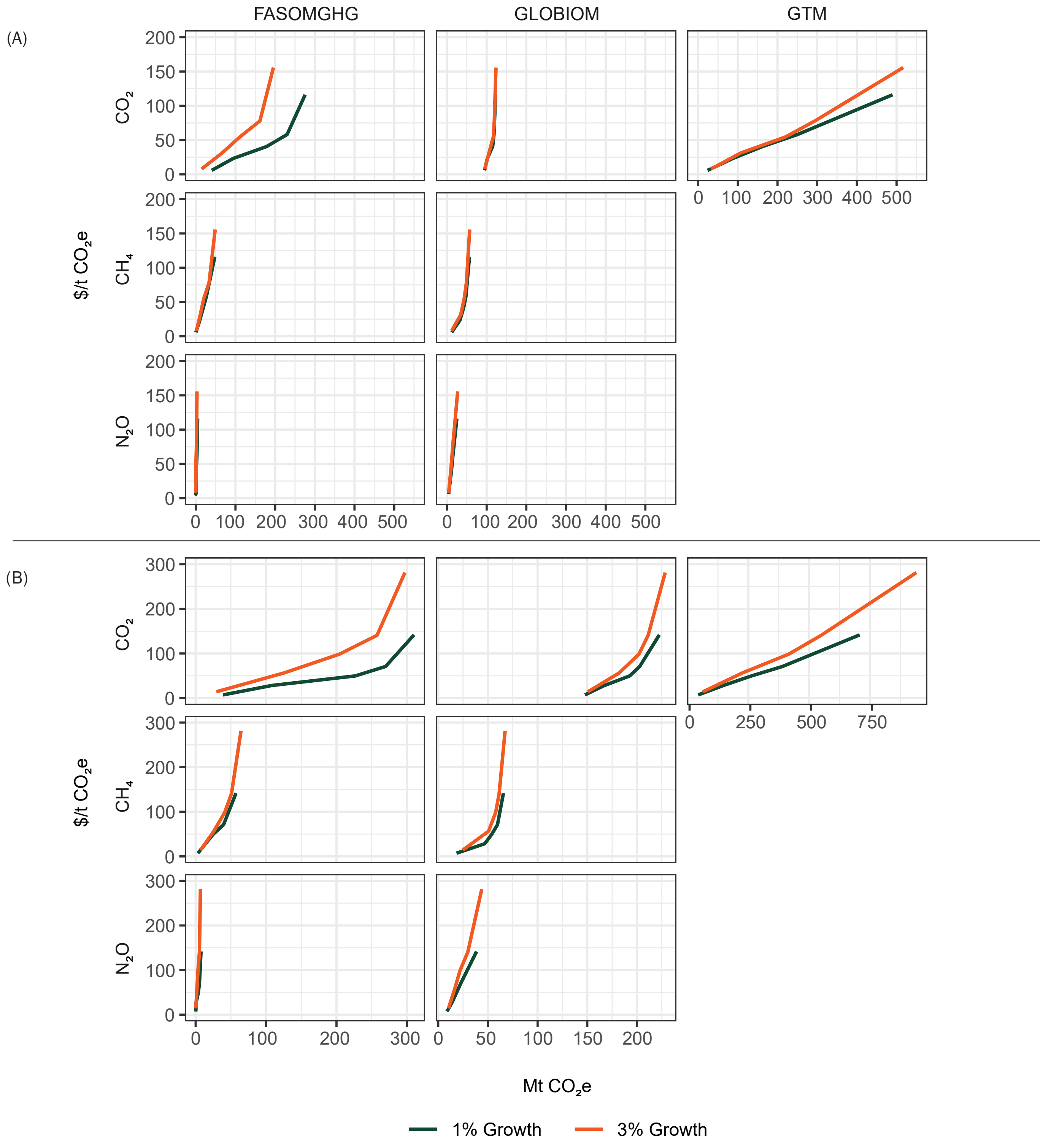
In 2030, at a GHG price of \$100/t CO_2e, mitigation of CO_2 varies across models. FASOMGHG projects about 130-254 Mt CO_2 yr^{-1}, GLOBIOM projects 110 Mt CO_2 yr^{-1}, and GTM projects 350-500 Mt CO_2 yr^{-1}. Across CH_4-MACCs and N_2O-MACCs, GLOBIOM consistently projects higher rates of mitigation than FASOMGHG for each price tested. In 2030, at a GHG price of \$100/t CO_2e, CH_4 mitigation is projected to be 50 Mt CO_2e yr^{-1} and 34 Mt CO_2e yr^{-1} in GLOBIOM and FASOMGHG, respectively. N_2O is lower than both CO_2 and CH_4—equal to 3 Mt CO_2e yr^{-1} and 18 Mt CO_2e yr^{-1} at a price of \$100/t CO_2—in FASOMGHG and GLOBIOM. In 2030, CH_4 emissions are projected to be below 30% relative to 2020 levels at a GHG price of 116\$/t CO_2e in GLOBIOM.

In 2050, the CO_2-only mitigation potential is higher than 2030 across models per GHG price tested. For instance, at a GHG price of \$100/t CO_2e, FASOMGHG projects 200–280 Mt CO_2 yr^{-1}, GLOBIOM projects 200–210 Mt CO_2 yr^{-1}, and GTM projects 350–500 Mt CO_2 yr^{-1}. For CH_4-MACCs, both FASOMGHG and GLOBIOM show increasing maximum mitigation potential to 42 and 57 Mt CO_2e yr^{-1} at a GHG price of \$100/t CO_2e, respectively. Finally, N_2O abatement potential also increases at the same GHG price of \$100/t CO_2e in 2050 relative to 2030 in FASOMGHG and GLOBIOM, with projections of 4 and 22 Mt CO_2e yr^{-1}, respectively.

While mitigation potential may be smaller for non-CO_2 gases, the MACCs show that there are ample cost-effective opportunities available for both CH_4 and N_2O and that they could play a role in achieving GHG mitigation goals. Finally, the forward-looking structure of FASOMGHG is likely to affect only CO_2 abatement opportunities while non-CO_2 MACCS are not sensitive to the growth rate of GHG prices because the benefits do not accumulate over time.

Fields of crops in a valley in the desert climate of Arizona just outside of Phoenix.

FIGURE 3-10 **GHG-based marginal abatement cost curves in (A) 2030 and (B) 2050**



MACCs are built using the abatement under each GHG price scenario starting at $5/t CO_2e. Five observations per year are used to build each MACC. MACCs show the level of abatement in Mt CO_2e (x-axis) associated with a specific monetary value of GHG emissions in $/t CO_2e (y-axis) for a specific reference year (2030 and 2050). GTM models only CO_2 emissions from forests and does not explicitly model mitigation opportunities outside forestry. Note the differences of scale on the x-axis.

3.3 Activity-Based MACCs

This section presents and describes the MACCs of the land sector divided by three subsectors: forestry, agriculture, and livestock.

Each subsection discusses the role of all the mitigation activities included in each model as shown in Figure 2-6, within the three main land categories (forests, cropland, and pastureland) to help interpret the MACCs results.

3.3.1 Mitigation in Forests

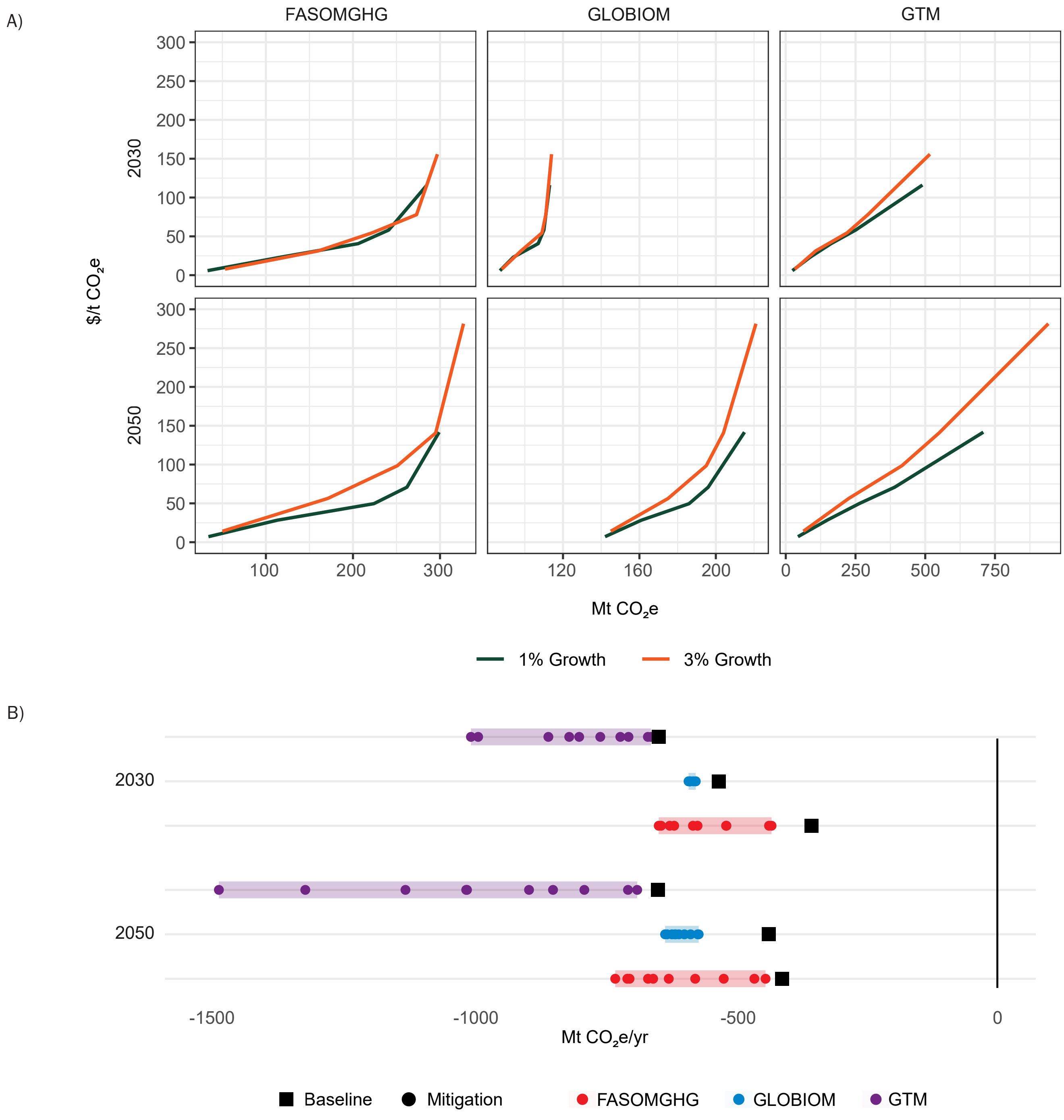
This section presents the MACCs for the forestry sector only across the three models in the short and medium term (2030 and 2050). FASOMGHG and GTM each represent all five abatement options (Appendix Figure A-6), while GLOBIOM includes three of the mitigation activities. Individual pools include existing forest (above- and belowground), new forest (above- and belowground), carbon stored in HWP, and soil organic carbon in forested lands. The models include multiple activities that can increase carbon storage in existing forests, and all three models can extend (or curtail) timber harvest rotation lengths. FASOMGHG and GTM allow for increased management intensity through activities such as intensive planting and thinnings, and all three models allow for avoided forest conversion. Each model also represents afforestation/reforestation and land use competition and tracks additional carbon stored in new or reforested lands. FASOMGHG and GTM also track carbon stored in HWP and each model can change the production levels of these products to optimize the amount of carbon stored in standing biomass and long-lived timber products. Each model also tracks carbon stored in soils on forestlands; however, there are not explicit mitigation activities that increase soil carbon. Instead, carbon stored in soils is a byproduct of LUC activities such as afforestation/reforestation.

Figure 3-11 shows the MACCs and the projected emissions from the forestry sectors in 2030 and 2050 across the three models. In 2030, at a price of \$100/t CO_2e, FASOMGHG projects abatement levels from forestry options of 260 MtCCO_2 yr^{-1}, GLOBIOM of 110 Mt CO_2 yr^{-1}, and GTM of 350–400 Mt CO_2 yr^{-1}. In 2050, at a GHG price of \$100/t CO_2, FASOMGHG projects abatement levels of 250–286 Mt CO_2 yr^{-1}, GLOBIOM projects 180–210 Mt CO_2 yr^{-1}, and GTM projects 350–500 Mt CO_2 yr^{-1}. Moreover, in 2050, GLOBIOM projects the largest abatement at low prices (\$5 at 1% scenarios), with net sequestration from forests increasing by 31% relative to baseline, while GTM and FASOMGHG increase net sequestration by 6% and 8% respectively.

Despite different representations of timber markets and different availability of forest-based mitigation activities (including management techniques), the three models project a similar net mitigation potential of approximately 32–244 Mt CO_2 yr^{-1} under lower GHG prices at \$50/t CO_2 in 2050. This outcome is in line with previous mitigation analyses of the U.S. forest sector (Baker et al., 2018; Cai et al., 2018; Daigneault et al., 2022; Van Winkle et al., 2017). Chapter 4 compares the outcomes of this report with other literature in more detail. On the other hand, mitigation estimates diverge significantly under GHG prices higher than \$100/t CO_2e, as GTM projects high rates of afforestation/reforestation. In general, GTM projects a much higher rate of mitigation available from the forestry sector compared to the other two models. Each of these two models increases forest area at increasing rates as GHG prices rise, but because of their explicit representation of agricultural markets, as agriculture production declines initially, commodity prices rise, which in turn increases the value of agricultural land. This progression leads to endogenous limits on afforestation/reforestation due to market responses, which result in lower projected amounts of overall mitigation in FASOMGHG and GLOBIOM compared to GTM.

Appendix Figure A-7 shows the projected reductions in emissions from the forestry sector until 2050. By 2050 under the highest GHG price scenario of \$100 at 3%, the maximum emissions reduction is equal to 375 Mt CO_2e yr^{-1} in FASOMGHG, 200 Mt CO_2e yr^{-1} in GLOBIOM, and 832 Mt CO_2e yr^{-1} in GTM. The wide range is explained by different GHG price pathways, alternative mitigation options available in each model, market dynamics, and other uses of land

FIGURE 3-11 **A) Forest marginal abatement cost curves; B) Forest absolute emissions under baseline and mitigation scenarios in 2030 and 2050**

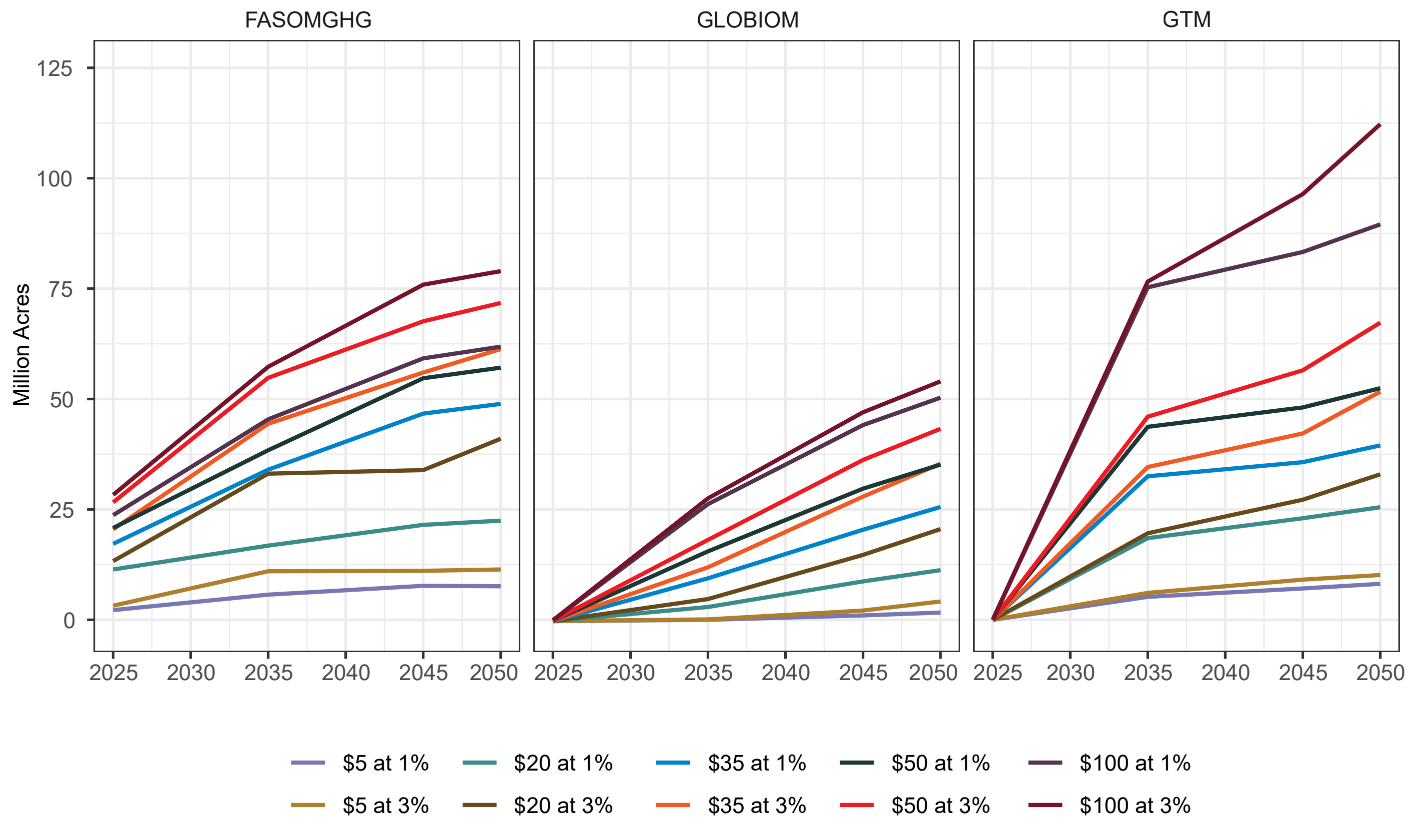


A) MACCs are built using the abatement from the forestry sector under each GHG price scenario starting at \$5/t CO_2e. GHG price applies to all GHG emissions from the land sector but only the abatement from the forestry sector is used to build the curves presented in this figure. Five observations per year are used to build each MACC. MACCs show the level of abatement in Mt CO_2 (x-axis) associated with a specific monetary value of GHG emissions in \$/t CO_2e (y-axis) for a specific reference year (2030 and 2050). Note that the x-axis is different for each model. B) Absolute emissions under baseline and mitigation scenarios from the forestry sector in FASOMGHG, GLOBIOM and GTM in 2030 and 2050. Results are presented in terms of atmospheric accounting. Therefore, positive flux equates with emissions; negative flux represents sequestration.

discussed below. Across the landscape, the introduction of a price incentive on carbon sequestration drives changes in land management and land use as well as changes in forest product markets.

Figure 3-12 compares changes in forest area relative to the baseline across the different models. All models project an increase in managed forestland and total forest area under mitigation scenarios. Projected investment in new forest stands is quite similar for GTM and FASOMGHG in early periods, with an increase in afforestation/reforestation of about 5–75 million acres between 2025 and 2035 across all mitigation scenarios. Over time, GTM continues to invest in afforestation/reforestation and forest management (especially under GHG price starting above \$50/t CO_2e) while FASOMGHG slows investment driven by high relative afforestation/reforestation cost parameters (see Cai et al., 2018) and begins to stabilize. In 2050, GLOBIOM and FASOMGHG project 2–80 million acres of new forest relative to the baseline (about 1%–9% increase from present), while GTM projects 8–112 million acres (about 1%–19% increase from present). Historically, absent major non-market incentives to increase forest area, the U.S. forest land base has remained relatively stable at about 690 million acres (excluding Alaska and Hawaii) (U.S. Forest Service, 2012). These different responses help explain the range of mitigation from the forest sector across each model after midcentury.

FIGURE 3-12 **Average annual change in total forest area from the baseline across scenarios and models (in million acres, 2025–2050)**



Baseline forest area by model is presented in Figure 3-4. Positive values equal an increase in forest area from the baseline. Initial values are different because FASOMGHG starts in 2015, GLOBIOM begins in 2000, and GTM starts in 2020.

Not only is more land projected to be converted to forests under mitigation scenarios, but the relative magnitude of intensively managed forest is projected to increase. When GHG prices are implemented, both FASOMGHG and GTM increase plantation forest area, with FASOMGHG increasing plantation forest by as much as 12 million acres, and GTM increasing by as much as 32 million acres in 2050 relative to the baseline (Appendix Figure A-8). The expansion of plantation forests results in both faster growing and higher carbon density stands relative to passively managed forests. This forest management decision allows each of these models to increase the mitigation potential while still supplying high amounts of HWP in the mitigation scenarios. GLOBIOM does not include explicit representation of intensively managed or plantation forest, which results in GLOBIOM increasing the imports of HWP relative to the baseline as the model capitalizes on U.S. forests' ability to efficiently sequester carbon.

The introduction of a GHG price affects the production of wood products since carbon stored in standing forests together with carbon in HWP is rewarded, but the magnitude and directionality (increased or decreased production) of HWP projected volumes varies across the models.

Interestingly, only the lower price scenarios within GTM result in an increase in forest timber products relative to the baseline while all GHG price scenarios in FASOMGHG and GLOBIOM, and moderate and high GHG prices in GTM, result in a decrease in harvesting and ensuing HWP. Specifically, from 2025 to 2050 under GHG price scenarios at or below \$35 at 1%, GTM projects that total harvest will increase by 0.4%–1.5% (5–20 mmt cumulatively) relative to the baseline. On the other hand, under all GHG price scenarios, FASOMGHG and GLOBIOM project a decrease in harvesting up to 10% from 2025 to 2050 (Appendix Table A-6).

Moreover, harvesting decisions under GHG price incentives vary in GTM and FASOMGHG due to different modeling approaches, including a global versus domestic modeling approach. For instance, in GTM, when GHG prices are included, the United States expands its forest sector to both increase carbon sequestration and increase HWP production long-term after 2050, while other regions (including the tropics) reduce production to set aside larger portions of their forest biomass and instead receive carbon rents (Austin et al., 2020). This outcome leads to an increase in carbon sequestered in the U.S.-derived forest products in GTM under low-priced GHG scenarios (1–5 Mt CO_2 yr^{-1}

A completed active timber harvest in the McBride Plantation area just southwest of Mount Shasta in the Shasta-Trinity National Forest in February 2023. The spacing, healthy crowns, and same-sized, straight, trees are the goal for what the plantation should look like. (USDA Forest Service photo by Paul Wade)

A fuel treatment area in the Accelerating Longleaf Pine Ecosystem Restoration Project in the Osceola National Forest, Florida. (Forest Service photo by Scott Ray)

in 2050 under the $5 at 1%, $20 at 1%, and $35 at 1% scenarios). On the other hand, FASOMGHG reduces domestic production of wood products by as much as 27 mmt by 2050 relative to the baseline scenario under high mitigation price assumptions (compared to total output of 396 mmt in 2050 in the baseline). This reduction in production is due to it being more cost-effective to sequester carbon through preservation in older forests and receive carbon payments than to produce HWP for consumption. Ultimately, GTM and FASOMGHG find the marginal benefit of leaving some forest stands on the landscape to continue storing carbon to be more valuable than harvesting them for forest products under high price scenarios, which leads to a smaller carbon sink stored in HWP relative to the baseline. That is, rising GHG prices will drive forest owners to hold trees for a longer time, effectively increasing the stock of carbon in forests and increasing the sink capacity while decreasing harvesting and carbon in HWPs. Tradeoffs between timber revenue and revenue from carbon stored in HWP relative to revenue from forest carbon rents are fully included in the models when they find the optimal solution.

Finally, as mentioned above, terminal years might affect the results in the models. Since GTM simulations are run for a much longer timeframe (200 years), there is a temporal shift in abatement across regions as mitigation price incentives increase in the long term. Near-term mitigation action is centered primarily in the tropics, supporting both reduced deforestation and net forest expansion through plantation systems because they are more cost-effective than other forest-based actions (as discussed in Austin et al., 2020). After 2050, a greater proportion of mitigation is expected in the temperate and boreal regions globally. Moreover, terminal years play an important role in explaining the difference in projected area and timing of plantation investments between GTM and FASOMGHG. With a shorter simulation timeframe, FASOMGHG increases plantation investments early in the simulation horizon and shifts forest harvests to newly established and converted plantation systems over time, while GTM has the incentive and ability to spread investment in plantation forests into the future because the model is run over a longer time horizon and planted forests can still be harvested and create a financial return prior to the terminal year.

Furthermore, projected mitigation results from the forestry sector are sensitive to the applied biophysical characteristics of forests, implementation of carbon sequestration payments, and intrinsic characteristics of the model used for the analysis. The following focus boxes use the detailed description of the forestry sector in GTM and FASOMGHG to test the results presented in this section under alternative scenarios to better inform the interpretation of the results. Specifically, Box 5 uses GTM to explore the effect of the potential mitigation and related costs of carbon sequestration in forests taking into consideration CO_2 fertilization effects. Box 6 explores how sensitive GTM results are to the terminal year and land availability for new forests. Box 7 provides a theoretical framework to explore the effects of endogenously determined participation rates in a forest sequestration program on the overall mitigation potential of forests with FASOMGHG.

Box 5

SENSITIVITY: Representing effects of CO_2 fertilization on forest mitigation

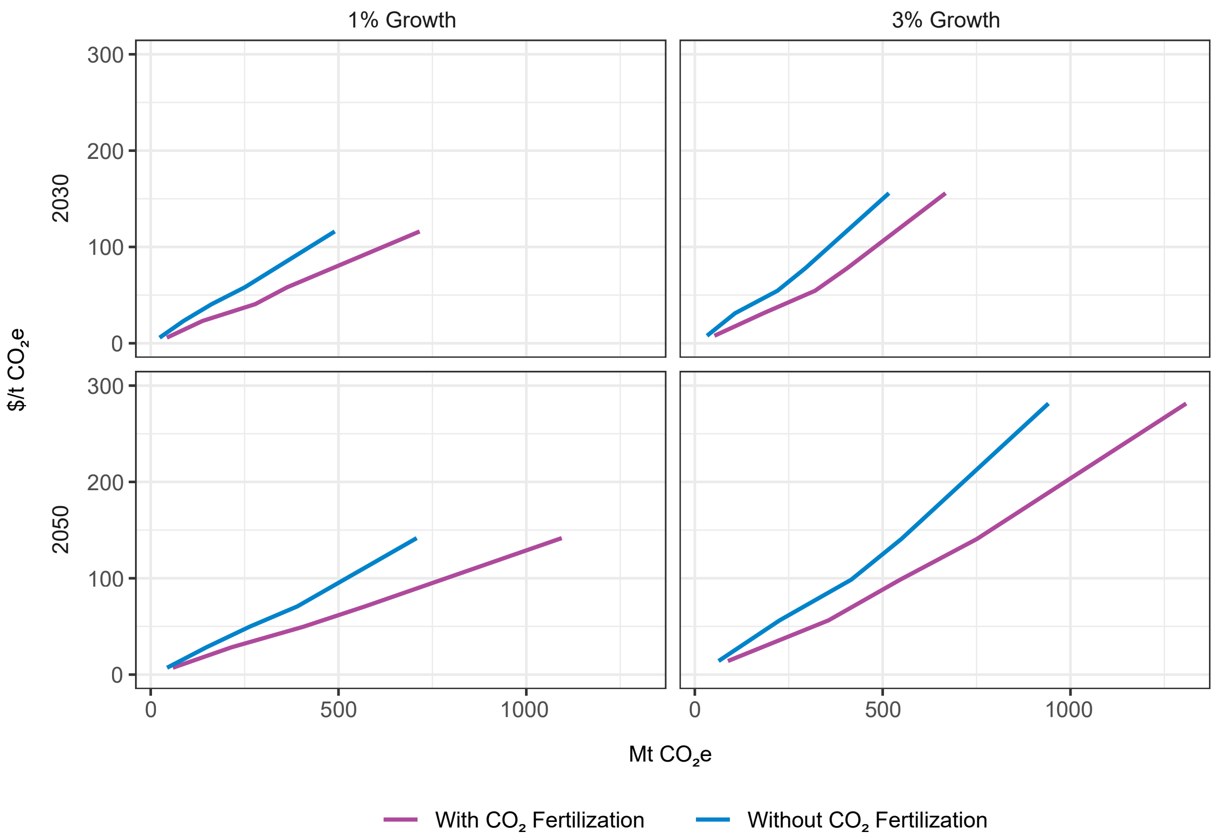
Forest carbon mitigation potential is likely to be affected by future changes in climate conditions that vary across regions and scenarios. Changes in climate conditions are going to affect forestland availability and productivity through changes in dieback rates, tree migration, and CO_2 fertilization (Favero, Mendelsohn, et al., 2018; Favero et al., 2021; Gonzalez et al., 2010; Kirilenko & Sedjo, 2007; Schimel et al., 2015; Sohngen & Tian, 2016). This box focuses on the effects of CO_2 fertilization on forest mitigation that emerge by running the same baseline and GHG price scenarios in GTM as found in the main report under an alternative assumption on CO_2 fertilization that includes climate change impacts. The version of GTM used in this box includes carbon fertilization effects in the function that represents regional forest natural productivity. Regional values of carbon fertilization are based on the estimates presented in Schimel et al. (2015) and Davis et al. (2022) and are in line with the Representation Concentration Pathway 4.5 scenario (RCP 4.5).

Under the baseline scenario, results show that when CO_2 fertilization is included, forests in the United States are likely to increase their sequestration potential by 28% by 2050. Since forests are more productive per hectare under the baseline scenario, less land is required to produce the same amount timber. That is, under the baseline scenario, for the same demand for timber products, 9 million less acres of land will be converted into forests in the United States when fertilization is included. Furthermore, fertilization affects regional timber supplies differently depending on the location and forest types. For instance, under the fertilization scenario, the United States is expected to increase its average supply by 15% relative to the same global demand scenario without fertilization between 2025 and 2050.

Under the mitigation scenarios, results show more abatement from the forestry sector when fertilization is considered. Specifically, when fertilization effects are applied along with the GHG price scenarios, more sequestration is projected to occur under each GHG price scenario, with the highest increase in absolute and relative terms under the $100 at 1% scenario. These changes will affect the MACCs under the same GHG price: that is, carbon fertilization is projected to abate 29%–82% more by 2030 depending on the price level. By 2050, the forestry sector—including above- and belowground biomass, forest soil carbon, and HWP—is projected to sequester between 31% and 58% more than the same price scenario without fertilization (Figure B5).

These findings show the importance of testing climate change impacts when estimating the mitigation potential of forests. Future research should explore other important impacts outside CO_2 fertilization.

Figure B5: Marginal abatement costs for forests in 2030 and 2050 with and without CO_2 fertilization, GTM



MACCs for forests in 2030 and 2050 with and without CO_2 fertilization in GTM by growth rate scenarios (1% and 3%). MACCs are built using the abatement under each GHG price scenario starting at $5/t CO_2e. Five observations per year are used to build each MACC. MACCs show the level of abatement in Mt CO_2e (x-axis) associated with a specific monetary value of GHG emissions in $/t CO_2e (y-axis) for a specific reference year (2030 and 2050). CO_2 fertilization is included in the GTM as the change in natural primary productivity in all forests around the world and it is specific to regions and forest types (Davis et al., 2022; Schimel et al., 2015). The Without CO_2 Fertilization Scenario reports the results presented in the main text of Chapter 3.

Box 6

SENSITIVITY: Accounting for price and land constraints

Results show that the U.S. forestry sector plays a considerable role in land use mitigation activities across scenarios and models applied in this report. When both sectors (agriculture and forest) are available, GLOBIOM and FASOMGHG show that more than 67% of future mitigation in the United States could come from forest by midcentury. Moreover, under moderate GHG price scenarios ($35 and $50/t CO_2e at 1% and $35/t CO_2e at 3%) forest mitigation potential across the three models is within a similar range (32–244 Mt CO_2e yr^{-1}). However, as more ambitious GHG prices are introduced in the system, GTM estimates higher potential than the other two models (e.g., 832 Mt CO_2e yr^{-1} vs. 375 Mt CO_2e yr^{-1} in FASOMGHG and 200 Mt CO_2e yr^{-1} in GLOBIOM in 2050). The discussion in this box tests two possible drivers of this gap in the projections.

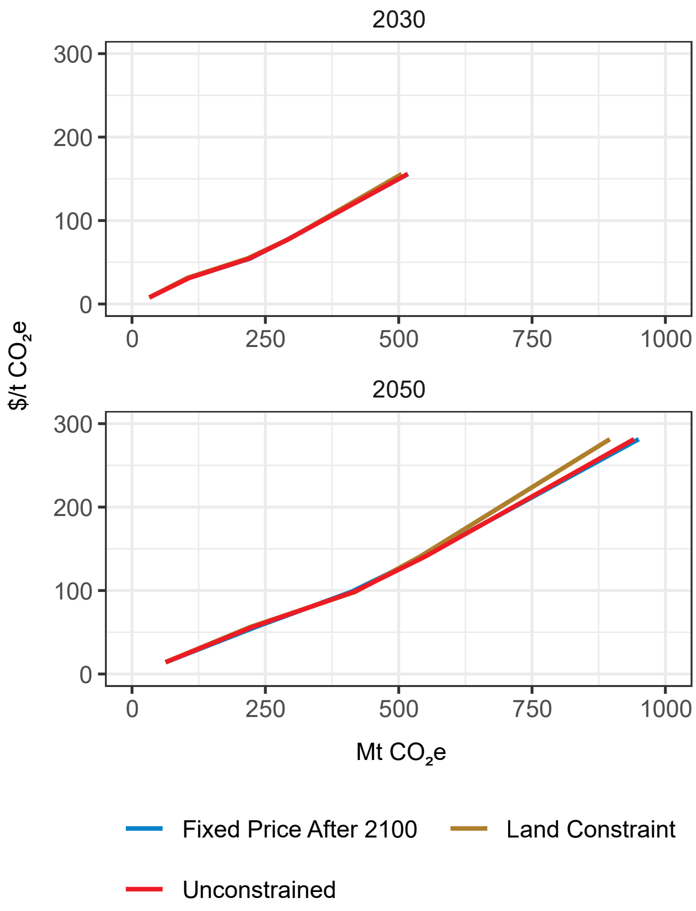
First, the assessment looks at whether the forward-looking framework of GTM combined with long-term terminal conditions (200-year simulation horizon) could drive more short-term mitigation actions than the other two models that have a shorter time horizon (they both end in 2100). To test this, the GHG price scenarios with 3% growth are fixed to their 2100 values for 2110–2200 (Fixed Price Scenario after 2100) in GTM. Under these scenarios, future GHG prices do not exceed $1,066 t/$CO_2$ after 2100. As a second test, the study assesses whether the representation of land available to be converted into forests using the GTM land rental functions is a cause of its higher estimated mitigation volume relative to FASOMGHG and GLOBIOM. For example, in 2050 under the $100/t CO_2 at 3% scenario, GTM projected 128 million acres of new forestland while FASOMGHG projected 82 million acres and GLOBIOM 61 million acres. In this sensitivity case, the same GHG price scenarios with 3% growth are simulated under a constraint on additional land available for conversion to forest of 82 million acres (Land Constraint Scenario). This value was chosen as it aligns with the volume estimated by FASOMGHG under the $100 at 3% scenario.

Results show that GTM mitigation potential estimates are more sensitive to the land constraint than to the cap on the GHG price (Figure B6 presents MACCs between the unconstrained model, the fixed price model, and the land constrained model). Interestingly, the price cap incentivizes a little more short-term mitigation largely because of the forward-looking structure of the model—with higher long-term GHG prices in the uncapped GHG price runs, the model waits until later periods to make large investments in forestry to capitalize on the higher expected returns. This outcome is more likely to happen under high GHG prices in the short

term, with mitigation potential projected to change relative to the unconstrained model within a range from an increase of 0.7% to a decrease of 0.5% in 2050.

On the other hand, constraining the amount of land available for afforestation/reforestation in the future means that some mitigation opportunities are lost, reducing mitigation to a maximum of 5% in 2050 under the highest GHG price scenario. For GHG price scenarios starting at a value higher than $20/t CO_2e, the constraint has a large effect on the level of abatement and the effect becomes even larger under higher GHG price scenarios. For instance, under the $100 at 3% Land Scenario, 68 million acres that were converted in the unconstrained scenario are not converted into forests, with a corresponding loss of 46 Mt CO_2e yr^{-1} in mitigation by 2050. Overall, these results suggest that the continued growth of GHG prices in GTM relative to FASOMGHG and GLOBIOM has little effect on differences in the projected mitigation potential across the models. However, when the afforestation/reforestation potential of the model is limited in GTM, it projects mitigation potential closer to that of GLOBIOM and FASOMGHG.

Figure B6: Marginal abatement costs for forests in 2030 and 2050 with and without land and price constraints using GHG price scenarios with 3% annual growth rates, GTM



MACCs are built using the abatement under each GHG price scenario starting at $5/t CO_2e. Five observations per year are used to build each MACC. MACCs show the level of abatement in Mt CO_2e (x-axis) associated with a specific monetary value of GHG emissions in $/t CO_2e (y-axis) for a specific reference year (2030 and 2050). The Fixed Price After 2100 Scenario holds GHG prices fixed to their 2100 values for the 2110–2200 period; therefore, future GHG prices do not exceed $1,066 t/$CO_2$ after 2100. The Land Constraint Scenario assumes a maximum of 82 million acres available to be converted to forests. This value was chosen as it aligns with the land size estimated by FASOMGHG under the $100 at 3% scenario. The Unconstrained Scenario has no constraints on GTM and reports the results presented in the main text of Chapter 3.

Box 7

SENSITIVITY: Accounting for opt-in program design

The market-based approaches employed in the models used in this report represent a theoretical method to evaluate mitigation potential of the land sector. It applies a GHG pricing system in which all carbon pools are tracked, and all agents and activities are affected by the price incentive. In effect, this approach simulates outcomes as if all carbon pools are monitored and market players make decisions knowing that a carbon payment will be delivered each year (i.e., there are no market failures or transaction costs).

In this box, a more applied approach explores the potential effects of implementing an opt-in system, more like the offset programs that have emerged in regional mitigation programs or the voluntary offset market. Offset providers choose to participate in these programs and are subject to carbon pool accounting and verification for a set amount of time. This modeling framework is adapted to simulate a 100-year improved forest management carbon offset program by expanding the land base representation to allow two classes of forest landowners: one that voluntarily participates and has the price incentive applied to their carbon accounts, and another that does not participate and does not have the price incentive applied to their carbon accounts. Moreover, payments are limited to easily observable/quantifiable/verifiable pools of live trees and HWP without rewarding participating landowners for increased carbon sequestration in soil and other forest pools (e.g., understory and shrubs).

Prior studies have expanded FASOMGHG to include voluntary participation for either forest (Latta et al., 2011) or agricultural (Wang et al., 2021) carbon offset programs. In each case, an opt-in program resulted in a shift of the MACC up and in (toward the y-axis) indicating less mitigation potential at a given GHG price than when the same scenario is modeled as an all-in program design.

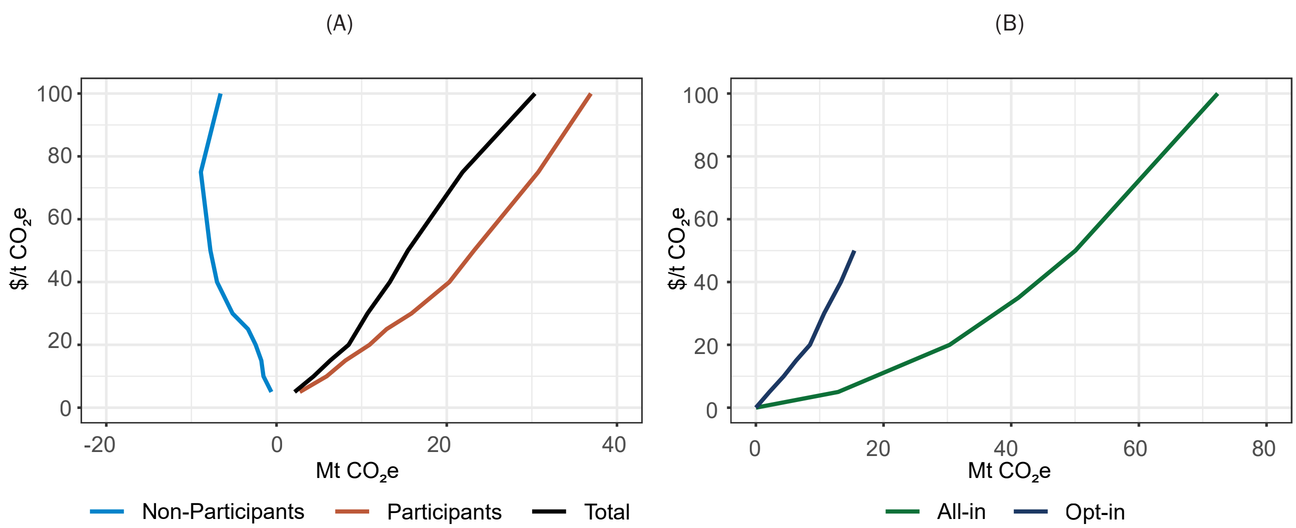
To demonstrate the degree to which increases in nonparticipating land emissions can potentially reduce net programmatic emissions reductions, the voluntary approach of Latta et al. (2011) is applied to the forestry sector in the updated FASOMGHG version of Wade et al. (2022) under the GHG price scenarios used in this report. To facilitate comparison, annualized CO2e emissions reductions results are presented in Figure B7. Panel (A) shows net emissions MACCs for two scenarios: 1) All-in participation in a forest sector only simulation (no interaction or competition with the agriculture sector), and 2) Opt-in participation in a forest sector only

simulation. Panel (B) deconstructs the opt-in participation MACC of scenario 2 to show a MACC for land participating in something like the voluntary forest offset program (participants), for nonparticipating land (nonparticipants), and for all land (total).

Looking at Panel (A), the scenario that considers the forest sector under the all-in program results in 50 Mt CO_2e yr^{-1} at \$50/t CO_2. There is a reduction in expected mitigation of 35 Mt CO_2e yr^{-1} at \$50/t CO_2 when the model considers only voluntary participation for carbon pools that are easily verified in the program. Panel (B) breaks the voluntary MACC out by the GHG emissions effects of offset program participants and nonparticipants. At \$50/t CO_2 participants in the voluntary program sequestered 23 Mt CO_2 but the market participation of some forest lands in the program led to increased offsite, or outside the project scope, emissions of 8 Mt CO_2 from nonparticipating lands that is, a leakage effect. This leakage phenomenon occurs as the management activities of the market participants change to reduce emissions and/or increase sequestration (such as extended rotations and reduced harvest levels), and as other land managers not participating in the program react to the reduced supply of timber and related higher prices on the market accordingly by increasing harvest levels, thus reducing the overall mitigation achieved by the program.

Future work using FASOMGHG with this opt-in construct will leverage the model's ability to differentiate between participants and nonparticipants to address leakage within voluntary forest carbon offset programs. It will also take an approach similar to that of Wang et al. (2021) and evaluate how quantification rules in a voluntary offset methodology contribute to that leakage.

Figure B6: Marginal abatement costs for forests in 2030 and 2050 with and without land and price constraints using GHG price scenarios with 3% annual growth rates, GTM



Panel (A) shows net emissions MACCs for two scenarios: 1) All-in participation scenario run and 2) Forest sector only opt-in participation. Panel (B) deconstructs the partial participation MACC of scenario 2 (forest sector only partial participation) to show a MACC for lands participating, lands not participating, and all land (Total). Please note the difference in the x-axis scale.

3.3.2 Mitigation in Agriculture

This section presents the MACCs for agriculture across FASOMGHG and GLOBIOM where each model chooses among a combination of cost-effective abatement options in this sector.

Results presented in Figure 3-13 show the MACCs for agriculture and the projected emissions under the baseline and GHG mitigation scenarios for the two models in 2030 and 2050. Despite the agriculture sector remaining a net emitter of GHG emissions under GHG mitigation scenarios, both models show significant mitigation potential in the sector with emissions projected to decline up to 15% (FASOMGHG) and 30% (GLOBIOM) in 2030 and 22% (FASOMGHG) and 36% (GLOBIOM)in 2050. Mitigation opportunities in each model are described below and are divided by sector (cropland and livestock).

3.3.2.1 Cropland

This section presents the MACCs for cropland in 2030 and 2050. In the cropland sector, mitigation options include the activities presented in Appendix Figure A-9 divided by GHG categories.

In 2030, under a price of \$100/t CO_2e, FASOMGHG projects abatement levels of 12–16 Mt CO_2e yr^{-1} and GLOBIOM projects 24–30 Mt CO_2e yr^{-1} from cropland. In 2050, under a GHG price as high as \$100/t CO_2e, FASOMGHG projects abatement levels of 16–26 Mt CO_2e yr^{-1} and GLOBIOM projects 30–47 Mt CO_2e yr^{-1}.

There is variation in activities used for agricultural mitigation across each model. For instance, FASOMGHG includes agricultural soil carbon changes from inputs and activities as a component of overall GHG flux while GLOBIOM only includes changes to above- and belowground biomass due to land conversion into and out of cropland. In FASOMGHG, the cost-effective mitigation mix favors soil carbon sequestration through tillage change, change in cover cropping applications, and LUC on agricultural lands (e.g., afforestation).[15]

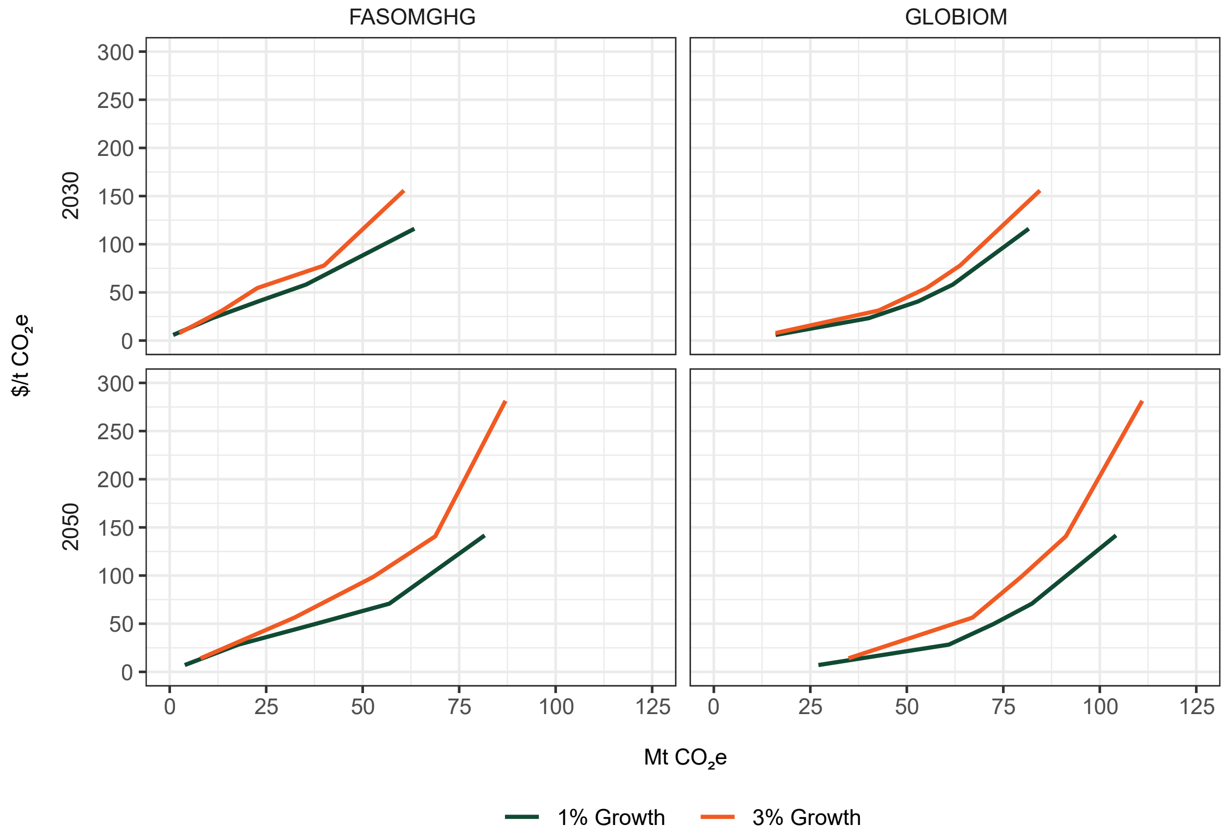
Like the EPA (2005) report, projected mitigation from agricultural soil carbon sequestration in FASOMGHG decreases over time and is smaller in magnitude under higher mitigation prices relative to low price scenarios. Historic and projected future soil carbon dynamics help explain this result: early investments in practices that enhance soil carbon (e.g., conservation tillage), as well as land use changes, eventually result in a new soil carbon balance equilibrium, and the model cannot effectively invest in many additional soil carbon-enhancing practices in the absence of significant cropland expansion in the GHG scenarios (see Box 2 for a description of soil carbon dynamics in FASOMGHG). Furthermore, soil carbon practices typically generate small net carbon gains per unit area (<1 t CO_2e per acre) (Dell & Novak, 2012; Johnson et al., 2005), so at higher price incentives the model opts for mitigation strategies that provide greater returns per unit area and per dollar investment (such as afforestation or improved forest management). FASOMGHG projects that other on-farm activities such as changes in input intensity, burning of crop residues, and diesel usage could result in mitigation rates of between 1 and 18 Mt CO_2e yr^{-1} by 2050. In 2050, FASOMGHG projects nitrogen fertilizer consumption decreases by 0%–10% relative to the baseline projected application amount of about 13 million tons, though fertilizer usage intensity increases with total cropland area declining at higher rates (0%–18%).

Conversely, GLOBIOM does not model soil carbon fluxes in croplands due to management changes in this analysis and thus projected mitigation activities concentrate on crop non-CO_2 and livestock non-CO_2 sources (discussed in Section 2.3). Crop non-CO_2 mitigation projections in GLOBIOM range between approximately 16 and 51 Mt CO_2e yr^{-1} by 2050. Projected mitigation potential for GLOBIOM clusters at the moderate and high mitigation price scenarios (e.g., those higher than \$20/t CO_2e as a starting point). This result occurs primarily through varying levels of representation of mitigation options. As a global model, GLOBIOM has a less detailed representation of the U.S. agricultural mitigation options such as practices that retain SOC or on-farm fossil fuel usage reductions. Additionally, GLOBIOM forecasts that there are more efficient agricultural mitigation opportunities

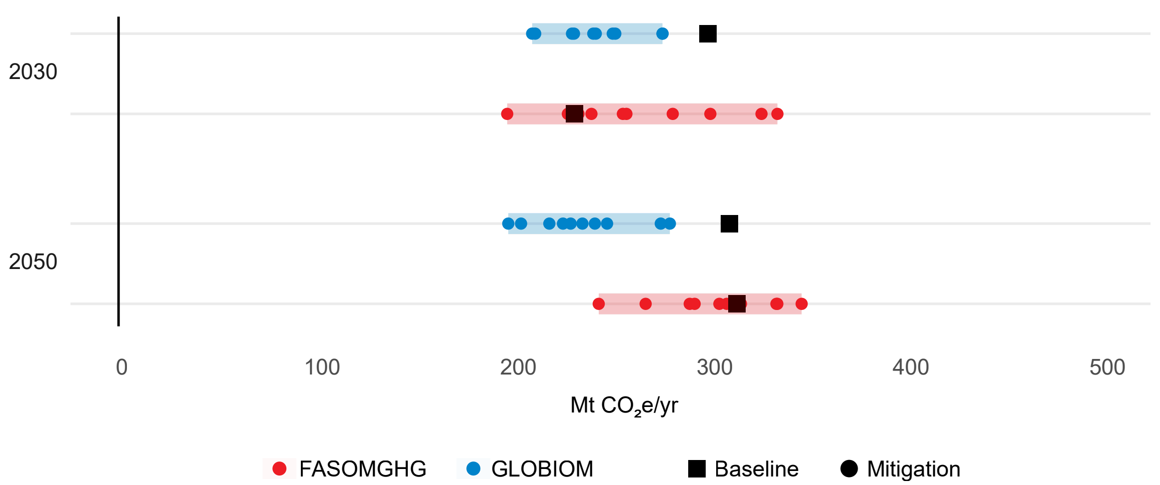
[15] FASOMGHG results do not fully disaggregate emissions/soil carbon changes from tillage practices, cover cropping, or LUC on agricultural lands. Recent meta-analyses of the effect of tillage changes on soil carbon found that soil organic carbon (SOC) storage can be higher under no-till management in some soil types and climatic conditions even with redistribution of SOC; and it can contribute to reducing net GHG emissions. However, uncertainties tend to be large (Ogle et al., 2019).

FIGURE 3-13 **A) Forest marginal abatement cost curves; B) Forest absolute emissions under baseline and mitigation scenarios in 2030 and 2050**

A)



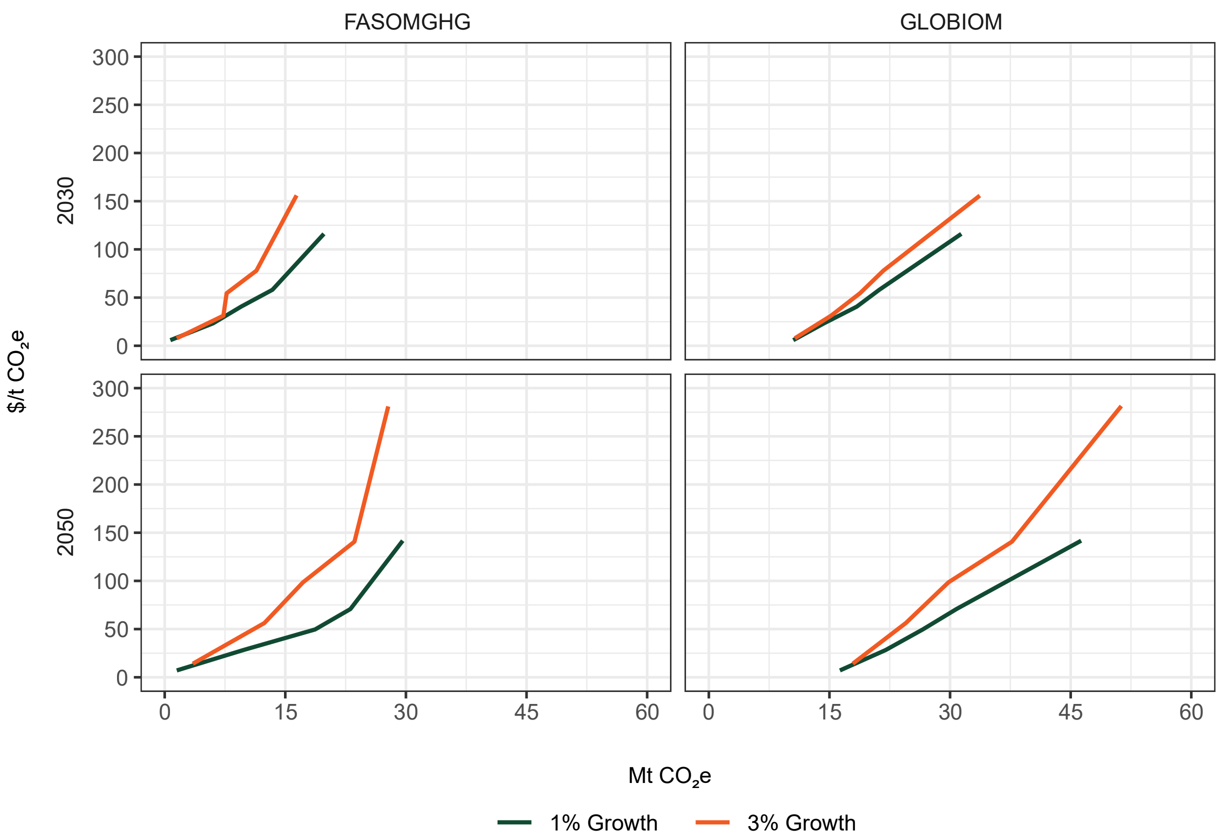
B)



Panel (A) MACCs are built using the abatement under each GHG price scenario starting at $5/t CO_2e. Five observations per year are used to build each MACC. MACCs show the level of abatement in Mt CO_2e (x-axis) associated with a specific monetary value of GHG emissions in $/t CO_2e (y-axis) for a specific reference year (2030 and 2050). GTM is not included in the figure because it does not explicitly model agriculture. Panel (B) Absolute emissions under baseline and mitigation scenarios from agriculture in FASOMGHG and GLOBIOM in 2030 and 2050. Results are presented in terms of atmospheric accounting. Therefore, positive flux equates with emissions; negative flux represents sequestration.

Changes in GHG fluxes in agricultural soils due to land use change are not included in the MACCs because this factor, on net, is a transfer of stored carbon from agriculture soils to forest soils. On the other hand, changes in GHG fluxes in agricultural soils due to land use change are included in the bar figure showing agriculture emissions under the baseline and GHG mitigation scenarios.

FIGURE 3-14 MACCs for cropland in 2030 and 2050



MACCs for cropland only in 2030 and 2050 by models and growth rate scenarios (1% and 3%). MACCs are built using the abatement from cropland under each GHG price scenario starting at $5/t CO_2e. GHG price applies to all GHG emissions from the land sector but only the abatement from cropland is used to build the curves presented in this figure (changes in soil carbon are not included). Five observations per year are used to build each MACC. MACCs show the level of abatement in Mt CO_2e (x-axis) associated with a specific monetary value of GHG emissions in $/t CO_2e (y-axis) for a specific reference year (2030 and 2050).

outside of the United States, as the domestic agricultural sector is currently producing at relatively low GHG intensities. GLOBIOM reduces nitrogen fertilizer usage considerably in the higher mitigation price scenarios, with usage declining by as much as 23% from 2025 to 2050 (with baseline nitrogen fertilizer application projected at 16 million tons per year over the same time horizon). This reduction in fertilizer application results in declining yields relative to the baseline scenario. At the same time, GLOBIOM expands irrigation to increase crop yields while overall crop area declines. This is the opposite of what happens in FASOMGHG partly because GLOBIOM does not explicitly account for emissions from groundwater pumping.

The introduction of GHG prices disincentivizes some common GHG-intensive agricultural activities in the two models such as the use of fertilizer, which—under high prices—can decrease the profitability of some cropland, resulting in a decline in total cropland area under these mitigation scenarios relative to the baseline in both models (Figure 3-15).

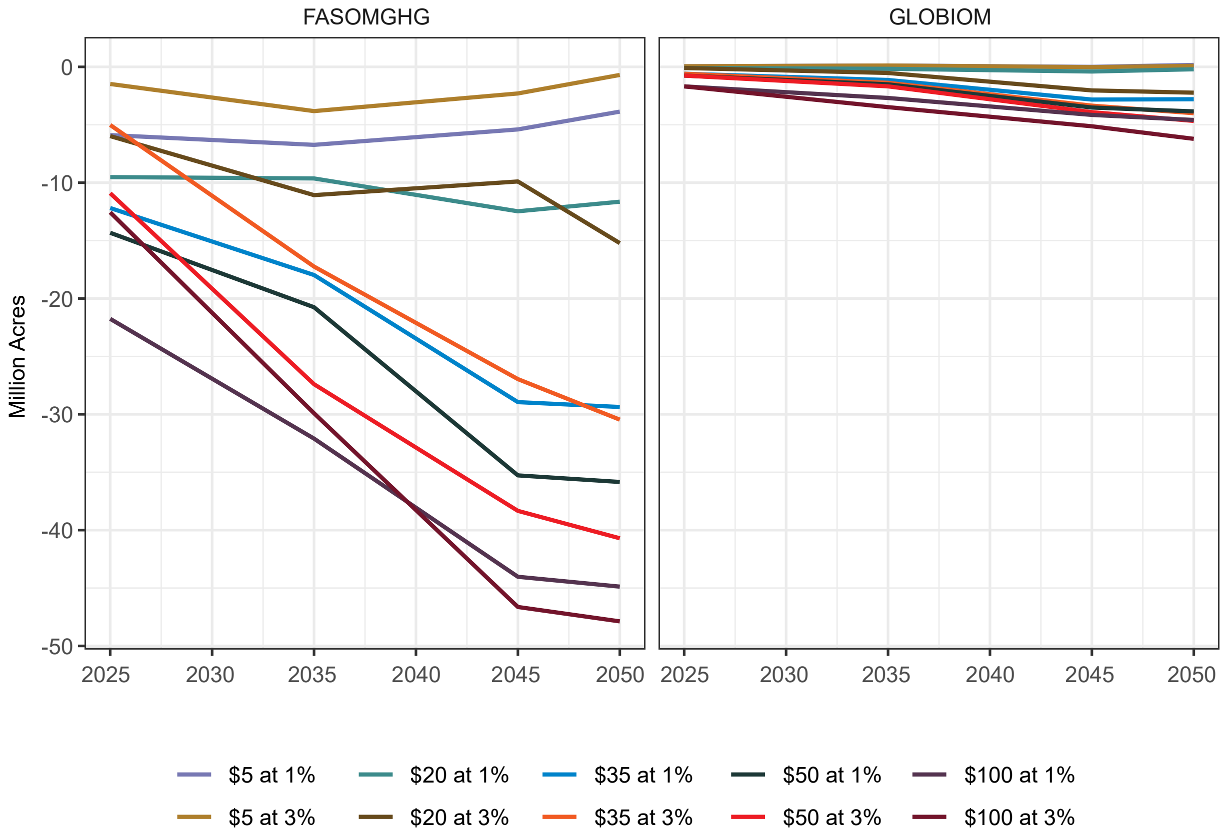
In FASOMGHG, total cropland area is more responsive to GHG prices than in GLOBIOM, with cropland area in 2050 either remaining constant relative to the baseline, or decreasing by up to 58 million acres. GLOBIOM projects a decline of between 0 and 6 million acres over the same timeframe. As presented in the earlier section, this difference in the magnitude of cropland area decline is partially driven by the difference between how the two models handle temporal dynamics, with FASOMGHG relying heavily on afforestation/reforestation to maximize the net benefit of sequestration under the GHG price scenarios (hence more land use conversion from agricultural lands). Agricultural input usage and intensity also vary across each model; under the $35 at 3% scenario, FASOMGHG and GLOBIOM project a relative reduction in the use of nitrogen fertilizer by 7% and 16% relative to the baseline in 2050 (13 million tons in FASOMGHG and 17 million tons in GLOBIOM). Moreover, the contraction is higher under high GHG price scenarios (e.g., $100 at 3%) because emissions from fertilizer applications are costlier, with reductions of N fertilizer increasing to 10% in FASOMGHG and 23% in GLOBIOM. FASOMGHG projects that the change in irrigation water consumption will range from a slight increase of 2% to a decrease of 8% across all GHG price scenarios, resulting in a relatively stable irrigation intensity level. GLOBIOM projects a slight increase in irrigation water consumption across all GHG price scenarios of 0% to 2%, but at the same time, irrigated area is increasing at a higher rate, resulting in a decline in irrigation intensity as GHG prices rise. Additionally, due to its global coverage, GLOBIOM also reflects tradeoffs between mitigation potential and agricultural production domestically versus internationally. Under the GHG price scenarios, the United States continues to have a competitive advantage over many regions in agricultural production, which results in the United States' relative reduction in agricultural production being less than in many other regions in GLOBIOM.

Each model also relies on crop switching as a response to GHG prices. The proportions of cropland dedicated to corn, soybean, wheat, and cotton all increase under the $50 starting price, growing at 3% annually relative to the baseline in GLOBIOM. At the same time, smaller crops, such as rice, beans, canola, and sugar, decline in their proportion of total crop area. Like GLOBIOM, FASOMGHG increases the proportion of cropland dedicated to corn, while the proportion of area dedicated to wheat remains constant, and the proportion of area dedicated to soybean declines. Other smaller crops, such as sorghum and barley, remain relatively constant. FASOMGHG also achieves mitigation in the agriculture sector by reducing domestic rice cultivation in most GHG price scenarios (>$5/t CO_2e) and relying on reduced exports and increased imports to meet domestic demand, with overall rice exports in 2050 decreasing by as much as 90% in the GHG price scenarios.

Since cropland is projected to decline to some degree under all the GHG price scenarios, Box 8 assesses how mitigation opportunities may change under policy scenarios reserving specific lands for agricultural production by running the same mitigation scenarios as the main report with restrictions on afforestation/reforestation activities inside the Corn Belt region.

Ripe barley in field below Wellsville Mountains, Utah.

FIGURE 3-15 Average annual change in total cropland area from baseline (in million acres, 2025–2050)



Baseline cropland area by model is presented in Figure 3-5. Positive values equal an increase in cropland area from the baseline. Initial values are different because FASOMGHG starts in 2015 while GLOBIOM starts in 2000. GTM is not included because it does not explicitly model cropland.

Corn growing in rural Augusta, Kansas.

Box 8

SENSITIVITY: Implications of limiting mitigation activities geographically

Land-based mitigation actions are likely to affect LUC and land use management decisions with possible implications for related commodities. As a general matter, applying a GHG price incentive to GHG reduction activities can drive land use management decisions to maximize net benefits for the land sector. Because the GHG price incentives are expected to increase over time, rational actors will seek to implement the activities that maximize GHG sequestration and GHG reductions over time, not solely in the immediate term. The model function is akin to how timber-related management decisions are often made—planting a tree today with expected returns decades into the future. Because trees sequester CO_2, store more and more carbon over time, and also provide some GHG benefits post-harvest in the form of HWPs, activities in forestry—especially those that generate the highest levels of sequestration/GHG reductions—are the most lucrative and selected by rational actors in the models. These highest levels of GHG benefits from forestry are often realized in places where lands have higher productivity rates—the reason being that trees, like crops, will grow faster on more productive lands, sequestering more carbon and thus earning higher returns under a GHG pricing system. Therefore, when modeling GHG mitigation across a suite of activities in FASOMGHG, many rational actors in the model will respond to the higher future returns offered in the long term via the activities that yield the most GHG benefits (e.g., forestry activities like afforestation and reforestation) on the most productive lands in the model, including in the U.S. Corn Belt, which has been shown to be one of the most productive areas in the world at growing crops (Guanter et al., 2014). This outcome is reflected in the regional results presented in this report.

While models including FASOMGHG are built to reveal both the most cost-efficient and/or welfare-maximizing outcomes favored by rational actors and the specific parameters of the modeling components and study design, these tools do not yet have the capabilities to reflect all the possible policy and other important monetary and non-monetary considerations that landowners incorporate into decision-making in practice. Examples include the choice to retain certain lands and/or land management practices as part of family legacies or common local social practices, or conforming with local, state, or federal land management or other policies. For this reason, researchers may elect to let the models generate the most cost-effective solutions without constraints, to conduct sensitivity analyses, or to evaluate simulated outcomes under specific conditions and constraints.

To that end, this box estimates the effects of preserving land allocation in the Corn Belt by limiting the amount of current agricultural land converting to forestry in FASOMGHG in response to the GHG mitigation price paths. Specifically, as a case study, 10 additional GHG price scenarios were run in FASOMGHG where afforestation/reforestation activities were not allowed in the U.S. Corn Belt region.

This land constraint emulates scenarios presented in other studies (e.g., Fujimori et al., 2019) where land conversion is constrained in the most productive land areas to preserve agriculture lands as a means to guarantee food security or to reflect landowner preferences to retain the land in agriculture despite the GHG price incentives.

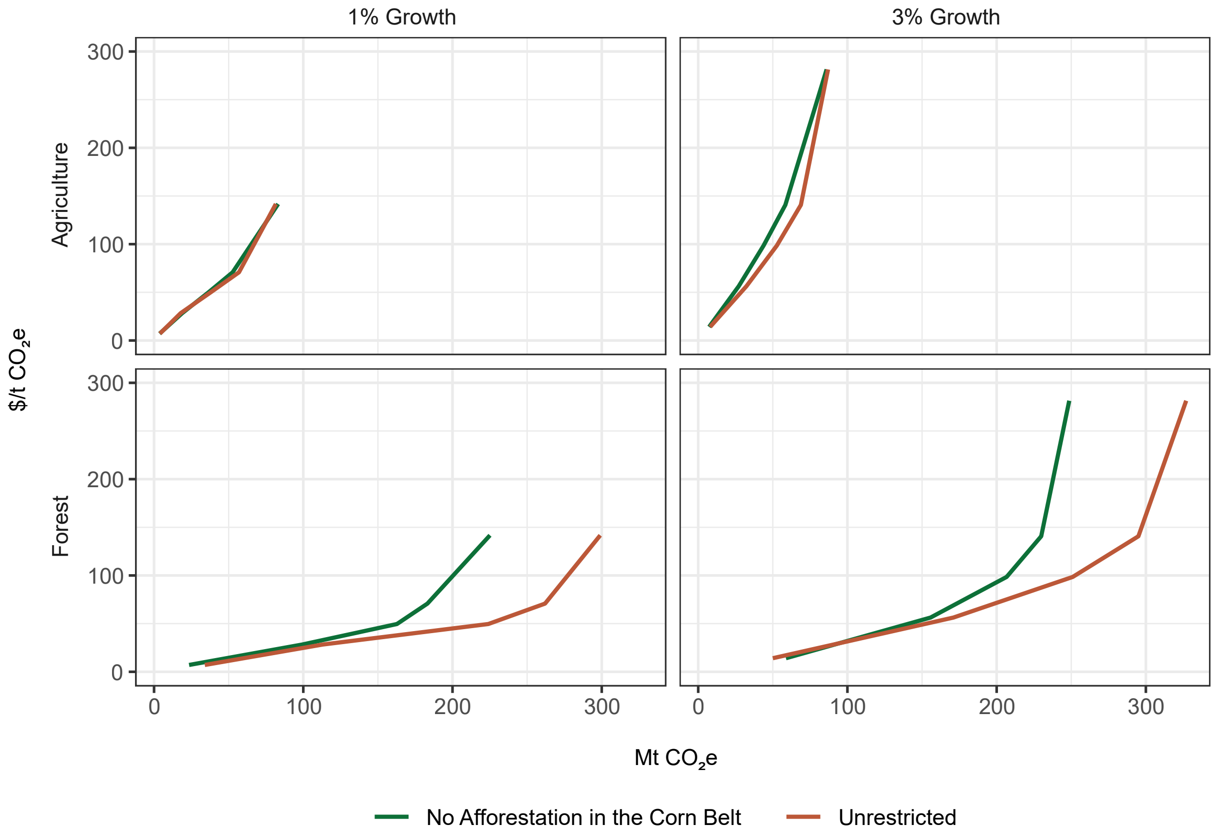
As discussed in Section 3.3.6, under the highest GHG price scenario in the main analysis, agricultural production for major feedstocks is projected to decline by 9% (corn), 20% (wheat), and 27% (soybeans) in 2050 relative to the baseline in FASOMGHG. Livestock production is also expected to decrease with a contraction of 21% (for beef), 10% (poultry), and 23% (pork) in 2050 under the same scenario. These results are driven by the conversion of agricultural land area into forests as the response to GHG price, despite FASOMGHG including increasing marginal costs associated with converting agricultural lands to forestry based on historical payments under the Conservation Reserve Program (Cai et al., 2018).

Under the land constraint scenario, national agricultural production under the mitigation scenarios is still projected to decline relative to the baseline scenario but at a slightly lower rate for all products than scenarios without the Corn Belt land constraint. That is, the impact the mitigation prices have on agriculture and livestock production is smaller in this sensitivity analysis, with a projected decline of 6% (corn), 16% (wheat), 16% (soybeans), 19% (beef), 8% (poultry), and 20% (pork) in 2050 under the highest GHG price scenario. Overall, restricting land conversion in the region does not reflect a significant change in agricultural commodity production, with the largest benefit in relative terms occurring to soybeans.

On the other hand, results show that under the land constrained scenarios, national mitigation drops by 2%–30% depending on the GHG price (Figure B8). This reduction in mitigation potential is largely isolated to the Corn Belt—it reflects that mitigation opportunities implemented outside of the Corn Belt are not cost-effective because of the differences in land productivity.

These results emphasize how scenario designs (e.g., limiting land conversion in specific regions) and more broadly, policy designs, could affect the total mitigation potential under the same GHG price scenario. This example illustrates how there may be tradeoffs associated with limiting what lands, landowners, and land management activities are eligible for GHG mitigation incentives, which should be considered during policy development.

Figure B8: Projected national MACCs in 2050 from the agriculture sector (top) and forestry sector (bottom) from FASOMGHG under the GHG price scenarios with no restrictions and scenarios with no afforestation in the Corn Belt region



MACCs are built using the abatement under each GHG price scenario starting at \$5/t CO_2e. Five observations per year are used to build each MACC. MACCs show the level of abatement in Mt CO_2e (x-axis) associated with a specific monetary value of GHG emissions in \$/t CO_2e (y-axis) for a specific reference year (2030 and 2050). The No Afforestation in the Corn Belt Scenario holds future land uses in the Corn Belt fixed to present uses. The Unrestricted Scenario has no constraints on FASOMGHG and reports the results presented in the main text of Chapter 3.

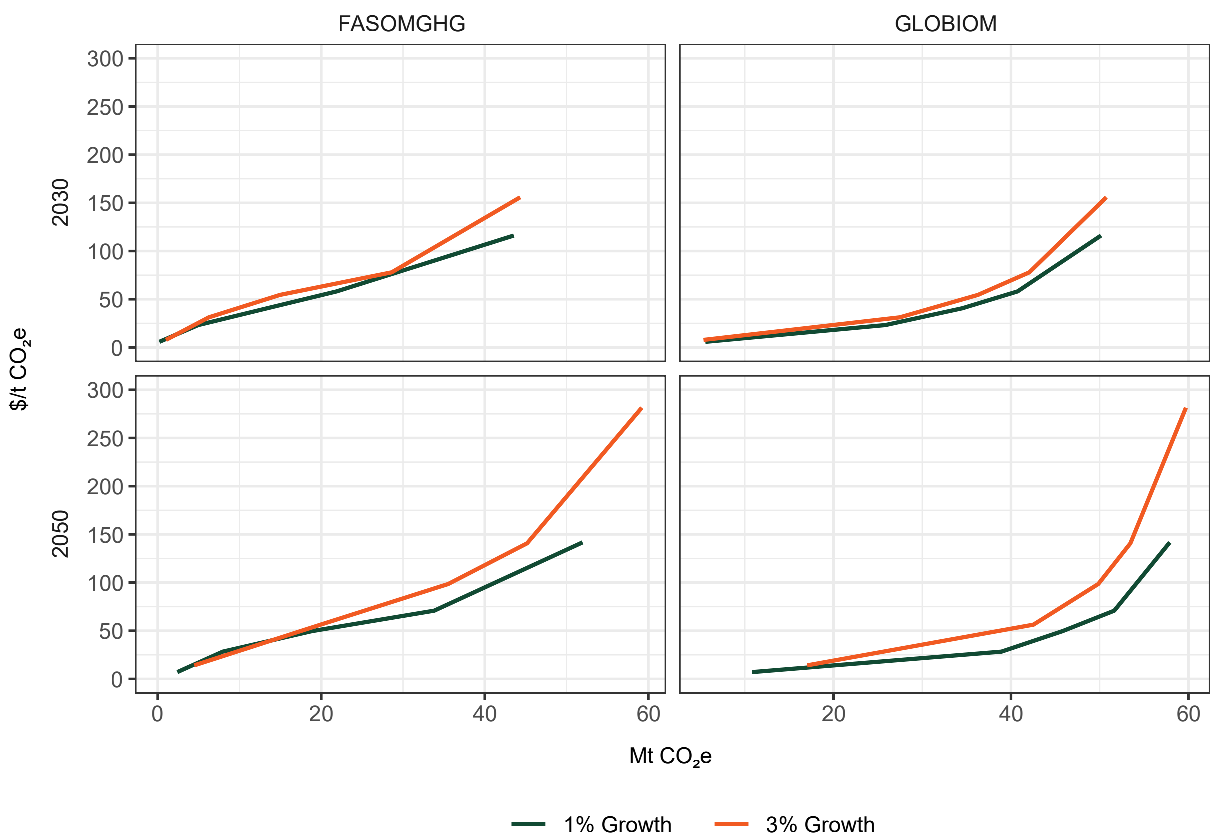
3.3.2.2 Livestock

Mitigation options in the livestock sector are summarized in Appendix Figure A-10 and the MACCs for livestock in 2030 and 2050 are presented in Figure 3-16.

In 2030, at GHG prices of \$100/t CO_2e, FASOMGHG projects abatement levels of 32–38 Mt CO_2e yr^{-1} and GLOBIOM of 42–48 Mt CO_2e yr^{-1} from livestock. In 2050, at prices of \$100/t CO_2e, FASOMGHG projects abatement levels of about 34–41 Mt CO_2e yr^{-1} and GLOBIOM of about 50–53 Mt CO_2e yr^{-1}.

Appendix Figure A-11 provides a comparison of projected livestock abatement activities (through either manure management or reduction in enteric fermentation) for FASOMGHG and GLOBIOM in 2050. In general, FASOMGHG livestock sector mitigation is projected to be more costly than in GLOBIOM, resulting in lower adoption rates of manure management and enteric fermentation abatement practices. At low GHG prices, FASOMGHG relies mostly on reducing enteric fermentation through changes in animal feeds. As GHG prices rise, manure management activities become price competitive and become the most prominent activity utilized to reduce emissions from livestock production. The response is similar in GLOBIOM even though manure management systems require higher GHG prices to become cost competitive, but eventually it projects higher abatement via enteric fermentation than in FASOMGHG.

FIGURE 3-16 **Marginal abatement cost curves for livestock in 2030 and 2050**



MACCs are built using the abatement from livestock under each GHG price scenario starting at \$5/t CO_2e. GHG price applies to all GHG emissions from the land sector but only the abatement from livestock is used to build the curves presented in this figure. Five observations per year are used to build each MACC. MACCs show the level of abatement in Mt CO_2e (x-axis) associated with a specific monetary value of GHG emissions in \$/t CO_2e (y-axis) for a specific reference year (2030 and 2050).

This slight divergence occurs for several reasons, including differences in baseline emissions projections (which are slightly higher for GLOBIOM, 190 Mt CO_2e yr^{-1} compared to 150 Mt CO_2e yr^{-1} in FASOMGHG) and cost structures (more regional variation in FASOMGHG technology-specific abatement cost assumptions, as documented in the supplemental appendix of Jones et al., 2019).

In addition to mitigation activities through livestock management, both models utilize LUC and global markets to achieve mitigation from the livestock sector. For example, under higher mitigation prices, GLOBIOM maintains U.S. livestock production at relatively consistent levels and invests more in abatement technologies that reduce enteric fermentation emissions, while FASOMGHG reduces domestic production and exports of meat products. Changes in land use dedicated to livestock production across both FASOMGHG and GLOBIOM are relatively consistent, with reductions of pastureland in 2050 between 2% and 27% (4 to 70 million acres) in GLOBIOM, and between 3% and 21% (4 to 31 million acres) in FASOMGHG relative to the baseline (Figure 3-17).

Despite similar trends in pastureland, U.S. meat production in GLOBIOM is expected to decline by no more than 3% across all mitigation scenarios, while FASOMGHG projects a maximum decline of more than 21% from their respective baselines in 2050. This difference in production highlights how national and global models may differ in their responses to mitigation incentives.

In GLOBIOM, all regions respond to the GHG price, finding their optimal cost-effective combination of abatement activities and livestock consumption and production quantities. Overall, the U.S. production declines under GHG price scenarios but its share of global supply is expected to increase because it has relatively cheaper abatement opportunities than other meat-producer regions. Under GHG price scenarios, the United States has a comparative advantage over many other countries (especially developing regions such as Brazil) in producing animal commodities at less carbon-intensive levels. Because of this, the U.S. increases exports and market share under GHG mitigation price scenarios relative to the baseline (see Appendix A, Table A-7).

In FASOMGHG, trade dynamics are limited and the supply of livestock from the rest of the world (outside the United States) is not affected by the GHG price, which makes domestic production relatively more expensive than the rest of the world. This drives a reduction in U.S. exports to meet domestic consumption under GHG price scenarios. Under the highest price scenarios, domestic consumption of chicken, beef, and pork all decline over time, in with chicken declining by about 8%, and beef and pork both declining by around 20%. While consumption is declining relative to the baseline, compared to current levels, future consumption increases for each commodity under all scenarios. Production and exports show similar trends: declines reach as much as 20% relative to the baseline but increase relative to current levels.

These results show how underlying model parameters and inputs (e.g., available abatement options) and structure (e.g., national versus global, forward-looking versus recursive dynamic) affect the mitigation strategies and potentials. Moreover, Box 9 discusses how modeling results diverge from techno-economic assessments and how their results can inform different policy-related questions using livestock as a case study.

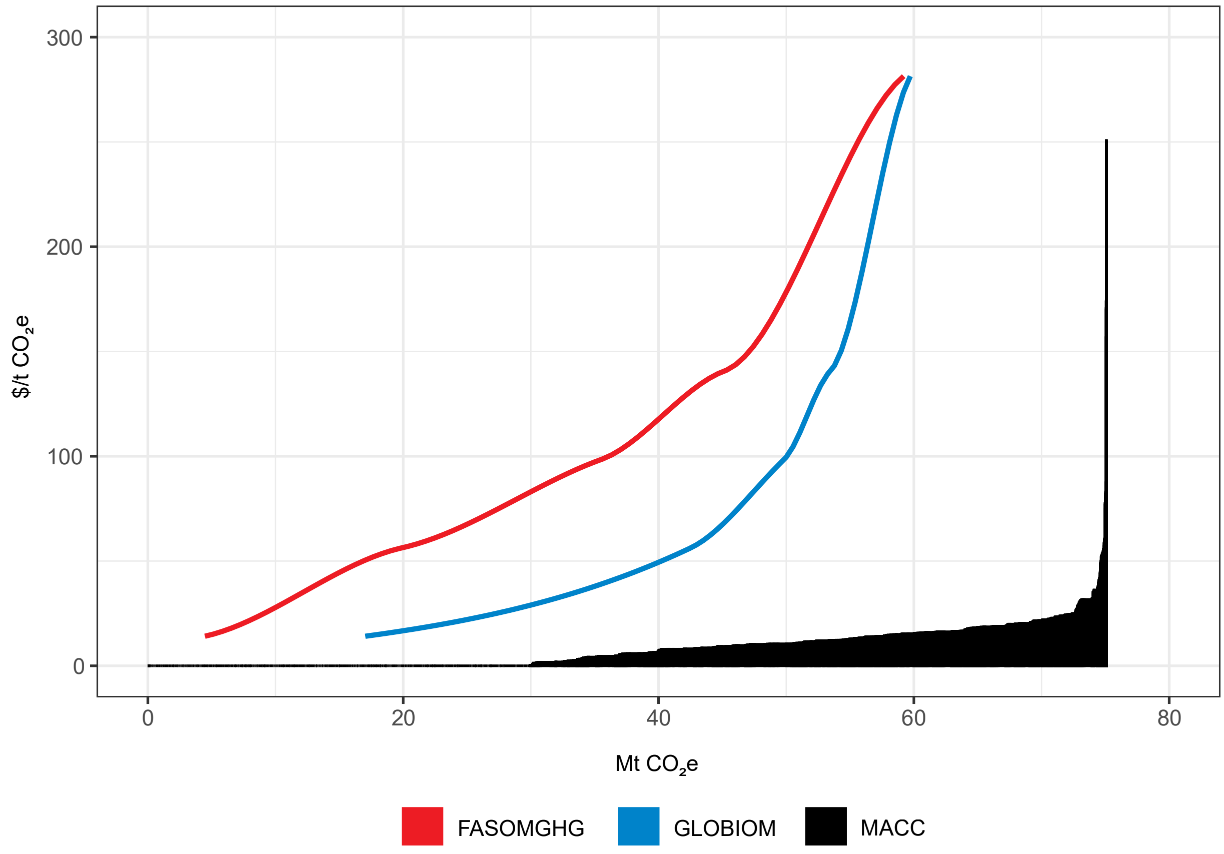
An Indiana poultry farm's storage shed for manure that will be applied to the fields later. (Photo by Brandon O'Connor/Indiana-NRCS)

Box 9

FOCUS: Technical potential vs. cost-effective potential—the case of livestock

Figure B9 compares MACCs from FASOMGHG and GLOBIOM for the livestock sector, including enteric fermentation and manure management opportunities in 2050 with the technical potential for the livestock sector from the U.S. EPA Non-CO_2 Mitigation Report (EPA, 2019b). The livestock sector can achieve a maximum technical potential of 75 Mt CO_2e yr^{-1} at a price of \$250/t CO_2e according to the 2019 U.S. EPA Non-CO_2 Mitigation Report, while in this report FASOMGHG projects a maximum mitigation potential of about 55 Mt CO_2e yr^{-1} and GLOBIOM reaches nearly 58 Mt CO_2e yr^{-1} for the same GHG price. The technical potential is not achieved by the livestock sector under the GHG price scenarios simulated via the competitive market approach used in this report. While the technical potential presents the maximum abatement available by a single sector/technology without considering market tradeoffs and the opportunity cost of a scarce resource like land, the results from FASOMGHG and GLOBIOM consider both the cost information of individual abatement activities and the interactions among activities, including competition for resources. The figure shows that with market opportunity costs included, the mitigation potential declines by about 29%–36% under a GHG price as high as \$240/t CO_2e in 2050. That is, the difference in mitigation potential from the modeled outputs from FASOMGHG and GLOBIOM and the technical potential from EPA is largely due to the market opportunity cost and resource competition discussed in Box 1, Chapter 2. This comparison shows that economic tradeoffs, such as those involving land use competition and synergies, are important to consider for estimating the potential impact of future strategies aimed at reducing emissions or increasing sequestration potential from the AFOLU sector.

Figure B9: Marginal abatement cost curves for livestock sector from FASOMGHG and GLOBIOM, and technical mitigation potential from EPA (2019b) in 2050



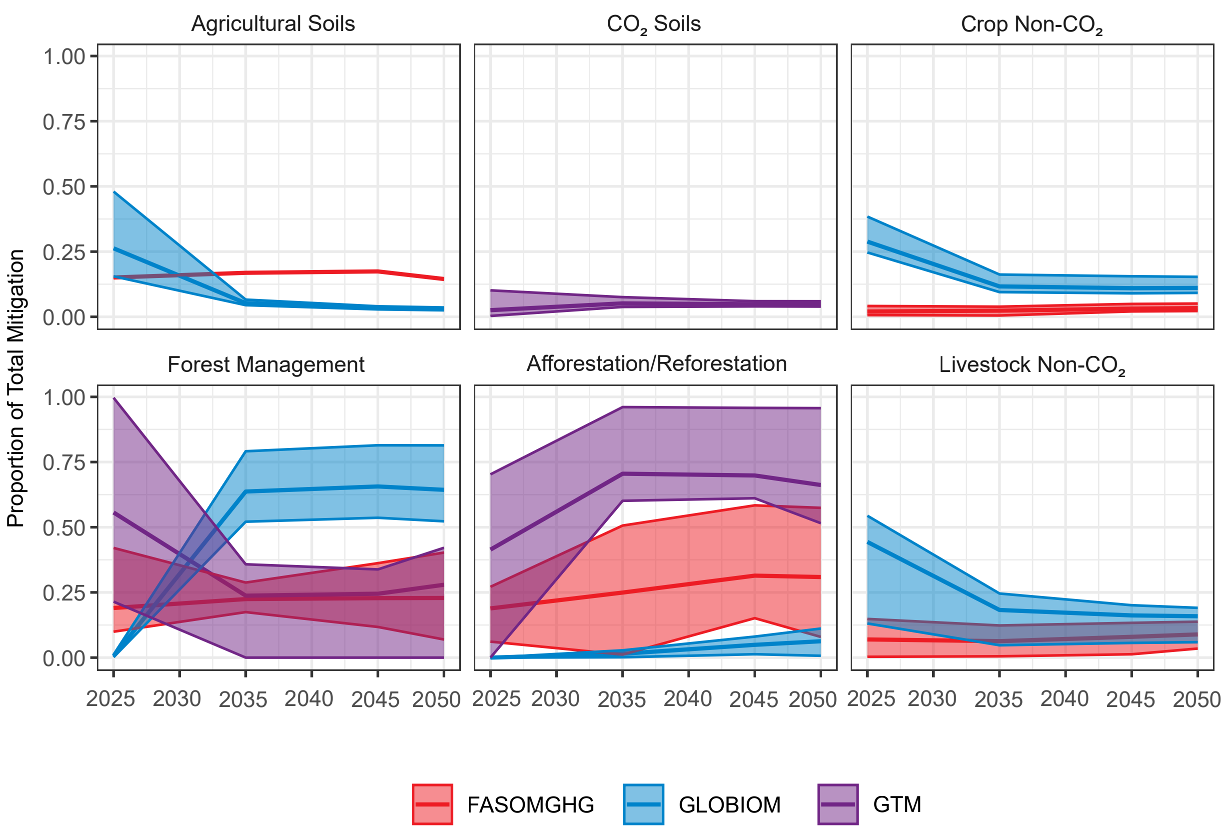
MACCs from FASOMGHG (red) and GLOBIOM (blue) are built using the abatement from livestock under each GHG price scenario starting at \$5/t CO_2e under both growth rate scenarios. GHG price applies to all GHG emissions from the land sector but only the abatement from livestock is used to build the curves presented in this figure. Ten observations per year are used to build each MACC. MACCs show the level of abatement in Mt CO_2e (x-axis) associated with a specific monetary value of GHG emissions in \$/t CO_2e (y-axis) for a specific reference year (2030 and 2050). The Technical Mitigation Potential from EPA (2019b) shows the abatement achieved under each \$/t CO_2e level as the black area underneath the curve.

3.4 Mitigation Across Land-Based Activities

For each GHG price scenario, each model not only projects the mitigation potential of the land sector but also determines the cost-effective composition of land-based activities in response to each price at any time, considering tradeoffs and synergies among activities.

Results across all models suggest that there is mitigation potential across multiple activities, with forest-based activities offering the highest level of abatement (Figure 3-18). There is not a dominant forest-based strategy across models. In GLOBIOM forest management provides, on average, more than half of the mitigation from the land sector while afforestation/reforestation has a larger share of total mitigation in FASOMGHG and GTM. The cost-effective combination of mitigation strategies is sensitive to the GHG price scenario and the time horizon. For instance, under GHG price scenarios higher than \$50/t CO_2e, in GLOBIOM and FASOMGHG, the forestry sector is still the primary source of mitigation, but its share declines as more land-based activities become cost-effective in livestock and cropping systems. Moreover, GLOBIOM shows a larger variation in the share of domestic mitigation delivered

FIGURE 3-18 **Share of mitigation by main activity by model, 2025–2050**



Solid lines indicate means and shaded areas show upper and lower bounds across models. Mitigation activities are described in Figure 2-4. All GHG price scenarios and growth rates are included in this figure.

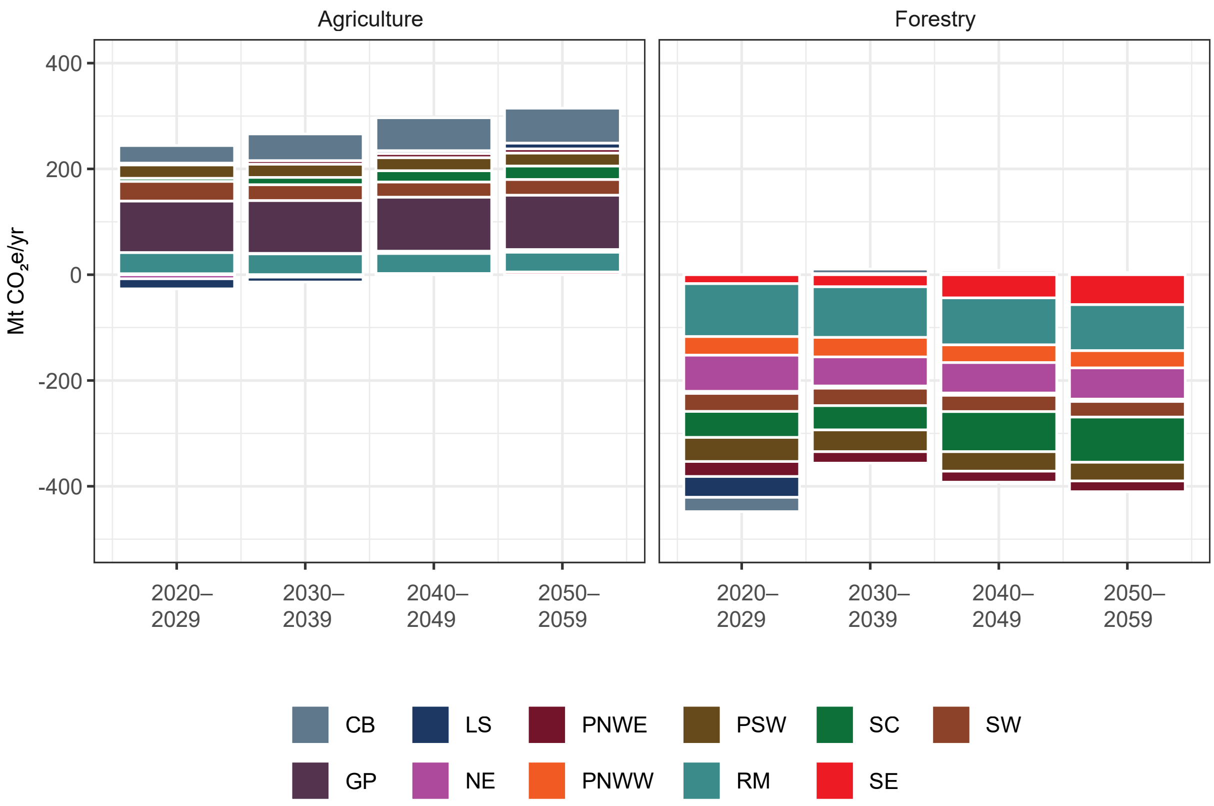
by croplands and livestock relative to FASOMGHG, with a minimum of 9% of total mitigation from crop non-CO_2 and 5% from livestock and a maximum of 38% from crop non-CO_2 and 52% for livestock. This is driven by the limited response of the forest sector in GLOBIOM compared to a forward-looking model like FASOMGHG. Under high prices, FASOMGHG invests heavily in afforestation and forest management activities to take advantage of high future GHG prices. Results from GLOBIOM show also that mitigation activities from the livestock and agriculture sector could provide more short-term reductions compared to forestry. Despite the variation, the models indicate mitigation activities in forestry may be dominant between now and 2050. Additionally, in all mitigation scenarios in both FASOMGHG and GLOBIOM, the agricultural sector is projected to remain a net GHG emitter.

3.4.1 Regional mitigation portfolio

This section presents U.S. regional results from FASOMGHG by starting with future emissions trends under the baseline scenario followed by the regional distribution of mitigation potential under the GHG price scenario of $50 at 3% used in the main report.

The version of FASOMGHG used in this report includes subnational representation of the land use sector, through the delineation of 11 different regions. Figure 3-19 shows regional emissions for agriculture and forestry from FASOMGHG at the baseline. At the regional level, some regions such as the Corn Belt (CB), Lake State (LS), and South Central (SC) project a significant increase in baseline emissions from agriculture driven by expanded production

FIGURE 3-19 **U.S. regional GHG emissions from agriculture and forestry under baseline scenario, FASOMGHG (in Mt CO_2e yr^{-1}, 2025–2050)**



Appendix Figure A-1 shows the 11 regions included in FASOMGHG.

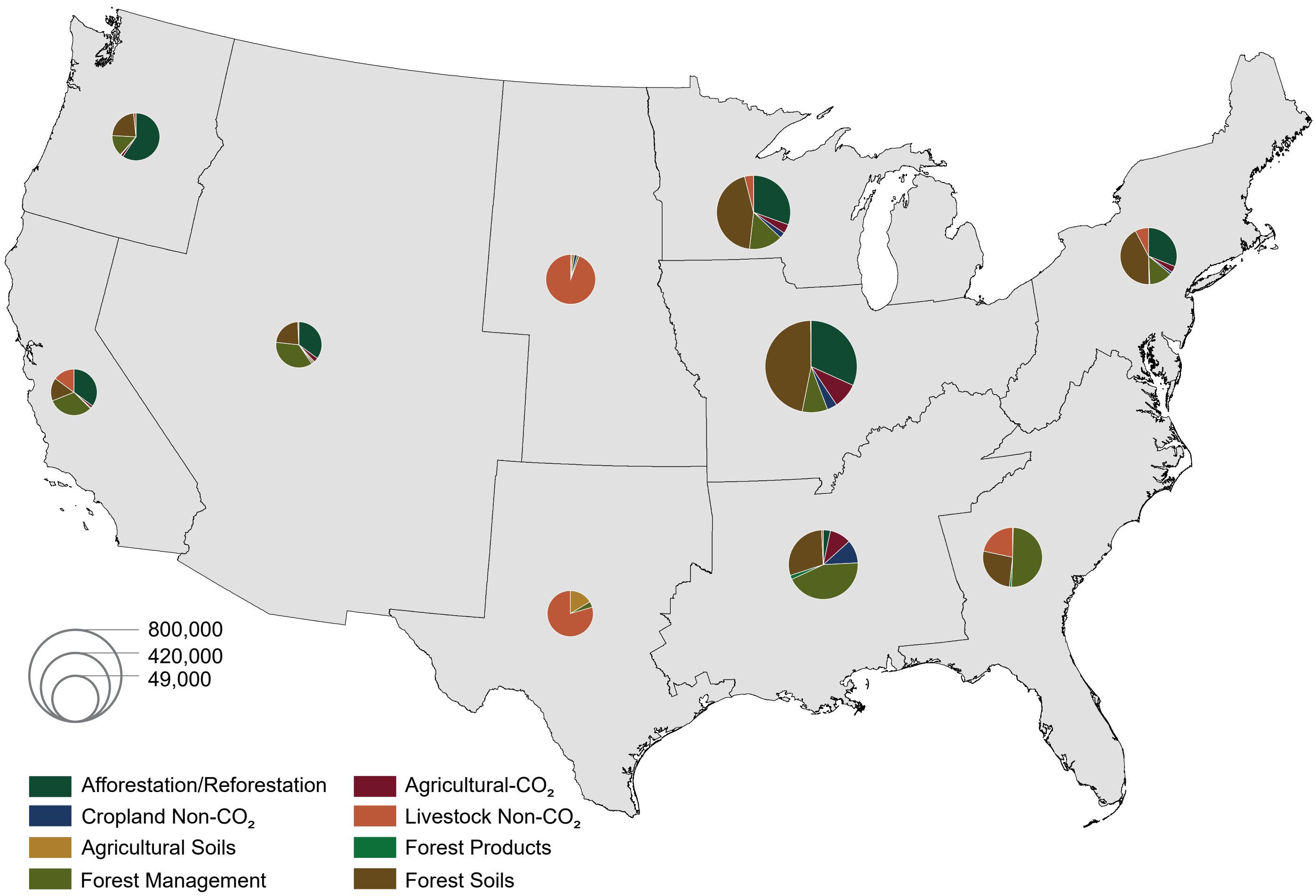
of agriculture commodities like corn, soybeans, and wheat. On the other hand, regions such as Great Plains (GP) and Rocky Mountains (RM), despite representing a large share of current emissions, are not expected to increase their share. Similarly, the remaining regions—Northeast (NE), Southeast (SE), Pacific Southwest (PSW), Pacific Northwest-east (PNWE), Pacific Northwest-west (PNWW), and Southwest (SW)—are projected to result in constant emissions levels from agriculture. In the forestry sector, SC and SE are expected to increase net GHG emissions reductions from 49 Mt $CO_2e\ yr^{-1}$ and 17 Mt $CO_2e\ yr^{-1}$ in 2025 respectively to 58 Mt $CO_2e\ yr^{-1}$ and 56 Mt $CO_2e\ yr^{-1}$ in 2050, as investments are made to continue to increase biomass growth in these productive regions to meet higher demand in the future. On the other hand, LS and CB are projected to experience a decline in forest carbon stock under the baseline scenario, driven by forest conversion to cropland. Finally, none of the other regions show significant changes from the current levels of carbon sequestration in forests in the baseline.

The mix of mitigation activities and mitigation levels varies across the nation as a function of spatially heterogeneous land productivity, production costs, and projected baseline land use and management. Moreover, regions respond differently to the price signal; some of them may find it more economically beneficial to increase production of agricultural and/or forestry products while other regions opt to reduce GHG-intensive activities and/or products. Figure 3-20 shows the distribution of cumulative abatement across each of the 11 regions, by mitigation activity under a GHG price of \$50 at 3% from 2025 to 2050. Under this scenario, the SE invests in reducing livestock non-CO_2 emissions around hog production, and the SC reduces agricultural CO_2 and non-CO_2 through reductions in rice production. The NE, LS, CB, RM, PSW, and PNWE all utilize afforestation/reforestation along with forest management as primary roles in mitigation. The CB and SC also reduce emissions from cropland production through reduction of fertilizer application and reduced on-farm fuel usage. CH_4 reduction from dairy farms is a key mitigation strategy in the NE and PSW, while the RM region has limited feasible emissions reductions from agricultural activities. The GP and SW achieve mitigation through the implementation of methane digesters and changes in grazing and feed mixes to reduce livestock non-CO_2. Finally, the PNWW (which only includes the forest sector in FASOMGHG), increases rotation lengths of existing forests to increase carbon sequestration.

Regions that rely heavily on afforestation/reforestation (CB and LS) and forest management (SC and SE) activities have the highest level of mitigation potential at low and moderate investment levels, while regions that rely more on livestock (GP, SW) or crop-based mitigation activities are more costly and smaller in total potential. Box 8 explores the dynamics of land use change under mitigation scenarios and how limiting land conversation will affect the abatement potential of the region. The U.S. regions with smaller total land area (PNWE, PNWW, NE, and PSW) are projected to have smaller mitigation potential due to high levels of land use competition and limited potential for low-cost mitigation through afforestation. Overall, a range of activities must be utilized to achieve the maximum mitigation from the domestic land sector; however, afforestation/reforestation and forest management activities are potentially the most cost-effective strategies to reach midcentury emissions reduction targets across much of the United States.

Pigs in a hoop barn on a central Iowa farm.

FIGURE 3-20 **U.S. regional distribution of cumulative mitigation by activity under the $50 at 3% scenario, FASOMGHG (2025 to 2050)**



The size of the pies represents the absolute level of abatement available in each region. Appendix Figure A-1 shows the map of the 11 regions included in FASOMGHG and Figure 2-4 describes the mitigation activities included in FASOMGHG.

Box 10

FOCUS: Beyond 2050

This section focuses on the modeling results after 2050 to provide some insights on long-term dynamics in the land sector with and without mitigation policies targeting the sector. Under the baseline scenario, models project that the AFOLU sector will sustain a net GHG emissions reduction but at a declining rate. While FASOMGHG projects increasing emissions from agriculture and livestock counterbalanced by a stable net sink of U.S. forests that will preserve the net AFOLU sector from being a net emitter, GLOBIOM expects stable emissions from agriculture and a decrease in the forest carbon sink. By 2070, the U.S. land sector in GLOBIOM is near to becoming a net source of GHG emissions. By comparison, the Forest Service 2020 Resources Planning Act Assessment projects that the U.S. forest sector will decline as a sink, with the potential to become a net source of emissions by 2070 (U.S. Forest Service, 2023).

Under the mitigation scenarios, the long-term trends do not diverge significantly from short- or medium-term results until 2050 with more abatement achieved in 2070 across GHG prices. When projected across longer time horizons (out to 2070), mitigation rates increase for all models compared to medium- and short-term projections. This outcome is driven largely by forest growth dynamics and further shows how investments made in earlier periods in afforestation/reforestation and forest management can maximize the growth rate of timber, and thus sequestration, in forestlands in the long term.

By 2070 under the lowest price scenarios FASOMGHG projects an average annual net mitigation potential of the land sector between 54 and 327 Mt CO_2e yr^{-1} while under the highest price scenarios the range increases to 306–422 Mt CO_2e yr^{-1}. On the other hand, GLOBIOM estimates an average annual mitigation potential that ranges from 213 to 447 Mt CO_2e yr^{-1} in 2070 across all scenarios.

The largest uncertainty in terms of abatement potential is projected in the forestry sector where in 2070, under a price as high as $440/t CO_2e, FASOMGHG projects abatement levels of 336 Mt CO_2e, GLOBIOM projects 306 Mt CO_2e, and GTM projects 1258 Mt CO_2e. On the other hand, agriculture shows a more defined trend, with annual mitigation ranging from 12 to 108 Mt CO_2e yr^{-1} in FASOMGHG and 39 to 134 Mt CO_2e yr^{-1} in GLOBIOM.

3.5 Investments in Land-Based Mitigation Activities

In the next decade, under investments of $2 billion per year in the land sector, this study estimates a potential to mitigate 50 to 78 Mt CO_2e yr^{-1}.

This section uses the output from the three models to assess the estimated level of investments needed to achieve specific GHG mitigation volumes over time. For each GHG price scenario and each model, the average future investments are calculated ex-post by discounting annual expenditures (GHG price times GHG abatement) to compensate landowners for their land-based mitigation activities. This approach is similar to the one presented in Austin et al. (2020).

Since each model responds differently to mitigation incentives, the level of abatement under different investments diverges significantly. Table 3-1 presents the average annual mitigation achieved under a range of possible investments in land-based abatement activities for the short term (2025–2035) and the medium term (2025–2050) for each model.

In the first decade, under annual investments between $50 million and $2 billion in the land sector, there is a potential to mitigate 78 Mt CO_2e yr^{-1} under FASOMGHG and 50 Mt CO_2e yr^{-1} under GLOBIOM. Moreover, if the same amount of investment is devoted only to forests, the results from GTM show a potential average mitigation of 50 Mt CO_2e yr^{-1}. Increasing the level of investments up to $5 billion per year, increases mitigation by 14% in FASOMGHG, and it is 32% higher in GLOBIOM and 74% higher in GTM.

By midcentury, more abatement opportunities are estimated to be available than in 2030 since investments made in forestry activities take longer to realize gains from forest growth dynamics. All models project that for the same level of annual investments in land-based mitigation activities (e.g., $5 billion–$15 billion yr^{-1}) more abatement can be achieved in 2050 than in 2030 per dollar invested. For instance, under annual investments of $500,000 to $2 billion, FASOMGHG and GLOBIOM project that the land sector can efficiently mitigate an average of 81 Mt CO_2e yr^{-1} and 131 Mt CO_2e yr^{-1} respectively between 2025 and 2050. Under the same range of investments and time period, GTM projects a mitigation potential of 94 Mt CO_2e yr^{-1}.

Paint Creek mountain view in East Tennessee.

TABLE 3-1 **Average annual mitigation (Mt CO_2e yr^{-1}) per range of annual investments in land-based mitigation activities (in billion US dollars)**

(A) 2025–2035 range of annual investments (Inv) in billion US dollars	**2025–2035** Expected annual average mitigation (Mt CO_2e yr^{-1}) under each range of investments		
	FASOMGHG	**GLOBIOM**	**GTM (forest only)**
Inv < 0.5	14	23	15
0.5 < Inv < 2	78	50	50
2 < Inv < 5	89	66	86
5 < Inv <15	133	86	125
Inv >15	232	N/A	195
(B) 2025–2050 range of annual investments (Inv) in billion US dollars	**2025–2050** Expected annual average mitigation (Mt CO_2e yr^{-1}) under each range of investments		
	FASOMGHG	**GLOBIOM**	**GTM (forest only)**
Inv < 0.5	24	96	19
0.5 < Inv < 2	81	131	94
2 < Inv < 5	155	158	193
5 < Inv <15	228	189	275
Inv >15	304	N/A	458

For each GHG price scenario and each model, the average future investments are calculated ex-post by discounting annual expenditures to compensate landowners for their land-based mitigation activities. This approach is similar to the one presented in Austin et al. (2020). To be consistent with the discount rate included in the models, future public finance to support land-based mitigation actions are discounted using a 5% discount rate. GLOBIOM does not provide abatement levels above investments of $15 billion.

Restoration thinning with understory removal in the Mark Twain National Forest, Missouri, 2012. (Forest Service photo by Michael Stevens)

Box 11

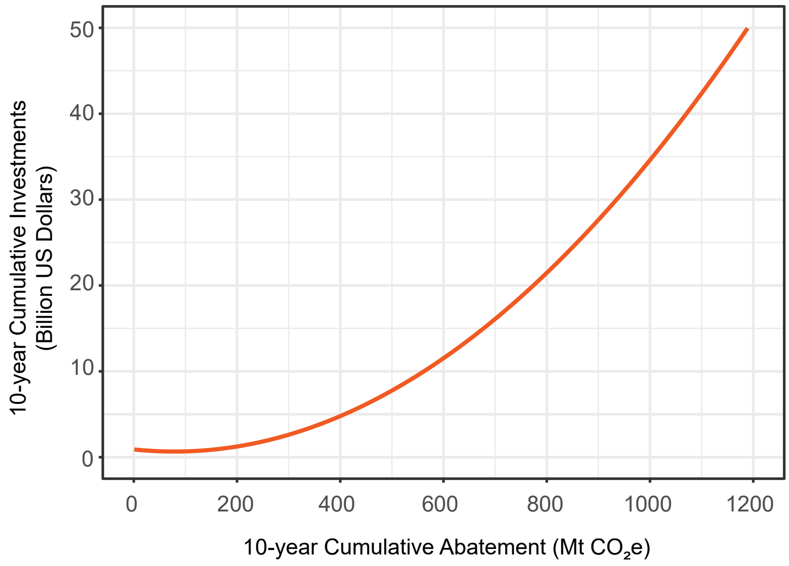
FOCUS: Investments in land mitigation

This box shows how the results presented in the report may be used to assess the mitigation potential of specific levels of investments across certain mitigation activities using FASOMGHG's results as an example.

While elsewhere in this report estimated mitigation potential is presented for a given GHG price, it is possible to use these same results to evaluate potential cost-effectiveness of investments across the AFOLU sector. Cost-effectiveness is a method for combining cost estimates with projected outcomes. It compares one scenario to another scenario by estimating how much it costs to gain a unit of the outcome, GHG mitigation in this case. This study lays out 10-year cumulative estimated abatement associated with specific levels of investments from FASOMGHG (Figure B11). For example, under a \$20 billion investment, the potential abatement is projected to be around 780 Mt CO_2e (around 78 Mt CO_2e yr^{-1}). Using these results, the average cost per ton of abatement is estimated to be about \$25 per ton of CO_2e.

This analysis indicates how results from the policy-agnostic analysis of the main report presented here can be used to assess a hypothetical investment being made in specific GHG reduction efforts across the land sector.

Figure B11: Projected 10-year mitigation potential vs. 10-year cumulative investments in land-based mitigation activities, FASOMGHG



For each GHG price scenario, the average future investments are calculated ex-post by discounting annual expenditures (GHG price times GHG abatement) to compensate landowners for their land-based mitigation activities. This approach is similar to the one presented in Austin et al. (2020). To be consistent with the discount rate included in the models, future public finance to support land-based mitigation actions are discounted using a 5% discount rate.

4 Discussion and Future Research

The United States has set ambitious climate mitigation targets in the short- to- medium term, including the national goal of reducing net GHG emissions by 50–52% by 2030 from 2005 levels and becoming net-zero by 2050 under the U.S. Long Term Strategy (LTS) (National Climate Advisor, 2021; U.S. Department of State and the U.S. Executive Office of the President, 2021).

Meeting these goals requires a portfolio of mitigation actions that spans multiple sectors and implementation times, and in this context, the land sector is expected to be a key player. For instance, the LTS projects a net sequestration level of about 1 Gt CO_2e yr^{-1} level of net sequestration from carbon removal activities including land-based activities, and other technologies[16] (U.S. Department of State and the U.S. Executive Office of the President, 2021), in 2050. The LTS also includes non-CO_2 abatement activities in the land sector (e.g., methane emission reductions from livestock management) as key strategies to achieve the 2050 target with projected reductions of methane and nitrous oxide from agriculture of about 72 Mt CO_2e yr^{-1} and 8.8 Mt CO_2e yr^{-1}, respectively (U.S. Department of State and the U.S. Executive Office of the President, 2021).

Recent federal policies also recognize the value of land-based abatement strategies by allocating funds to preserve forests' natural capacity to sequester and store carbon, to implement agricultural GHG mitigation actions, and to increase forest resilience. For instance, the Inflation Reduction Act has directed investments in land-based mitigation programs, including the Environmental Quality Incentives Program, the Regional Conservation Partnership Program, the Conservation Stewardship Program, the Agricultural Conservation Easement Program, the Conservation Technical Assistance Program, and the Agricultural Conservation Easement Program.[17] The Bipartisan Infrastructure Investment and Jobs Act of 2021 provides the USFS over $5 billion to tackle pressing issues, including wildfire fuel removals, to develop national reforestation plans, and to encourage innovation in the wood product industry and bio-based product development.[18] Finally, the USDA has directed approximately $3.1 billion to selected projects under the Partnerships for Climate-Smart Commodities program.[19]

In this context, it is important to create a technical foundation of projected mitigation potential of the land sector that can be used, among other applications, to

[16] The LTS aggregates the mitigation potential of carbon removal technologies, including the LULUCF sector and direct air capture, so it is not possible to determine the exact contribution of the LULUCF sector.
[17] Inflation Reduction Act | USDA (https://www.usda.gov/ira)
[18] https://www.fs.usda.gov/managing-land/infrastructure
[19] https://www.usda.gov/climate-solutions/climate-smart-commodities

A large reforestation project replacing native trees in previously cleared lands. This project, one of many nationwide, is located in north Florida near Jacksonville.

Meeting GHG emissions goals requires a portfolio of mitigation actions that spans multiple sectors and implementation times, and in this context, the land sector is expected to be a key player.

inform future policy development and implementation and investment strategies. Moreover, given the potential contribution of the land sector to national GHG emissions reductions and sequestration targets, it is essential to update and refine estimates of the magnitude and cost of GHG mitigation activities from this sector in the short and medium terms. This report provides information on estimated future cost-effective levels of GHG mitigation potential of U.S. land sector activities across multiple models that consider a detailed representation of forestry and agricultural resource management, land-based commodities markets, and GHG accounting under certain conditions. The results presented in this report could help stakeholders understand the general implications of different future conditions and GHG reduction strategy designs and the potential outcome of investments in the land sector across time and activities.

This chapter's outline is as follows. First, the results from this report are compared to historic annual emissions fluxes and emissions trends from the U.S. GHGI (EPA, 2023) and to the recent literature. Second, some practical applications of the results are discussed. The chapter concludes with a summary of the limitations and directions for future research in land-based mitigation actions.

Planting corn into a stand of cover crop in Porter County, Indiana, May 2023. (Photo donated to USDA by Jacob Tosch, Porter County Soil and Water Conservation District)

4.1 Context for the Report Results

Mitigation potential of the land sector in this report is within the ranges presented in previous versions, the U.S. GHGI, and the broader literature. The results tend to be more conservative than some recently published estimates as this analysis accounts for land use competition, tradeoffs between mitigation activities, and market dynamics.

This report updates and expands the estimates of the potential magnitude and cost of GHG mitigation from the land sector presented in the 2005 EPA Report to provide a range of future mitigation pathways for the land sector. Both EPA reports use economic tools with biophysical information, but this new report advances the research in the field by using two additional partial equilibrium models of land (only FASOMGHG was included in 2005), identifying eight GHGs emissions categories (seven categories in 2005) and 24 mitigation activities in the land sector (23 activities in 2005). Since the 2005 report, FASOMGHG has also been updated with revised representation of the U.S. forestry sector based on FIA data, which reflects the evolution of the U.S. forest inventory over the last two decades and new macroeconomic inputs (e.g., U.S. population and GDP growth rates) from the AEO (EIA, 2022). Moreover, the current report's use of increasing GHG price scenarios compared with either fixed or constant prices drives to different outcomes versus the 2005 report. Specifically, by using a constant price in forward-looking models like FASOMGHG, the incentive to invest in long-term mitigation strategies would be minimized, reducing the potential for higher abatement levels in the future. Finally, by applying global land models (GTM and GLOBIOM) in conjunction with a domestic model, this report considers possible effects of trade dynamics on the U.S. abatement potential that were not included in the previous report.

In this report, all models run a baseline scenario that does not include hypothetical GHG price scenarios, and future land emissions are driven by market dynamics (e.g., demand for timber products), other socioeconomic conditions, and changes in biophysical characteristics (e.g., aging trees) in the baseline and via the 10 GHG price scenarios. Baseline projections are key elements to assess the GHG mitigation potential of specific activities or sectors across time because the estimated mitigation is determined by the difference between future emissions projected under the baseline and future emissions projected under the applied scenarios. For this reason, key socioeconomic drivers are harmonized across models, and the same price incentives in the form of carbon-equivalent payments are used uniformly across the three models in this study. Each model responds to the price incentive by finding the most cost-effective mix of land use activities and production, and the resulting GHG reductions. Consequently, model results are comparable, in a relative sense, as the difference between the results under the baseline and the GHG price scenarios.

4.1.1 GHGI Historical Emissions and Projected Trends

In this section, model results from the report are compared with the historical emissions from 1990 to 2021 from the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (EPA, 2023). It is important to put the estimated results in the context of the GHGI to get a sense of where and to what extent historic and projected trends (in terms of directionality and magnitude) align or not. For example, in the AFOLU sector, according to the GHGI, net sequestration decreased by 5.9 Mt CO_2e yr^{-1} from 2000 to 2020 and, using results from this study, is projected to decrease by 5.3 Mt CO_2e yr^{-1} from 2030 to 2050 under the baseline scenario.

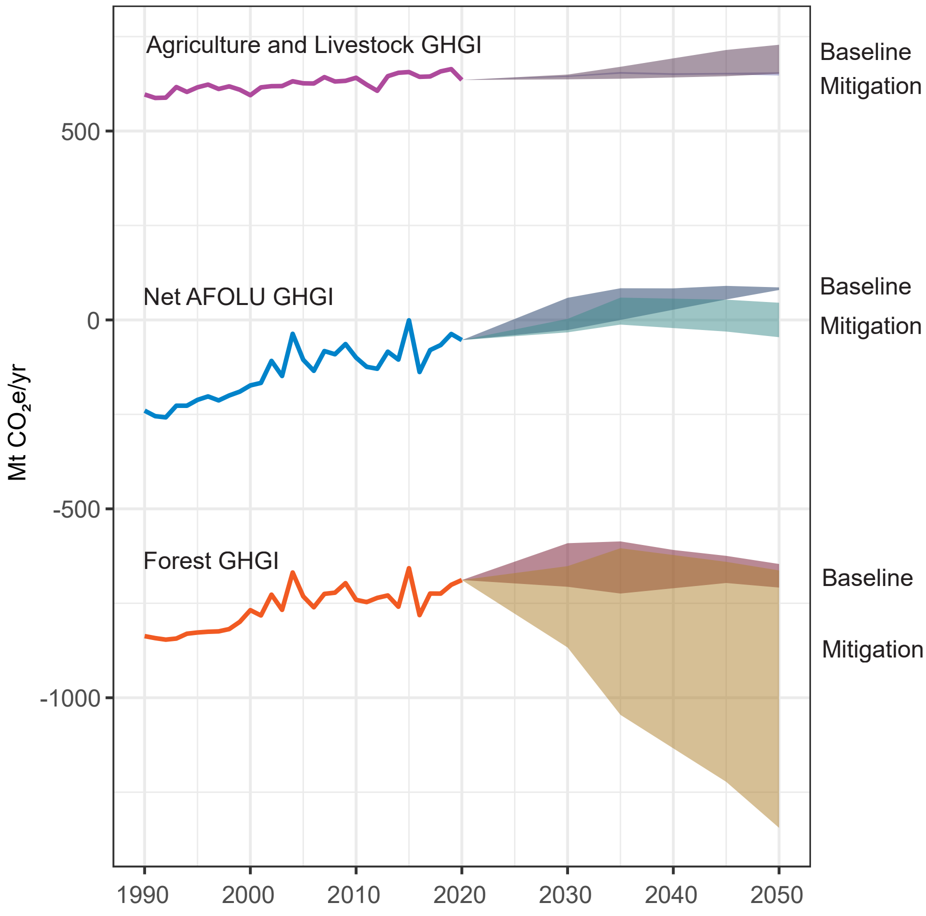
To compare the direction of future emissions trends for the baseline and mitigation scenarios to historical changes, the models' projections are pegged to the emissions reported in 2020 in the 2023 GHGI (see Figure 4-1 for a detailed description of how projected future emissions have been aligned to 2020). This adjustment, in effect, puts the estimated projection results of this study in the context of the GHGI estimates in a simplified manner.[20] In essence, the baseline trends and mitigation volumes are appended to the terminal reporting year of the GHGI for illustrative purposes. This comparison between adjusted projections and historical data shows that they generally follow the trend of increasing emissions.

In the baseline scenarios, the adjusted projected emissions from the agricultural sector indicate a slight increase relative to historical emissions reported in the 2023 GHGI. From 1990–2020, annual net emission rates for these emissions ranged from 587 to 663 Mt CO_2e yr^{-1}, while projected net adjusted emissions are 652 to 728 Mt CO_2e yr^{-1} in 2050. Under the GHG mitigation scenarios, the adjusted agricultural emissions would be in line to the late 1990s in the 2023 GHGI, with levels of just over 640 Mt CO_2e yr^{-1} in 2050.

In the forestry sector, in the adjusted projected emissions, the maximum net carbon sink under the baseline scenario across all three models is about 708 Mt CO_2e yr^{-1} in 2050, which falls between the historical bounds as reported over the last 30 years—the annual net sequestration rate ranged from 657 to 846 Mt CO_2e yr^{-1} from 1990–2020. Moreover, the minimum projected net carbon sink in the baseline of about 646 Mt CO_2e yr^{-1} is near the lower bound of what has been experienced in the same period. Box 12 provides a detailed discussion of the historical evolution of GHGI emissions and a comparison with projected emissions from the forests.

[20] Adjusted baseline emissions from the AFOLU sector are projected to be higher than the results presented in Chapter 3 because they are adjusted to be in line with 2020 values.

FIGURE 4-1 **Historic and projected adjusted GHG emissions for U.S. agriculture, forestry, and net AFOLU (in Mt CO_2e yr^{-1}, 1990–2050)**



Historical emissions for agriculture, forestry, and net AFOLU are from the 2023 GHGI. Included GHG emissions pools from the GHGI are crop cultivation, livestock, and fuel combustion for agriculture and livestock; and land converted to forest, forestland remaining forestland, and LULUCF emissions for forestry. Historical forestry sector emissions were calculated as the sum of three categories included in the U.S. GHGI: (1) Forestland remaining forestland, (2) land converted to forest, (3) LULUCF emissions.
Projected emissions (E) from each model i for each sector (Agriculture and Livestock, AFOLU, and Forest) at any time t are aligned to 2020 values from the 2023 GHGI following this formula:

$$E(i,t+n) = E(GHGI,2020) + \sum_{t=2025}^{n} E(i,t+n) - E(i,t)$$

Where t is the initial year of the results from the models (2025) and n is equal to 5 years. In the figure, for visualization purposes, 2025 values are estimated as the average between 2020 and the 2030 adjusted value for each model. For agriculture from 2020 to 2050, adjusted results are from GLOBIOM and FASOMGHG and include CO_2 and non-CO_2 emissions while adjusted forest emissions show results from GLOBIOM, FASOMGHG, and GTM from 2020 to 2050. Net AFOLU emissions, aggregate adjusted agriculture and forest emissions from GLOBIOM and FASOMGHG. Shaded areas show upper and lower bounds of the baseline scenario and the GHG price scenarios across models.

Each model's results were adjusted to 2020 reference levels from the 2023 GHGI; therefore, the results presented in this figure offer a different perspective compared to Chapter 3, where the GHG scenario results do not estimate the net AFOLU sink to become a net source.

Across recent studies, there is a low agreement on future U.S. forest sequestration trends under baseline scenarios. Some studies project U.S. forests will constitute a net sink but with a declining sequestration rate in the future, mainly due to forest dynamics, including disturbances and aging (Jones et al., 2019; Latta et al., 2018; U.S. Department of Agriculture Forest Service, 2012; Wear and Coulston, 2015), while other studies show an increased carbon sink in the future driven by investments in more forestland and more managed forests than current levels (Austin et al., 2020; Daigneault et al., 2022; Nepal et al., 2012; Tian et al., 2018). Finally, other studies show that under a business-as-usual scenario, U.S. forests will become a net source of emissions before or by 2050 (Nepal et al., 2012; Oswalt et al., 2014; Ryan et al., 2012). The 2020 Resource Planning Assessment (RPA) (U.S. Forest Service, 2023) is another example of a study that uses different tools to address different analytical questions—in this case, to assess future potential land-based resource outcomes. That study applies a range of future socioeconomic and climate scenarios to project the potential availability and condition of forest and rangeland resources over the next 50 years to offer insights about how underlying socioeconomic and climate drivers can affect the natural resources in the United States. Since the 2010 RPA (U.S. Forest Service, 2012), this analysis uses selected socioeconomic and climate scenarios to assess future potential land resource outcomes but does not specify a specific baseline or apply GHG mitigation scenarios, and therefore does not offer estimated mitigation potential. While it does not assess mitigation potential, the RPA does offer projections on future forest carbon stocks. The RPA projects across 4 future climate and 20 socioeconomic scenarios that the forest sector net sink could decline, similar to the general baseline trends from FASOMGHG and GLOBIOM in this report; and in some cases, the RPA projects that the forest sector will become a net source after midcentury, with projections ranging from -165 to 95 Mt CO_2 in 2070.

Under GHG mitigation scenarios examined in this study, forestry-related emissions show larger variation (and greater mitigation potential) in projected changes relative to historical levels from 1990 to 2020. Note that the levels of GHG incentives in this report under the hypothetical GHG pricing scenarios, especially in the longer term, constitute levels of financial incentive that have not yet existed for GHG mitigation in the land sector. The upper bounds of these results illustrate the potential magnitude of GHG mitigation practices adopted in response to GHG prices over the simulated timeframe of this study, including high GHG price incentives by the medium term, which could spur high rates of afforestation and increasing investments in forest management in the United States.

Tree and shrub canopy in the Chicago region of Illinois. (USFS photo by Preston Keres)

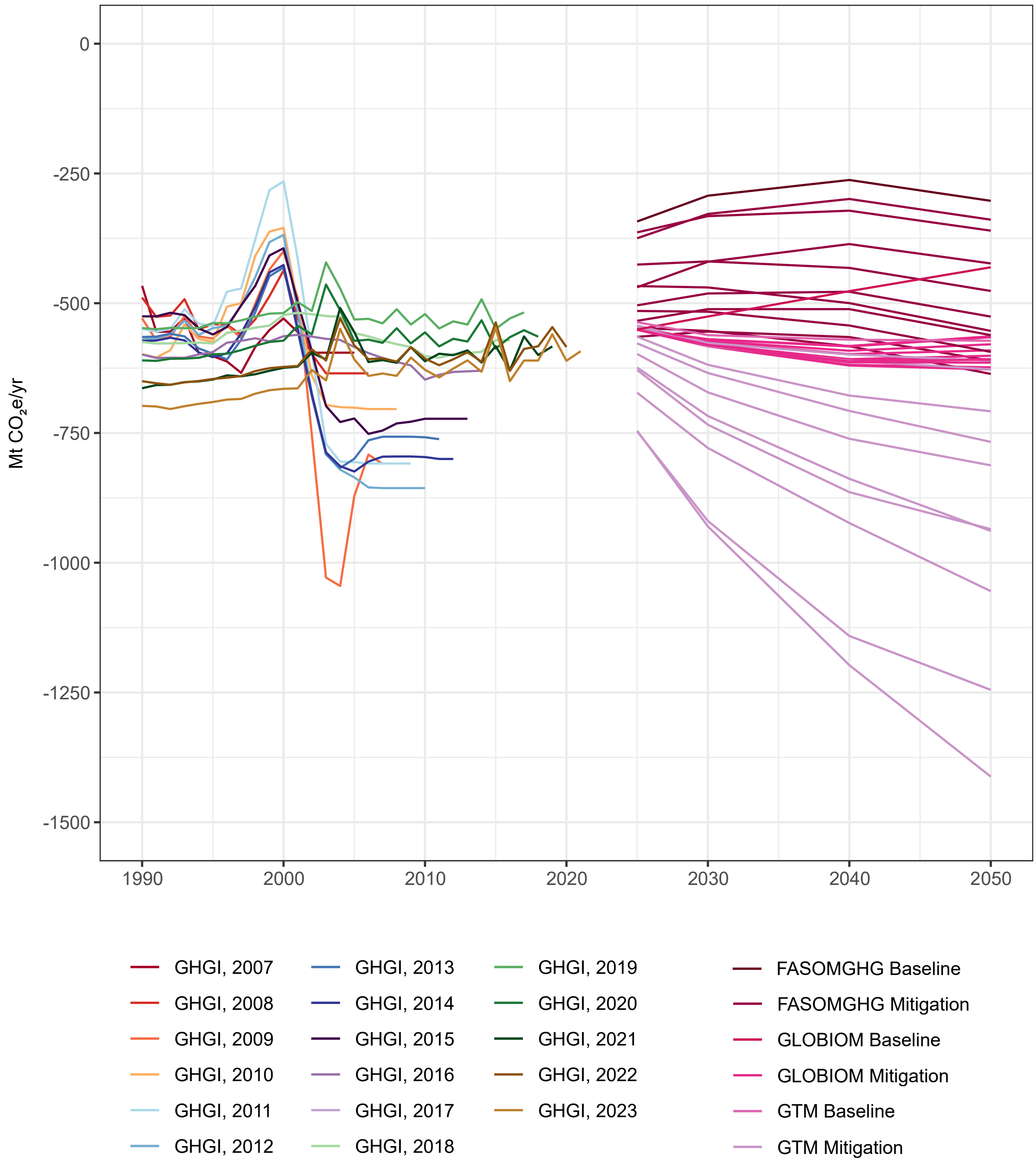
Box 12

FOCUS: Historical and projected carbon fluxes from forests

Every year, the historic data in the GHGI (from 1990 to the present) is re-estimated according to the updated data and methodologies as required by IPCC guidelines.[21] This annual re-estimation can at times significantly change the estimated flux in a specific year or years across inventories. Focusing on total forest ecosystem carbon fluxes, Figure B12 shows the historic data from 1990 to 2021, using data from 16 GHGIs published between 2007 and 2023, and compares them with the projected results from this report (baseline and GHG price mitigation scenarios). The comparison shows that future baseline projections from the three models are projected to be within the range of historical estimates. Furthermore, emissions under the GHG mitigation scenarios are projected to be within the range, except for a few high GHG price runs from GTM. While it is insightful to compare projected GHG estimates to historic values, these historic values are indeed estimated and revised annually to incorporate scientific and technological advances. Moreover, the large uncertainty of historical emissions can also be driven by changes in carbon pools included and changes in measurements.

[21] 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).

Figure B12: Conceptual illustration of market opportunity costs for a hypothetical commodity market and MACC for an abatement strategy that generates a loss in yield or total production



Historic emissions from 1990 to 2021 are sourced from the GHGIs published between 2007 and 2023, and the legend shows the year in which the GHGI was published. Projected fluxes from 2025 to 2050 report the results presented in this report from baseline and mitigation scenarios by models. Note that GHGI emissions included here reflect only forest remaining in forests, while the result from the report also includes flux from land converted to forests.

4.1.2 Mitigation Projections in the Report and Comparisons to Recent Literature

As discussed in Chapter 1, there are different methodologies to assess land mitigation potential, and recent literature presents a large range of estimated future abatement opportunities in the forestry and agriculture sectors, driven largely by model type and different underlying scenario parameters. Chapter 1 identified 39 studies, including both peer-reviewed articles and reports published between 2000 and 2022, where land-based mitigation potential was assessed using one or multiple GHG price scenarios. Among the 39 studies, 8 provide the total aggregate potential of the land sector across different GHG price scenarios (see Appendix B). Across these studies, the abatement estimated varies significantly due to different methodologies, input data, and assumptions, with a range of 5–624 Mt CO_2e for GHG prices below $35/t CO_2e and 550–1,168 Mt CO_2e for GHG prices up to $200/t CO_2e between the present and 2050 (Table 4-1). These estimates are higher compared to this report's findings of 63–181 Mt CO_2e under GHG prices below $35/t CO_2e and 268–269 Mt CO_2e under GHG prices up to $250/t CO_2e, and the difference could be explained by several factors.

Recent bottom-up studies, such as Cook-Patton et al. (2021) and Eagle et al. (2022), found that the U.S. land sector could mitigate around 1 Gt CO_2e yr^{-1} and 700 Mt CO_2e yr^{-1} by 2030, respectively, at less than $100/t CO_2e, while this study finds much lower mitigation rates, with maximum values of around 200–300 Mt CO_2e yr^{-1} in 2030 under the same price. The difference lies mainly in differing methodologies and different data, as well as modeling a shorter overall timeframe, which limits the mitigation potential from afforestation and reforestation activities. Bottom-up approaches used in Fargione et al. (2018), Cook-Patton et al. (2021), and Eagle et al. (2022) usually aggregate estimated abatement potential under specific GHG price ranges from a variety of different sources and models. By aggregating the results ex-post, this methodology does not endogenously account for land use competition and economic tradeoffs, and potentially overestimates the rates of mitigation relative to PE models where there is an explicit representation of economic tradeoffs, land use competition, and market responses. By not representing these interactions and tradeoffs between agriculture and forestry activities, bottom-up assessments of land mitigation usually provide higher abatement estimates for the same level of GHG price than PE models. This effect is particularly significant under high GHG prices (>$50/t CO_2e) and in the long term. On the other hand, the effect is smaller under low GHG prices and/or short- to medium-term time horizons when PE models might find opportunities for mitigation activities to complement each other (Baker et al., 2019; Galik et al., 2019). Another driver of higher mitigation potential estimates from bottom-up studies lays in the inclusion of new/nascent mitigation options (e.g., biochar, agroforestry) that are not included in the models used for the report to date because there are not yet sufficiently comprehensive datasets for such practices applied in the United States and/or consistent reporting guidelines established by IPCC or other coordinating bodies.

Comparing the results presented in this report with recent studies using PE models like FASOMGHG, there are still some important differences driven by different parameters and assumptions rather than methodological frameworks. Different projections in mitigation from the land sector may be driven by, for example, different study objectives that affect choices in scenario design, either in the baseline or in the portfolio of mitigation activities available at the sector level. For instance, Wade et al. (2022) used FASOMGHG to apply different socioeconomic pathways (SSPs; Riahi et al., 2017) that affected both baseline emission projections and the cost-effective composition of the mitigation portfolio. On the other hand, Baker et al. (2013) selected a different set of abatement options available in the same model. Specifically in their analysis, bioenergy is included in the land-based mitigation portfolio, and authors found higher mitigation potential for the same GHG price range.

Other factors that help explain the difference in results across approaches and models include recent changes in data and other parameters, such as upfront costs for different technologies, maximum technical potential of technologies, new land use and market conditions (e.g., new timber products), changes in carbon dynamics of terrestrial ecosystems (e.g., natural productivity of land), and management responses to market incentives.

Each methodology used to calculate mitigation potential provides information useful for different stakeholders, such as decision, makers and the broader GHG modeling community, despite differences in methods and outcomes. For example, in the GHG reduction strategy design process, technical potential is valuable to assess the estimated upper bound of potential of specific technologies.

TABLE 4-1 **Mitigation potential in the land sector per price range from literature review and this report**

Study	Estimated Annual Average Mitigation Potential per Price Range (Mt CO_2e)	GHG Price Range ($/t CO_2e)	Method
EPA (2005)*	5	$1–$35	Partial Equilibrium Model (PE)
	627	$36–$200	
Roe et al. (2019)	550	$36–$200	Techno-economic / Bottom-up
Roe et al. (2021)	957	$36–$200	Techno-economic / Bottom-up
Fargione et al. (2018)	300	$1–$35	Techno-economic / Bottom-up
	1,100	$36–$200	
Cook-Patton et al. (2021)	1,168	$36–$200	Techno-economic / Bottom-up
Eagle et al. (2022)	827	$36–$200	Techno-economic / Bottom-up
Baker et al. (2013)	624	$1–$35	Partial Equilibrium Model (PE)
Wade et al. (2022)	386	$1–$35	Partial Equilibrium Model (PE)
EPA (2024) – FASOMGHG**	63	$1–$35	Partial Equilibrium Model (PE)
	269	$36–$200	
EPA (2024) – GLOBIOM**	181	$1–$35	Partial Equilibrium Model (PE)

Annual average mitigation potential of the land sector in Mt CO_2e per price range in the United States has been calculated using data from Van Winkle et al. (2017) and original sources listed in Appendix B. Price ranges are considered for 2020–2100. However, many studies report mitigation potential until 2030, whereas other studies (e.g., Cook-Patton et al., 2020; Roe et al., 2021) do not explicitly mention the time horizon used in their analyses. Some studies (e.g., Fargione et al., 2018) include mitigation activities not included in this report. Some studies present more estimates per price range; these estimates have been averaged in the table.

*Tables 3.8, 4.A.1, and 4.A.4 (EPA, 2005). For comparison purposes, all values from EPA (2005) exclude biofuels.

**Results from this report are reported as average values for 2050 and include all GHG price scenarios that reach a maximum GHG price of $240/t CO_2e in 2050.

4.1.3 Mitigation Across Land-Based Activities

In this report, each model not only projects the GHG abatement potential of various land sector mitigation activities but also estimates the cost-effective composition of land-based activities in response to the mitigation incentive. Results across all models in this report suggest that forest-based activities offer the highest level of mitigation potential. Despite different methodologies, parameters, and inputs, recent studies broadly agree with the results of this study that improved forest management and afforestation are the practices with the largest and/or cheapest GHG mitigation potential in the U.S. land sector (Table 4-2). For instance, Roe et al. (2021) shows that afforestation/reforestation has the largest maximum mitigation potential of 307 Mt CO_2e yr^{-1} under a GHG price between \$36 and \$200/t CO_2e. On the other hand, Eagle et al. (2022) estimated that improved forest management and avoided forest and grassland conversion provide the largest mitigation potential at a GHG price scenario of \$10/t CO_2e, while other mitigation actions will be available at higher GHG prices.

Table 4-2 also shows the high variability of estimated mitigation potential from soil carbon activities, with recent studies projecting lower potential relative to previous estimates (e.g., Schneider and McCarl [200]). Note that there has been increased focus on the high uncertainty related to the biophysical potential of soil carbon mitigation activities due to the lack of physical observations and data (Ogle et al., 2019).

Finally, a recent USDA report (Jones and O'Hara, 2023) estimated the technical mitigation potential of agriculture and livestock-based activities to be in the range of 38–140 Mt CO_2e (cropland non-CO_2) and 26–40 Mt CO_2e (livestock non-CO_2), depending on the price range. The results presented in the report fall within this range with a maximum of 50 Mt CO_2e (GLOBIOM) and 12 Mt CO_2e (FASOMGHG) potential for cropland non-CO_2 and 58 Mt CO_2e (GLOBIOM) and 55 Mt CO_2e (FASOMGHG) for livestock in 2050. The estimated potential from livestock is below the maximum technical potential of 75 Mt CO_2e presented in the EPA Non-CO_2 Mitigation Report (EPA, 2019b), as discussed in Box 9.

4.2 Potential Applications of the Results

This technical report could be used by different stakeholders across different applications, such as supporting policy design assessment and improving current modeling frameworks and the state-of-knowledge on mitigation potential assessments. Some theorical applications are described below.

First, the integrated assessment and energy modeling community could use results from this report to reflect the potential magnitudes and costs of abatement from the agriculture and forest sectors (not related to bioenergy supply), as well as baseline emissions from the land sector.

As discussed in the IPCC AR6 WGIII, Chapter 7 (Nabuurs et al., 2022), the number of land-based measures used in IAMs is limited compared with sectoral models like those used in this report. In addition, the resolution of land-based measures in IAMs is less granular compared to sectoral models and may lead to higher uncertainty on the mitigation potential of a single land-based mitigation strategy. Specifically, IAMs usually represent limited or less detailed representations of land sector ecosystems and markets, and therefore represent a limited set of mitigation possibilities from forests and agricultural systems through management changes and technologies. Furthermore, IAMs often do not represent detailed landscape carbon dynamics via afforestation and avoided deforestation, like the three models used in this study.

Given these different characteristics, sectoral models could be used to augment the results from IAMs, while IAMs could be used to provide a more comprehensive representation of dynamics across sectors. The results from this report could help close these gaps by improving the representation of the land sector baseline emissions and mitigation potential (CO_2 and non-CO_2) across a wide range of GHG price scenarios and abatement activities.
Second, public- and private-sector entities could use results

TABLE 4-2 **Average mitigation potential per land-based mitigation activities in the literature**

Mitigation Activities in the U.S.	Estimated Range of Average Mitigation Potential per Price Range (Mt CO_2e yr^{-1})	GHG Price Range ($/t CO_2e)
Afforestation/reforestation/avoided deforestation	3–918	$1–$35
	10–1,290	$36–$200
Forest management	10–413	$1–$35
	12–1,256	$36–$200
Soil carbon sequestration	1–546	$1–$35
	6–195	$36–$200
Cropland non-CO_2	3–150	$1–$35
	3– 140	$36–$200
Livestock non-CO_2	11–71	$1–$35
	16–75	$36–$200

Average annual mitigation potential in Mt CO_2e per price range of $1–$35/t CO_2e and $36–$200/t CO_2e across five key land-based activities in the United States. Estimated range of average mitigation potential shows the minimum and maximum amounts of abatement reported across the 33 studies listed in Appendix B. Price ranges are considered for 2020–2100; many studies report mitigation potential until 2030, while other studies (e.g., Cook-Patton et al., 2020; Roe et al., 2021) do not explicitly mention the time horizon assumed in their analyses. The table considers studies using different methodologies. For instance, it includes recent estimates from a USDA report on mitigation from agriculture (Jones and O'Hara, 2023) and the EPA Non-CO_2 Mitigation Report (EPA, 2019b). Both reports provide a static representation of maximum technical potential of abatement opportunities as they represent annual potential mitigation consistent with a given cost; therefore, they diverge from the methodological approach used in this report. As discussed in Chapter 3, the two approaches complement each other by proving different sets of information.

from this study to prioritize land mitigation investment and strategies designed to increase carbon sequestration and other beneficial GHG outcomes. Results from this report offer insights into how mitigation efforts could be prioritized across activities and over time to maximize emissions reductions given budget constraints or mitigation price thresholds. Depending on a stakeholder's primary needs, the use of model results from a single model or set of scenarios could represent a different strategic choice.

Such users could include federal, state, or regional government stakeholders, nongovernmental organizations investing financial resources in GHG mitigation and related land conservation initiatives, and private-sector entities seeking to decarbonize their supply chain through various investments in the land sector. Specifically, the wide range of mitigation potential and cost estimates provided in this report can help implementors evaluate which types of projects to invest in, where to focus investment and outreach efforts, and related considerations on investment timing. Moreover, the U.S. regional results could lend insights to those interested in the potential mitigation outcomes and economic tradeoffs of different mitigation options in different regions. However, these subnational results might not provide sufficient insight for stakeholders interested in understanding abatement costs for a specific location or under specific localized circumstances.

Appendix C presents all the key results discussed in the report, and the next subsections present three examples of practical applications to show possible ways to use the results.

4.2.1 Application 1: Abatement Potential and Cost

Policymakers, investors, and members of different research communities might be interested in using the results presented in this report in their own analyses. One potential application is in the estimation of abatement potential from various sectors and associated costs. Alternatively, users can use the results to calculate per-ton mitigation costs of various targets, dependent on time and scope. Finally, the results can be utilized to assess the potential contribution from the AFOLU sector in meeting long-term climate stabilization targets or the feasibility of specific land-based mitigation goals, as the two examples below show.

The U.S. LTS (U.S. Department of State and the U.S. Executive Office of the President, 2021) projected about a 1 Gt CO_2e yr^{-1} level of net sequestration from land-based activities and other carbon removal activities to achieve the net-zero emissions goal by 2050. Overall, the findings presented in this report estimate that the forestry sector has the capacity to increase its net sequestration to 1 Gt CO_2e yr^{-1} over the next three decades under a GHG price higher than \$67/t CO_2e.[22]

The Global Methane Pledge launched in 2021 by the United States and the European Union aims to reduce global methane emissions by 30% below 2020 levels by 2030 (The White House, 2021). Though this global goal includes all the sectors emitting methane (e.g., energy, lands), the results in this report could be used to estimate the potential reduction of U.S. methane emissions in the land sector. Results show that the land sector could reduce methane emissions by 28% in FASOMGHG and by 31% in GLOBIOM in 2030, relative to 2020, under a GHG price higher than \$110/t CO_2e.

4.2.2 Application 2: Sensitivities to Model Frameworks and Primary Scenario Parameters

This report could provide insights into the selection of policy design elements to help achieve different analytical goals. While the main results presented in Chapter 3 rely on a modeling framework in which a universal GHG price is applied to the land sector and all agents respond to the price in a rational way with perfect information, the boxes explore alternative land-based mitigation policy designs by combining the GHG price scenario with other policies (Box 8) and by introducing an opt-in program (Box 7).

4.2.3 Application 3: Unintended Consequences

A third element of this report is the consideration of unintended consequences and potential indirect effects of land-based activities domestically. Through the application of a suite of models with differing scope and detail, this report allows for assessment of potential unintended consequences stemming from hypothetical GHG pricing scenarios. Unintended consequences can result from market or non-market changes, and this report employs a variety of models, scenarios, and sensitivity cases to bring a broader range of results into consideration.

4.2.3.1 Leakage Effects

Results in this report demonstrate the advantages of coordination of strategies across jurisdictions (landowner type, sector, geography, and economic market are all attributes of scope that can be considered) and estimate the carbon leakage resulting from unilateral action (measured as the difference between the abatement achieved under the coordinated action and the abatement achieved under unilateral action).

Box 4 compares the results of a uniform global GHG price (main results of Chapter 3) with a unilateral GHG price applied to the United States only. Results show that a unilateral (domestic only) pricing scenario is likely to

[22] Note that 1 Gt CO_2e is the projected net flux of CO_2 from forests in GTM in 2050 under the \$50 at 1% scenario, which is expected to deliver a net mitigation of about 362 Mt CO_2e relative to the baseline in 2050.

create the conditions for GHG leakage with a possible 11% increase in emissions from the rest of the world under a U.S.-only GHG price. Also, note that there might be opposite effects in terms of leakage if other jurisdictions/countries implement policies independently.

4.2.3.2 Tradeoffs Between Land Conservation and Mitigation Potential

The main results of this report generally reinforce the understanding that the land sector can be responsive to incentives for GHG mitigation by converting land from one use to another use due to financial incentives. However, some land use changes are anticipated to occur in certain places where other forces (like cultural reasons or local preservation goals) may limit conversion. Also, land use changes may be restricted to achieve other goals, like the cultivation of food crops. For these reasons, this report looks at sensitivity analyses that investigate limits on land use changes and the implications on estimated GHG outcomes. In these specific cases, there are tradeoffs associated with limiting what lands, landowners, and land management activities are eligible for GHG mitigation incentives, which should be considered during policy development and the assessment of a specific policy's potential outcomes (which is beyond the scope of this report).

Box 8 estimates the effects of preserving land allocation in the Corn Belt by limiting land use transitions from cropland into forestry. This land use conversion restriction could mimic a situation in which landowners do not respond to the GHG price signal by shifting to the most remunerative use of land, but maintain the current use of land because of high transaction costs or imperfect information on the mitigation incentive. Conversely, the restriction could represent a strategy to preserve agriculture land to avoid disruption to crop and livestock production levels as a means to guarantee food security. Results from the sensitivity show that under the constrained scenarios, national estimated GHG mitigation is reduced by about 20% with a $100/t CO_2e GHG payment relative to the unconstrained scenario. The case study represents a simplified application of the model's results and does not provide an assessment of the tradeoffs between land-based climate change mitigation efforts and food security, which requires a stand-alone analysis that goes beyond this report. Specifically, multiple socioeconomic and technological scenarios, which include alternative assumptions on economic growth, technological innovation, and diet preferences, should be considered when projecting future demand for food commodities and the demand for land. Alternative demand scenarios for food should be used to test the effects on the costs of specific land-based mitigation activities, the MACCs, and the total mitigation potential of land.

Cover crops are aerially seeded over corn at Scully Family Farms in Spencer, Indiana, in September 2022. The cover crops mix includes cereal rye, crimson clover, and rapeseed and was spread over 160 acres of no-till farmland that will be planted with soybeans in the spring. (Natural Resources Conservation Service photo by Brandon O'Connor)

4.3 Limitations and Future Research

> Future research should advance the knowledge of land mitigation potential by including new mitigation strategies, climate change impacts on land availability and productivity, and social and environmental co-benefits associated with their implementation.

As with any simulation scenario analysis or multi-model comparison effort, there are several data gaps and limitations of this analysis that warrant additional consideration and offer future research avenues, as discussed below.

This study focuses only on direct land-based GHG mitigation opportunities through land management and land use without considering other mitigation activities outside the land sector that are likely to affect land use and land management and indirectly change its GHG balance. For instance, while future demand for biofuels and bioenergy is likely to compete for land with direct land-based abatement strategies and with consequent implications on the GHG emissions from land, these are not GHG mitigation measures that could directly apply to the land sector to address its future mitigation potential. That is, bioenergy and biofuels are GHG mitigation strategies employed in the energy sector as a response to climate mitigation actions to reduce GHG emissions from energy; therefore, the assessment of their effects on land is outside the scope of this report. Similarly, this report does not include future demand for land for solar or wind energy production, which is likely to increase under decarbonization scenarios (van de Ven et al., 2021). Finally, the models do not include demands for non-traditional land-based commodities (e.g., cross-laminated timber), which might be driven by decarbonization activities outside the land sector and will have effects on emissions fluxes from the land sector.

Moreover, there is high uncertainty on future demand projections for bioenergy and biofuels, which would have increased the complexity of the number of scenarios simulated for the report and the inability to assess the actual mitigation potential of land. For instance, a recent analysis using the two IAMs projects an annual demand for biomass in the United States of 0 to 3 exajoules per year (EJ yr^{-1}) when no GHG price is assumed, and increases to approximately 9–22 EJ yr^{-1} in 2060 with a carbon price trajectory of \$26/t CO_2e in 2020 to \$413/t CO_2e in 2060, depending on the model (Vimmerstedt et al., 2023). Finally, IAMs expect high demand for bioenergy associated with carbon capture and storage (BECCS) under stringent mitigation scenarios, which are associated to high GHG prices (above \$100/t CO_2) and in the long term (Favero et al., 2023). Both of these conditions do not apply to the report (only three scenarios have a GHG price higher than \$100/t CO_2e in 2050, and the results are reported up to 2050).

Given all these aspects, the implications of bioenergy and biofuels production on the land sector emissions balance would be better explored in a stand-alone analysis where energy models and land models (like the models used for this report) integrate the information in a dynamic fashion to provide important insights on the mitigation potential of the two sectors. As suggested in other studies, bioenergy and mitigation from the land use sector could either complement each other or create additional resource competition when considered conjunctively (e.g., Baker et al., 2019; Favero et al., 2020; Favero and Mendelsohn, 2014; Favero et al., 2017). Further research on these topics should include the effect of climate mitigation policies on biomass demand and corresponding implications on land competition and MACCs. In terms of direct land-based mitigation strategies, the report does not include emerging options such as agroforestry and new developments in livestock feed additives due to a lack of comprehensive historic data on environmental outcomes and costs. As more options are developed on a larger scale and related data on costs and GHG outcomes become available, they can be included in future assessments of the abatement potential of the land sector using models from this suite of tools. Furthermore, in the current mitigation portfolio applied in this report, the study and the models do not differentiate between available activities for their inherent riskiness related to permanence, additionality, and leakage considerations, but those could be further explored in future research.

In terms of future supply of mitigation options available from the land sector, this analysis does not include potential impacts associated with climate change on land availability and productivity above what is inherently included via the input data used in the models. Some key impacts that are likely to affect the results presented in this report are changes in crop productivity, natural disturbances, increased CO_2 fertilization, and tree species migration, among others. For example, Box 5 (Chapter 3) shows that forest carbon fertilization driven by higher concentration of GHGs in the atmosphere is likely to increase the projected mitigation outcomes of GTM. Climate change feedbacks beyond climate fertilization are particularly important to assess investment incentives over long time horizons (Baker et al., 2023; Davis et al., 2022; Favero et al., 2021). Future research should expand on this application to test the current results under different climate change scenarios to assess the sensitivity of the findings to changing climate conditions by including the role of changing temperature and precipitation patterns, fluctuations in crop growing regions, and changes in occurrences of natural disasters such as drought, floods, and fires.

The model results presented in this report show potential future trends across different scenarios. Though this report does have some sensitivity analysis to evaluate uncertainties related to specific modeling variables and other parameters, it does not provide a comprehensive analysis of uncertainty of the results. However, the three models have been used in several peer-reviewed studies to explore: (1) key policy questions related to complementarity of mitigation investments across sectors (Baker et al., 2018; Favero et al., 2020); (2) indirect mitigation co-benefits of asymmetric mitigation pricing schemes (Baker et al., 2019); (3) the spatial and temporal distribution of forest sector mitigation potential under different incentive structures (Austin et al., 2019); (4) U.S. and global forest and agricultural sector mitigation potential across alternative SSP baselines (Daigneault et al., 2022; Wade et al., 2022); (5) impacts of shifting diets on land sector emissions (Kozicka et al., 2023; Latka et al., 2021; Wu et al., 2023); and (6) impacts of climate change–driven water scarcity on agricultural production (Awais et al., 2023; Fitton et al., 2019). This comprehensive collection of complementary analyses provides a fuller set of sensitivity tests for individual models.

As shown by the sensitivity tests, the design of GHG mitigation policies can affect projected mitigation potential across sectors and time. Future research should explore alternative policy designs and implications of multiple policies targeting the land sector simultaneously. For instance, this report is constructed with only a hypothetical universal GHG price without considering other policies that could either complement it or increase the costs of land mitigation activities.

Finally, the results presented in this report provide an estimated cost-effective composition of specific land-based mitigation activities under a different range of GHG price pathways under specific future conditions, without considering macroeconomic costs and socioeconomic benefits outside GHG mitigation. Future research should include these additional layers of analysis by estimating, for example, the social benefits of reducing GHG emissions and the potential co-benefits on biodiversity together with equity and environmental justice considerations.

A Midwest ethanol plant.

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