Impact of Forest Management and Wood Utilization on Carbon Sequestration and Storage in Pennsylvania and Maryland

Results for

State of Pennsylvania

Kendall DeLyser

Chad Papa

Kylie Clay

Daphna Gadoth-Goodman

Lauren Cooper

Todd Ontl

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Authors

Kendall DeLyser* is Director of Climate Science at American Forests in Washington, DC.

Chad Papa is a PhD candidate in the Department of Forestry and a Research Assistant for the Forest Carbon and Climate Program at Michigan State University in East Lansing, MI.

Kylie Clay is Associate Director of the Forest Carbon and Climate Program at Michigan State University in East Lansing, MI.

Daphna Gadoth-Goodman is a Research Assistant with the Forest Carbon and Climate Program at Michigan State University in East Lansing, MI.

Lauren Cooper is Program Director of the Forest Carbon and Climate Program at Michigan State University in East Lansing, MI.

Todd Ontl is a Climate Adaptation Specialist with the Northern Institute of Applied Climate Science in Houghton, MI (Present affiliation: USDA Forest Service, Office of Sustainability and Climate, Durham, NH).

*Corresponding author: Kendall DeLyser (kdelyser@americanforests.org)

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Summary and Implications for Decision Makers

Forests as a Natural Climate Solution

Climate change presents a global challenge to society and the ecosystems we rely on. In turn, forests have become increasingly important in international climate change dialogue, as seen in the Paris Agreement and the COP26 Glasgow Leaders' Declaration on Forests and Land Use (COP26 2021; Popkin 2019). There is also increasing scholarly recognition of forests' importance as a nature-based solution to climate change, or natural climate solution (NCS) (Drever et al. 2021; Griscom et al. 2017; Fargione et al. 2018).

US forests and the forest products sector already play an important role in mitigating climate change, a benefit which can be significantly impacted by forest management decisions and policies. The overall carbon benefit of the forestry sector is determined not only by the trees growing in a forest, but also by what they are used to produce (i.e., harvested wood products, HWP) and how HWP are used and ultimately retired. In 2020, US forests captured and stored nearly 750 million metric tons of carbon dioxide ($MtCO_2e$), enough to offset 17% of carbon emissions from fossil fuels in that same year (EPA 2022a). Almost 90% of this climate benefit was provided by existing forests and forest products, and assessments of natural climate solutions potential indicate that we could nearly double the carbon-capturing power of forests with the right set of actions (Fargione et al. 2018). However, this carbon savings potential is expected to decrease in the future due to forest loss and forest health declines fueled by climate change (Wear and Coulston 2015; Oswalt et al. 2019).

State governments can leverage the climate benefits from forests, and protect them from future climate impacts, through their strong influence on forest management, implementing climate-smart practices on state-owned lands and providing technical and financial support for other forest landowners. States like Pennsylvania and Maryland plan to use information about the impact that forests and forest management currently have on emissions levels, as well as an understanding of their future impacts on forest health and climate benefits, to inform decision-making and shape policy regarding forests and climate action. This report is designed to guide Pennsylvania toward decisions that optimize forest management for both carbon sequestration and economic benefits and encourage the inclusion of forests and the forest products sector in state-level climate action planning. Here, we present carbon modeling results for a broad range of forward-looking forest management scenarios and assess the carbon sequestered in forests and stored in HWP for each one, along with an analysis of the substitution benefits from using wood in place of other emissions-intensive materials.

Modeling Forest Management and Wood Utilization in Pennsylvania

Following Dugan et al. (2018; 2019; 2021) we assess carbon trends and management scenarios in the forest ecosystem and forest products sector for Pennsylvania utilizing a systems-based approach. This systems approach accounts for the influence of forest management activities beyond the forest itself and allows us to examine potential trade-offs or synergies between management strategies that maximize forest ecosystem carbon stocks, HWP volumes, or other important forest ecosystem services (Dugan et al. 2018). Our modeling process includes:

1) Consultation with state natural resource agency staff and forestry experts to understand forest management priorities, concerns, and goals in Pennsylvania;

2) Development of business-as-usual (BAU) and alternative forest management scenarios – including forest management, natural disturbance, and land-use change – to project future forest carbon trends under various management practices;

3) Modeling scenarios with i) a growth and yield-based forest ecosystem model - the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) - parameterized for conditions in Pennsylvania, ii) a customized lifecycle harvested wood products model (CBM-HWP-PA) built using the Abstract Network Simulation Engine (ANSE) framework, and iii) displacement factors to evaluate substitution benefits from using wood products and bioenergy in place of more emissions-intensive materials; and

4) Engagement and discussion with state agency staff to explore modeling results, consider implications for forest management programs and policies statewide, and inform state climate action targets.

Through a series of meetings with Maryland DNR Forest Service, Pennsylvania DCNR Bureau of Forestry, and US Forest Service staff, we identified several management priorities and concerns for forests in Pennsylvania: **harvesting practices**, **forest health and regeneration**, **land-use change**, **species distribution**, and **climate change**. From these stated priorities, we developed 18 modeling scenarios to cover a broad range of forest management and wood utilization practices, grouped into 6 categories representing similar management objectives: 1) changes in rotation length; 2) tree planting; 3) maintaining forest health and regeneration; 4) climate change; 5) no harvest; and 6) wood utilization (Box 1). For full scenario descriptions and parameters, see **Table 3**.

These priorities align well with the three pillars of *climate-smart forestry (CSF)*, a sustainable forest management approach that seeks to balance the ability of forests to adapt to and mitigate climate change while continuing to provide fundamental wood products and ecosystem services (Nabuurs et al. 2018; Bowditch et al. 2020; Verkerk et al. 2020). This approach acknowledges the importance of maintaining or increasing carbon storage in forests and forest products as a climate solution, but also emphasizes the need for robust carbon sequestration rates to help draw carbon out of the atmosphere as part of a global effort to mitigate climate change. CSF techniques also focus on long-term forest health and resilience in the face of climate change as part of sustainability in forest management, and they aim to accomplish all these goals while still supporting a strong wood products sector. The management priorities identified with our state partners align closely with these CSF goals, making CSF a useful framework for evaluating performance of the scenarios modeled in this analysis.

> ### *BOX 1.* MODELED SCENARIOS
>
> - Business-as-usual
> - Alter rotations*
> - Afforestation*
> - Silvopasture*
> - Restock understocked stands*
> - Timber stand improvements*
> - Control deer browse*
> - Reduce diameter limit cuts (high grades)*
> - Reduce deforestation*
> - Climate change growth
> - Climate change disturbance
> - No harvest
> - Portfolio (concurrent implementation of scenarios marked with *)
> - Utilize mill residues for bioenergy

Climate-Smart Forestry in Pennsylvania

Forests and the forest products sector already contribute climate mitigation benefits in Pennsylvania, though under business-as-usual (BAU) management these benefits decrease through 2025, when forests are projected to transition from net carbon sink (sequestering more carbon than they emit) to net carbon source (emitting more carbon that they sequester). Undertaking changes in land use and forest management can help slow or even reverse this trend, increasing forest-climate benefits

substantially compared with BAU. Key factors for successfully undertaking CSF include establishing and maintaining a diverse and multi-age forest landscape and reducing forest loss to balance the two key mechanisms through which forests benefit the climate – *carbon sequestration* (removing carbon from the atmosphere and converting it into wood through photosynthesis) and *carbon storage* (holding that carbon in forests and wood products rather than emitting it to the atmosphere).

Some forestry practices have nearly universal climate mitigation benefits no matter where they are applied. Yet, Pennsylvania's forests and wood products sector offer their own unique case, and certain practices are particularly promising for the state from a carbon perspective. This analysis demonstrates that a diverse set of climate-smart strategies exists for Pennsylvania (Box 2).

BOX 2. CLIMATE-SMART FORESTRY PRACTICES IN PENNSYLVANIA

✓ **Maintain and increase forest extent** through *reducing deforestation, afforestation,* and s*ilvopasture* (the integration of low-density tree canopy into active pastureland without removing the land from productive pasture use).

✓ **Protect the ability of forests to naturally regenerate** and foster forest diversity by *controlling deer browse* and *restocking understocked stands* where it is ecologically appropriate to add more trees.

✓ **Encourage sustainable management practices** on private lands, e.g., by *reducing diameter limit cuts* (also known as high grading, an ecologically damaging practice which encourages landowners to harvest the largest and most valuable trees from their forests and leave only smaller or stunted trees behind).

✓ **Increase forest carbon stocks while sustaining timber supply** by *extending rotations* to optimize tree growth.

✓ **Prepare for potential negative impacts of climate change**, especially from increasing forest pests and diseases.

The benefits of expanding climate-smart forestry in Pennsylvania

When implemented concurrently across the landscape, these **CSF practices could increase Pennsylvania's annual forest carbon sink by 38% by 2030**, relative to BAU. This is a significant near-term benefit, and yet it is just the start – many of these CSF practices yield increasing mitigation benefits with time as forests continue to grow, strengthening the forest carbon sink by 124% over BAU by 2100. The sooner these practices are implemented, the more impactful investments in CSF will be, especially when considering the global need for immediate climate action (IPCC 2018) and the potential to avoid the worst of future damages and climate impacts.

By implementing a *portfolio* of CSF actions, Pennsylvania's forests and wood products could sequester and store an additional 14.53 $MtCO_2e$ in total by 2050, with this benefit increasing to 264.61 $MtCO_2e$ by 2100, all while continuing to support the state's timber supply. Rapid expansion of CSF adoption could help the state on its path to 80% emissions reduction from 2005 levels by 2050, a goal recently established by the Pennsylvania Climate Action Plan 2021 (Pennsylvania Department of Environmental Protection 2021). Beyond 2050, these practices will continue to deliver carbon removal benefits and can contribute to future emissions reduction efforts.

If there is no change from BAU management, carbon stocks in Pennsylvania's forests and wood products are projected to decline gradually over time, losing 11.5% from 2020-2100. *Net carbon sequestration* from forest ecosystems (the rate at which forests remove carbon dioxide from the atmosphere, accounting for both growth and decomposition) exhibits a more dramatic decline – forests and forest products remain a net carbon sink until 2025, after which point the state is projected to become a net forest carbon source through 2100.

The anticipated decline in carbon stocks is largely influenced by forest loss trends in the state. From 2007-2019, Pennsylvania lost a net average of 17,294 acres of forest each year (a loss of 25,829 acres of mature forest coupled with a gain of 8,535 acres of new forest). If this rate of loss continues, this adds up to a 7% drop in forest area from 16.2 million acres in 2020 to 15 million acres in 2100. This decrease in forest area, especially the loss of typically carbon-dense mature forest acres, has a strong influence on both carbon sequestration and storage dynamics (Hansis et al. 2015; Williams et al. 2021): when forestland is cleared, some carbon stocks in existing trees are transferred to HWP or emitted over time through decomposition, and future carbon sequestration from the growth of those trees is lost. Both dynamics contribute to the projected decrease of forest carbon stocks under BAU management. CSF practices like *reducing deforestation* and *afforestation* are especially important in minimizing or reversing net forest loss in Pennsylvania.

A key factor contributing to the forecasted declining carbon sequestration rate is a shift in forest age diversity, with a continuation of BAU practices resulting in a greater proportion of older forest and decreasing amounts of younger forest over time. At a forest stand or landscape scale, aging forests often exhibit slowing rates of growth and productivity (Binkley et al. 2002; Sleeter et al. 2018), so a growing proportion of older forest brings about slower carbon sequestration rates in Pennsylvania's forests. CSF practices that help maintain and balance forest age diversity – such as *afforestation, silvopasture, reducing deforestation, controlling deer browse,* and *restocking understocked stands* – are important techniques for counteracting this trend and keeping the forest carbon sink strong.

Further, this study concludes that if timber harvesting ceased in Pennsylvania and all forests were simply left to grow, net forest carbon emissions would increase enough to drive forests and the forest sector to become a net carbon source by 2041. While a *no harvest* scenario accumulates the largest amount of additional carbon in the forest ecosystem relative to BAU, it also suffers from the highest anticipated rates of harvest leakage to forests outside Pennsylvania, foregone wood products production, and the likely use of more emissions-intensive materials in place of wood – leading to the cumulative sequestration and storage of 45 MtCO$_2$e less than under BAU by 2100, and nearly 6 times this deficit compared with implementing a climate-smart forestry portfolio.

Other Considerations
Adopting a *portfolio* approach to CSF – implementing several climate-smart practices concurrently – in Pennsylvania provides opportunities across the full diversity of urban, suburban, and rural areas of the state. The state has a long history of successfully combining financial and technical assistance programs to incentivize farm and forestry practices for soil and water conservation. Many of these practices are already increasing carbon sequestration and storage in Pennsylvania's forests (e.g., riparian forest buffers). This study illustrates that significant additional potential remains, much of which can occur without land-use conflicts.

For example, the *silvopasture* scenario provides the single largest mitigation benefit of all practices modeled in this analysis. Low-density tree plantings in pastures represent a large new opportunity for the state, both for its potential scale of climate benefits and the ability of silvopastoral systems to

integrate with existing grazing operations (Nair 2014). This integration of trees into active pastureland helps farmers and ranchers diversify their income, reduces the potential for heat stress in livestock, and produces additional feedstock for pasture animals (Smith et al. 2022; Garrett et al. 2004). Here, the *silvopasture* scenario models low-density tree plantings on about 66% of Pennsylvania's pastures that have potential for sustaining trees without taking land out of production – helping maintain and enhance Pennsylvania's rural character and economic vitality. Experience with this practice is limited, so increasing rates of adoption would require significant education, technical assistance, outreach, and engagement with the agriculture sector.

For Pennsylvania's forested lands, maintaining a diversity of forest ages is a critical CSF approach, both for mitigating climate change and adapting to it. Future forest management will need to both allow for aging into old forest (>120 years old) and establishment of additional areas of young forest (<10 years old). It can take many years to realize changes in forest age diversity, extent, and rates of carbon sequestration and storage (Shifley and Thompson 2011), and any gains in forest carbon brought about by expanding young forest acreage can quickly be counteracted by losing mature forests. Reducing the rate of forest loss, as discussed above, is therefore a critical action in a *portfolio* approach to CSF. This may have implications for Pennsylvania's current and future Forest Action Plans and land-use planning.

This analysis provides decision makers with new information to consider how best to leverage Pennsylvania's forests and forest products to mitigate climate change. Investments in conservation, technical and financial assistance, and markets targeted to realizing a portfolio of climate-smart forestry practices will need to be weighed against continuing current management practices. The state may work to achieve climate-smart outcomes by adjusting management priorities and interventions on public lands and through education, incentives, and engagement with consulting forestry professionals to reach private actors. The sooner climate-smart practices are implemented in Pennsylvania, the sooner the climate benefits illuminated by this study can be realized.

Introduction

Forests as a Natural Climate Solution

Climate change presents a global challenge to society and the ecosystems we rely on. In turn, forests have become increasingly important in international climate change dialogue, as seen in the Paris Agreement and the COP26 Glasgow Leaders' Declaration on Forests and Land Use (COP26 2021; Popkin 2019). There is also increasing scholarly recognition of forests' importance as a nature-based solution to climate change, or natural climate solution (NCS) (Drever et al. 2021; Griscom et al. 2017; Fargione et al. 2018).

High-level NCS assessments have considered various potential nature-based climate solutions both in terms of opportunity scale (e.g., metric tons of carbon dioxide equivalent, or tCO_2e) and cost of implementation. Results of these assessments at the international (Griscom et al. 2017) and US national levels (Fargione et al. 2018) point to forested land as the dominant opportunity for nature-based climate change mitigation by reducing emissions and increasing carbon sequestration from the atmosphere. The largest opportunities typically come through reforestation, forest conservation, or forest management pathways (Griscom et al. 2017; Fargione et al. 2018), which can include the extension of carbon retention times in harvested wood products such as mass timber buildings (Xie et al. 2021).

US forests and the forest products sector already play an important role in mitigating climate change, a benefit which can be significantly impacted by forest management decisions and policies. The overall carbon benefit of the forestry sector is determined not only by the trees growing in a forest, but also by what they are used to produce (i.e., harvested wood products, HWP) and how HWP are used and ultimately retired. In 2020, US forests captured and stored nearly 750 million metric tons of carbon dioxide ($MtCO_2e$), enough to offset 17% of carbon emissions from fossil fuels in that same year (EPA 2022a). Almost 90% of this climate benefit was provided by existing forests and forest products (excluding any possible displaced emissions from product substitution), and NCS assessments like those above indicate that we could nearly double the carbon-capturing power of forests with the right set of actions (Fargione et al. 2018). However, this carbon savings potential is expected to decrease in the future due to forest loss and forest health declines fueled by climate change (Wear and Coulston 2015; Oswalt et al. 2019).

Assessing Forest Climate Benefits in Pennsylvania and Maryland

State governments can leverage the climate benefits from forests through their strong influence on forest management, implementing climate-smart practices on state-owned lands and providing technical and financial support for other forest landowners. Because of the urgent threat of climate change, US states are striving to develop policies and programs that lower greenhouse gas emissions, maintain current carbon storage, increase stored carbon pools, and enhance sequestration rates. As part of this push, more states are supporting lateral efforts (e.g., participating in the US Climate Alliance) and undertaking assessment, planning, and monitoring within their jurisdictions. Given the NCS power and potential of forests, states are exploring measures to demonstrate, promote, and support an active sustainable forest industry and are considering options for increasing the role of forests and HWP in state climate mitigation plans.

To achieve such ambitious climate targets, states need new information about the impact that forests and forest management currently have on emissions levels, as well as an understanding of their future impacts on forest health and climate benefits. States like Pennsylvania and Maryland plan to use this information to inform decision-making and shape policy regarding forests and climate action. Pennsylvania and Maryland collectively contain 19.6 million acres of forest, and both states are seeking information about climate mitigation and adaptation opportunities in their forests to incorporate in

revisions to state-level Forest Action Plans and Climate Action Plans. By working together in this regional study, Pennsylvania and Maryland can learn about shared forest management challenges and goals and collaborate to develop effective management and policy strategies.

This report is designed to guide Pennsylvania toward decisions that optimize forest management for both carbon sequestration and economic benefits and encourage the inclusion of forests and the forest products sector in state-level climate action planning. Here, we present carbon modeling results for a broad range of forward-looking forest management scenarios and assess the carbon sequestered in forests and stored in HWP for each one, along with an analysis of the substitution benefits from using wood in place of other emissions-intensive materials. An associated project managed by Penn Soil RC&D will also consider the economic tradeoffs of these modeled forest management actions to consider their potential impacts on the forestry sector in each state.

This report focuses on modeling and results for Pennsylvania. A comparable report has been prepared for Maryland (DeLyser et al. 2022).

Research and Modeling Process

Following Dugan et al. (2018; 2019; 2021) we assessed carbon trends and management scenarios in the forest ecosystem and forest products sector for Pennsylvania utilizing a systems-based approach. This systems approach accounts for the influence of forest management activities beyond the forest itself and allows us to examine potential trade-offs or synergies between management strategies that maximize forest ecosystem carbon stocks, HWP volumes, or other important forest ecosystem services (Dugan et al. 2018). Our modeling process included:

1) Consultation with state agency staff and forestry experts to understand forest management priorities, concerns, and goals in Pennsylvania;

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4) Engagement and discussion with state agency staff to explore modeling results, consider implications for forest management programs and policies statewide, and inform state climate action targets.

The sections below summarize our process for each of these steps. Specific data sources and model parameterization methods can be found in the **Appendix**.

Systems-Based Forest Carbon Modeling

Forest Carbon Science

Trees capture carbon as they grow, which then cycles through various components of the forest. Accrual of carbon in the forest ecosystem also depends on accumulation of dead wood, leaf litter, and soil (Smith et al. 2006), as well as decomposition – all complicated dynamics that affect the carbon sequestration

and storage potential of forests. Here, *carbon storage* refers to the amount of carbon physically held by living and dead trees, contained in the soil and forest floor material, and carried in wood products throughout the economy (**Figure 1**). *Carbon sequestration* refers to the annual rate of carbon capture from the atmosphere by forests, affected by rates of tree growth, mortality, and decomposition. These elements combine as forests sequester carbon and store it away in trees each year to represent the forest's climate mitigation potential. Forests that sequester and store more carbon than they release from decomposition and respiration each year represent a *net carbon sink*; conversely, forests that release more carbon than they sequester and store become a *net carbon source*.

To understand the role forests can play in mitigating climate change, we need accurate assessments of these forest carbon dynamics and interactions with other sectors. The systems approach used in this analysis provides a critical comprehensive look at not only the forest ecosystem dynamics at play, but also forests' interactions with land use change, the wood products sector, and substitution of wood products in place of emissions-intensive materials (**Figure 1**). Excluding any one of these components would lead to an incomplete accounting of forest carbon, misrepresenting net forest emissions and climate mitigation potential – therefore, a systems approach is necessary (Smith et al. 2006; Dugan et al. 2018; Kurz et al. 2009; Nabuurs et al. 2007).

The CBM-CFS3 partitions carbon into 14 ecosystem pools, including living vegetation (above- and belowground biomass), dead wood (biomass in standing dead, downed wood, and forest floor material), and soil carbon (**Figure 1**). Ecosystem carbon moves between these pools and the atmosphere in each year of the model, representing typical flows in the forest carbon cycle. Carbon can enter or leave this system as land transitions between forest and alternative land uses. Carbon can also leave the forest
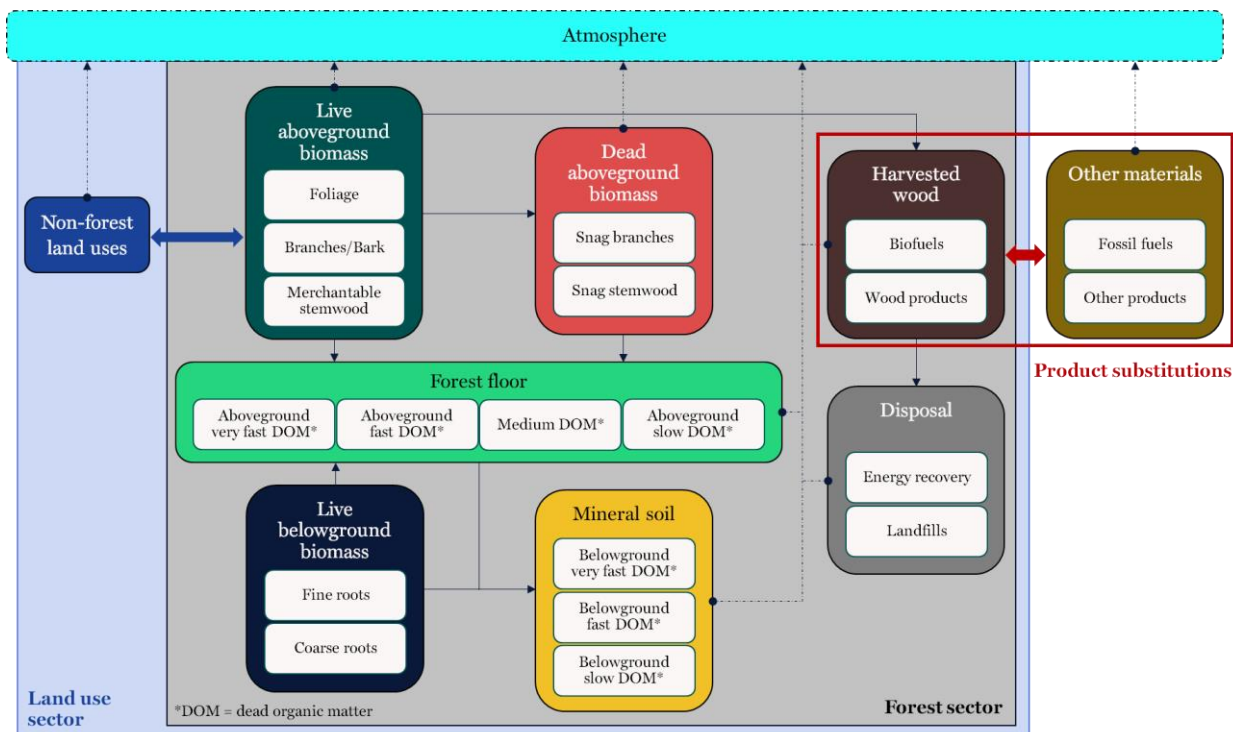
Figure 1. Simplified systems view of land uses and sectors influencing forest carbon stocks and sequestration. The forest sector (gray box) shows the forest carbon pools and transfers used in the CBM-CFS3 and CBM-HWP-PA models. For DOM (dead organic matter) pools, "very fast", "fast", "medium", and "slow" refer to various decomposition rates of dead organic matter in the forest ecosystem. Transfers between the land use sector (blue box) and the forest sector (gray box) represent land use changes (either forest loss or forest gain). Product substitutions (red outline) represent the use of harvested wood in place of other materials in the economy. Adapted from Kull et al. 2019 and Nabuurs et al. 2007.

through harvested wood, which is further assessed and tracked through its usage (in wood products and energy) and end of life (e.g., landfill storage and wood energy). Wood products from sustainable forest management are also counted as a climate solution by providing renewable and lower-emissions materials that can substitute for more emissions-intensive products like concrete and steel (McKinley et al. 2011).

Forest Ecosystem Model

The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) is an operational-scale carbon model designed to simulate the dynamics of forest carbon stocks over time, following guidelines and carbon pools established by the Intergovernmental Panel on Climate Change (Kull et al. 2019; Kurz and Apps 1999; Kurz et al. 2009). The model has had wide applications within Canada (Kurz et al. 2013; Kurz et al. 2018), the United States (Dugan et al. 2018; 2019; 2021), and internationally (Olguin et al. 2018; Pilli et al. 2013; 2014; 2017; 2022) while being thoroughly evaluated against ground plots (Shaw et al. 2014) and with respect to model uncertainty (Metsaranta et al. 2011; 2017). Though originally developed for Canadian forest conditions, the CBM-CFS3 is widely customizable and can be parameterized with location-specific data; for this analysis, we use state-specific data from the US Forest Service Forest Inventory and Analysis (FIA) Program (USDA Forest Service 2019) to ensure accuracy for Pennsylvania forests. We use the CBM-CFS3 for this study at the request of Pennsylvania DCNR Bureau of Forestry staff, to expand on previous modeling efforts for state forests in Pennsylvania (Dugan et al. 2018).

The CBM-CFS3 utilizes forest inventory data and empirically-derived growth and yield curves, in combination with schedules of management activities, natural disturbances, and land-use change, to calculate forest carbon trends throughout a simulation (**Figure 2**). The forest inventory is spatially referenced rather than spatially explicit, meaning that exact locations of inventory records are not known or tracked. Instead, inventory data are categorized by a series of *classifiers* that define relevant characteristics of the forest landscape (i.e., forest type, ownership, or stocking class) or reference spatial units within the study area (i.e., counties or ecoregions; see **Appendix** for full list of classifiers used in this project). These classifiers are also used to develop specific volume-age curves, or yield curves, so that growth and yield trends can be appropriately linked to inventory records in the simulation. The CBM-CFS3 uses allometric equations to predict wood volume-to-biomass relationships during model runs (Boudewyn et al. 2007), which have been customized for this project to accurately represent Eastern US tree species. Finally, process-based equations simulate dynamics between soil, dead organic matter, and forest processes like litter fall and decomposition in the model (Kurz et al. 2009).

Management and natural disturbance data are also necessary inputs – the CBM-CFS3 does not independently predict future events, but instead follows a user-determined schedule of annual management, disturbance, and land-use change events (collectively termed *disturbances*) for the simulation period. For this analysis, our disturbance data come from FIA (USDA Forest Service 2019), LANDFIRE (USGS 2016), National Interagency Fire Center (National Interagency Fire Center 2021),
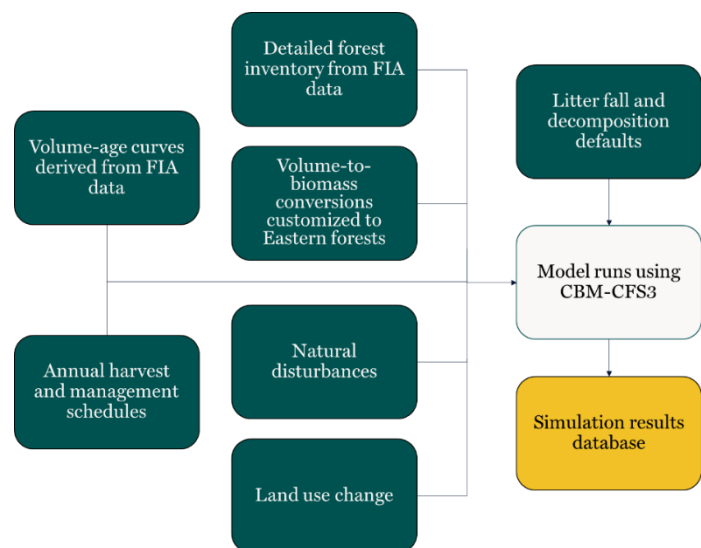

Figure 2. Modeling inputs and process for CBM-CFS3. Adapted from Kull et al. 2019.

prescribed fire data provided by the Pennsylvania DCNR Bureau of Forestry, National Insect and Disease Detection Surveys (USDA Forest Service 2020), and the National Land Cover Database (Wickham et al. 2021). See **Table 1** for BAU ecosystem disturbance parameters. In addition to event schedules, the CBM-CFS3 utilizes *disturbance matrices* to represent specific impacts of disturbance events on mortality, the transfer of carbon between pools, the transfer of carbon to the forest products sector, and the emissions of carbon to the atmosphere (Kurz et al. 2009). See for more information on data and assumptions used in model parameterization.

Harvested Wood Products Model

To calculate and assess carbon stored by and greenhouse gases (GHG) emitted from forest products across diverse forest management scenarios, we employed the CBM-HWP-PA model. This model was built using the ANSE modeling framework and contains custom parameters, export regions, and modeling flows specific to Pennsylvania products and markets. ANSE is a carbon accounting tool developed by the Canadian Forest Service (CFS) and used for Canada's national GHG inventory reporting in tandem with the CBM-CFS3. The modeling framework facilitates tracking, modeling, and calculating of embodied carbon storage and emissions associated with HWP.

Disturbance events (particularly, though not exclusively, harvest events) in the CBM-CFS3 transfer specific amounts of carbon into the wood products sector, which in turn become the main data inputs for the CBM-HWP-PA model. Carbon inputs are partitioned into various wood product streams based on current practices in the forest products sector in Pennsylvania (**Figure 3**). First, a portion of harvested carbon is allocated to expected roundwood exports. Exported roundwood is assumed to go toward wood, paper, and fuel products, the proportions of which are determined by importing country wood use weighted by their share of exported Pennsylvania roundwood. All remaining carbon is allocated toward domestic commodity production, with a certain proportion going toward mill residues that either become fuel or feed into additional commodity production. Each commodity has a corresponding half-life that determines the longevity of the carbon in use before moving to a product
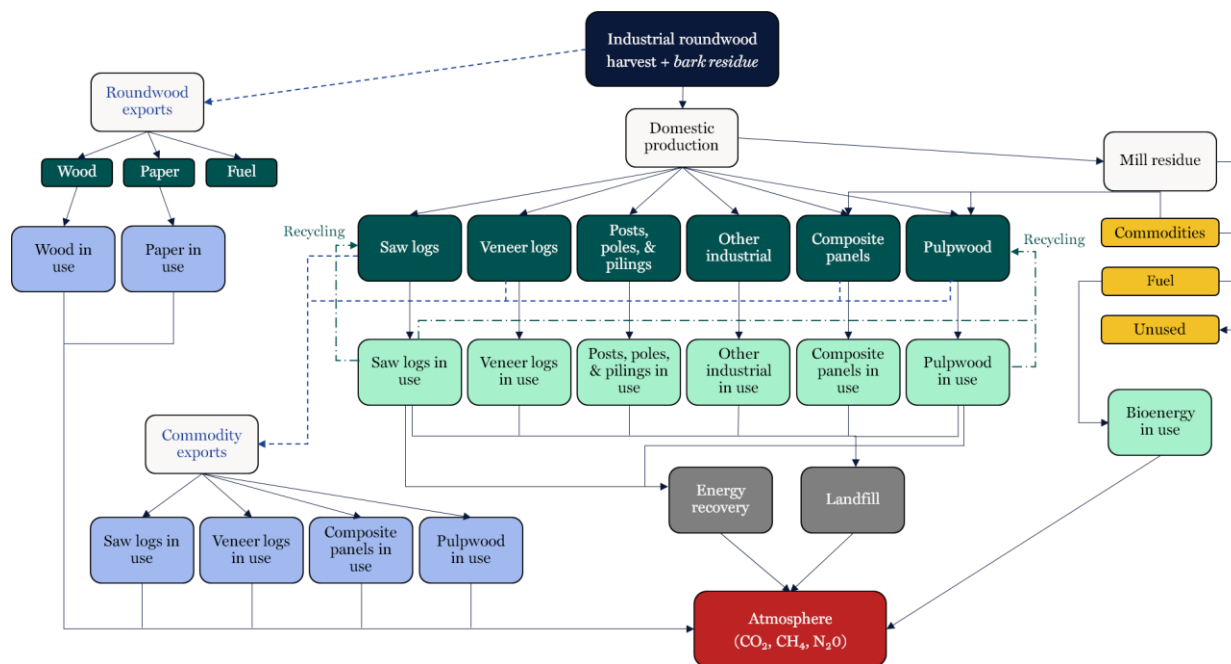

Figure 3. Pathways for carbon in harvested wood products in CBM-HWP-PA model used for analysis of the fate of harvested carbon in Pennsylvania.

retirement pathway (i.e., recycled, burned for energy, or sent to the landfill) and, eventually, emitted back to the atmosphere.

In cases where HWP substitute for alternative, more emissions-intensive products (e.g., concrete, steel), the change in production of those commodities relative to the BAU is associated with *displaced emissions*, also referred to as *substitution benefits*. When additional wood products are manufactured relative to BAU, we assume those additional products will be used in place of alternative emissions-intensive materials and credit those scenarios with the corresponding substitution benefits, representing a reduction of atmospheric GHG emissions. Likewise, a decrease in harvest and commodity production may be associated with increased emissions (or negative substitution benefits) in cases where more emissions-intensive products are assumed to replace the less emissions-intensive wood products. Substitution benefits are applied only to saw log, composite panel, and bioenergy products.

For any scenario resulting in less harvest relative to the BAU in a given year, we apply a *leakage* factor to represent an assumed increase in out-of-state harvest activity compensating for the decrease in harvesting in-state. We assume demand for wood (or substitute) products will remain constant despite reductions in harvest (e.g., due to continued construction demand) and assume a portion of that demand will be met via additional wood imports from increased out-of-state harvest (i.e., leakage). We assume all remaining product demand (that which is not met by in-state harvest or out-of-state imports) will be met by product substitution (i.e., increased use of non-wood materials in place of wood). Determination of leakage rates in the United States depends in part on the degree of assumed regional collaboration (e.g., less leakage occurs when neighboring states or regions are engaging in similar harvest reduction activities) and estimates in the literature range from 63.9% with regional collaboration (Gan and McCarl 2007) to 84.4% without (Wear and Murray 2004). In this analysis, we apply a leakage factor of 63.9% given the multi-state nature of this project, meaning that 63.9% of reduced harvest relative to the BAU is assumed to leak out-of-state and the remaining 36.1% of reduced harvest relative to the BAU is subject to additional emissions from product substitution, as noted above. In all cases, leakage is only assumed to result from reduced in-state harvest; any additional in-state harvest relative to BAU is assumed to result in increased in-state wood use rather than reductions in out-of-state harvest.

Note that substitution benefits are only included for the assessment of scenario and policy alternatives. For the purpose of reporting GHG emissions and removals in the land sector, substitution benefits are not attributed to the forest sector. They appear as emissions reductions in other sectors, when wood products have reduced the use of other products. Those actual emission reductions will also reflect any actual leakage that may have occurred. See **Appendix** for more details on substitution and leakage calculation methods.

To parameterize the CBM-HWP-PA, we use state-specific trade and commodity data from Resource Planning Act (RPA) assessments (USDA Forest Service 2021), US Commodity Flow Surveys (US Department of Transportation and US Department of Commerce 2021), US International Trade Commission (2021) trade database, and Howard and Liang (2019) wherever available, and US averages from the same sources otherwise. We rely on the FAOSTAT statistical database (FAO 2021) to determine the commodity distributions of exported roundwood. Softwood products are parameterized and modeled separately from hardwood products, as the two wood types differ in exports and commodities produced, as well as their associated product half-lives and displacement factors. We use end-use product half-life and product use data from Dymond (2012) and Howard et al. (2017), respectively, to calculate softwood- and hardwood-specific half-lives for Pennsylvania sawn wood and veneer products, while we rely on literature estimates for other products (Smith et al. 2006; Skog 2008).

To calculate substitution benefits associated with wood product substitution, we couple Pennsylvania-specific production data (USDA Forest Service 2021), US consumption rates (Howard et al. 2017), product weights (Smyth et al. 2017), and LCA data (Bala et al. 2010; Dylewski and Adamczyk 2013; Hubbard et al. 2020; Puettmann 2020; Puettmann and Salazar 2018; 2019; Puettmann et al. 2020b; 2020c; 2020a; Athena Sustainable Materials Institute 2019; Meil and Bushi 2013), following the calculation methods developed by Smyth et al. (2017). Landfill carbon dioxide and methane emissions rely on IPCC defaults for methane generation (k) and landfill half-lives for wet, temperate climates (Pipatti et al 2006). See **Table 2** for BAU HWP parameters and **Appendix** for more details on data and assumptions used in model parameterization.

Identifying Forest Management Priorities

Through a series of meetings with Maryland DNR Forest Service, Pennsylvania DCNR Bureau of Forestry, and US Forest Service staff, we identified several management priorities and concerns for forests in Pennsylvania. Discussions were focused on how these priorities and concerns would relate to influences on forest carbon stocks, and therefore did not cover an exhaustive list of forest management issues within each state. We used this information to construct various scenarios for our model, both for a forward-looking BAU scenario and alternative management scenarios representing a departure from BAU practices. Priorities indicated for Pennsylvania include:

- **Harvesting practices** commonly used throughout the state, such as clearcuts, seed tree cuts, shelterwood cuts, and thinnings. These practices are important for meeting various management objectives, like providing wildlife habitat, and for supporting the state's forest products sector. There is concern about the prevalence of diameter-limit cuts (DLCs, also called high grades) on private lands, a practice which encourages landowners to harvest the largest and most valuable trees from their forests and leave only smaller or stunted trees behind. DLCs are not considered a long-term sustainable harvesting practice, as they leave the forest in a degraded ecological state with unpredictable regeneration and diminished future growth (Kenefic et al. 2005; Ward et al. 2005; Nyland et al. 2016). Additionally, some climate action advocates are pushing state agency staff for a complete reduction of harvesting practices to increase forest carbon stocks, though this tactic comes with tradeoffs in carbon sequestration rates and the forest products sector as forests age and wood supply declines. Any potential changes to the frequency or use of harvesting practices in Pennsylvania can be expected to affect forest carbon dynamics, and therefore lend themselves well to sets of alternative management scenarios.

- **Forest health and regeneration practices** such as timber stand improvements, prescribed burns, controlling invasive plants and insects, controlling invasive vines in urban and peri-urban environments, age class redistribution, and facilitating natural regeneration. Forest regeneration is of particular concern (and relates to the need for age class redistribution), as Pennsylvania's forests experience heavy browsing pressure from deer which creates a deficiency of seedlings and saplings. This means Pennsylvania's forests are dominated by older trees and lack the new cohort of trees needed to replace aging trees as they die or are harvested. Deer browse control, mainly accomplished through exclusion fencing, is difficult and expensive, and therefore is not currently widespread across the state. Additionally, Pennsylvania's aspen forests are often maintained in an early successional stage to provide wildlife habitat, which helps counteract the decline in younger trees elsewhere.

- **Land-use change**, both in terms of tree planting opportunities and permanent forest loss, driven by development on private lands statewide.

- **Species distribution**, as some native species, like hemlock and ash, are threatened by invasive insects and diseases. Other species, like chestnut, elm, and ash, may be targets for reintroduction

practices after decimation by historic insect and disease outbreaks. Additionally, some forest types in Pennsylvania are experiencing concerning changes in species composition, such as red maple dominance in the understory of oak/hickory stands and the loss of pines from mixed oak/pine forests. These concerns can both be addressed with the use of prescribed fire and other resilience practices described above.

- **Climate change** is expected to affect forests in Pennsylvania in various ways: through changes in growth rates, changes in natural disturbances, and changes in tree mortality.

These priorities align well with the three pillars of *climate-smart forestry (CSF)*, a sustainable forest management approach that seeks to balance the ability of forests to adapt to and mitigate climate change while continuing to provide fundamental wood products and ecosystem services (Nabuurs et al. 2018; Bowditch et al. 2020; Verkerk et al. 2020). This approach acknowledges the importance of maintaining or increasing carbon storage in forests and forest products as a climate solution, but also emphasizes the need for robust carbon sequestration rates to help draw carbon out of the atmosphere as part of a global effort to mitigate climate change (a balance of the two important factors discussed in the **Forest Carbon Science** section above). CSF techniques also focus on long-term forest health and resilience in the face of climate change as part of sustainability in forest management, and they aim to accomplish all these goals while still supporting a strong wood products sector. The management priorities identified with our state partners align closely with these CSF goals, making CSF a useful framework for evaluating performance of the scenarios modeled in this analysis.

Developing Modeling Scenarios

Starting from the priorities and concerns listed above, we developed modeling scenarios based on available data and expected relevance for landscape-scale carbon dynamics. Some of the identified concerns, though important for forest resilience or individual tree health, are not expected to have a demonstrable impact on carbon at the landscape scale of the CBM-CFS3. Other identified priorities may have reasonably been expected to influence carbon on a landscape scale but were novel or unstudied enough that available data quantifying those carbon influences were limited. Given the input data and pre-determined disturbance schedule requirements of the CBM-CFS3, these priorities could not be included in our analyses. After narrowing the above list to practices with sufficient data and carbon impact to incorporate as a scenario, we parameterized each scenario as described below.

Business-as-Usual Baseline

A core objective of this project is to estimate the differential carbon impacts of various forest management practices in Pennsylvania. This requires the construction of a business-as-usual (BAU) baseline to provide the basis for comparison to alternative scenarios. The BAU represents a continuation of current management practices (i.e., harvests, thinnings, prescribed burns), land-use changes (afforestation and deforestation), and natural disturbances (i.e., wildfires, windthrow, and insect and disease outbreaks), which allows for quantification and projection of current practices into the future. Though this does not account for changes in policies, climate, and economics, it is a useful exercise to explore how the continuation of current behaviors and disturbances may affect future forest dynamics and carbon cycling.

This analysis covers the period from 2007-2170, capturing historical events from 2007-2019 and starting with projections of the BAU based on historical averages in 2020 (**Table 1**). We use this long model period to capture multiple rotations of management though Pennsylvania's hardwood forests. HWP model results extend to 2100, rather than 2170, due to uncertainties in future market dynamics, so full ecosystem and HWP model results will be reported to 2100 to harmonize these model timeframes.

Table 1. Pennsylvania BAU ecosystem disturbance parameters. Values are based on historical average rates from 2007-2019. All carbon values are in metric tons (t C).

Land-use change			
Forest loss	-25,829 acres/year	Forest gain	+8,535 acres/year
Natural disturbances			
Wildfire	2,373 acres/year	Disease	9,778 acres/year
Insect defoliation	118,193 acres/year	Abiotics	12,486 acres/year
Insect mortality	924 acres/year		
Forest management practices			
Prescribed fire *(~40% understory consumption)*	6,590 acres/year		
State forests			
Clearcut *(90% merchantable biomass removal)*	7,894 t C/year (1,405,759 cu ft/yr)	Group selection/overstory removal* *(30% merchantable biomass removal)*	95,869 t C/year (13,122,108 cu ft/yr)
Shelterwood cut* *(50% merchantable biomass removal)*	206,873 t C/year (27,817,108 cu ft/yr)	Thinning *(30% merchantable biomass removal)*	49,718 t C/year (6,857,414 cu ft/yr)
Private forests			
Clearcut *(90% merchantable biomass removal)*	49,462 t C/year (8,662,052 cu ft/yr)	Shelterwood cut* *(50% merchantable biomass removal)*	173,546 t C/year (20,893,002 cu ft/yr)
Seed tree cut* *(70% merchantable biomass removal)*	281,346 t C/year (38,611,505 cu ft/yr)	Group selection/overstory removal* *(30% merchantable biomass removal)*	205,761 t C/year (28,368,271 cu ft/yr)
Diameter limit cut* *(70% merchantable biomass removal)*	203,833 t C/year (27,960,055 cu ft/yr)	Thinning *(30% merchantable biomass removal)*	543,168 t C/year (73,248,434 cu ft/yr)
US Forest Service/other Federal forests			
Shelterwood cut* *(50% merchantable biomass removal)*	21,911 t C/year (3,023,309 cu ft/yr)	Thinning *(30% merchantable biomass removal)*	66 t C/year (9,349 cu ft/yr)
Group selection/overstory removal* *(30% merchantable biomass removal)*	11,660 t C/year (1,652,656 cu ft/yr)		

*Applies to hardwood forest types only

Alternative Management and Disturbance Scenarios

Within this analysis, we construct alternative *scenarios* by changing BAU parameters beginning in 2020, representing potential changes in future management decisions or disturbance events. Scenarios relate to one specific practice or objective, where only one BAU practice is changed and the rest of the BAU remains the same. This allows us to examine the specific influences of each altered management practice on forest carbon dynamics and evaluate their relative power as climate mitigation actions. Our 16 scenarios cover a broad range of forest management and wood utilization practices, and are grouped into 6 categories representing similar management objectives and priorities: 1) changes in rotation length; 2) tree planting; 3) maintaining forest health and regeneration; 4) climate change; 5) no harvest; and 6) wood utilization (**Table 3**; see **Appendix** for additional scenario details).

While each individual scenario represents a potential CSF management tactic, these practices would rarely be implemented alone across the state. To better represent comprehensive forest climate action, we also construct a *Portfolio* management scenario – an ensemble of all scenarios or practices that could

Table 2. Pennsylvania BAU HWP parameters. Values are based on most recent available data from 2007-2020. Percentages may not sum to 100% due to rounding.

Roundwood exports			
Softwood exports	0%	Hardwood exports	1.34%

Commodity distribution (proportion of carbon distributed to various commodities)

Softwood commodities			
Sawlogs	8%	Pulpwood (from mill residue)	17.8%
Veneer logs	0.01%	Composite panels (from mill residue)	1%
Pulpwood	39.5%	Bioenergy (from mill residue)	12.4%
Composite panels	0.4%	Unused mill residue	7.4%
Posts, poles, pilings	0.01%	Fuel (from exported roundwood)	0%
Other industrial uses	13.4%	Paper (from exported roundwood)	0%
		Wood (from exported roundwood)	0%

Hardwood commodities			
Sawlogs	29.5%	Pulpwood (from mill residue)	26.4%
Veneer logs	0.9%	Composite panels (from mill residue)	3.1%
Pulpwood	19.7%	Bioenergy (from mill residue)	11.2%
Composite panels	2.9%	Unused mill residue	4.2%
Posts, poles, pilings	0.3%	Fuel (from exported roundwood)	0.7%
Other industrial uses	0.4%	Paper (from exported roundwood)	0.2%
		Wood (from exported roundwood)	0.4%

Product half-lives

Domestic use			
Softwood lumber	47.2 years	Posts, poles, pilings	30 years
Hardwood lumber	22.9 years	Other industrial uses	30 years
Composite panels	27 years	Bioenergy	0 years
Pulp	3 years		

International use			
Wood	30 years	Fuel	0 years
Paper	2 years		

Product retirement

Sawlogs	67.2% landfill 15.7% energy recovery 17.1% recycled	Pulp	25.6% landfill 6.7% energy recovery 68.2% recycled
Veneer logs	100% landfill	Composite panels	100% landfill
Composite panels	100% landfill	Other industrial uses	100% landfill

Landfills

Decomposable materials	50%	Methane generation rate k	Paper: 0.06 m³/yr Wood: 0.03 m³/yr
Landfilled product half-lives	Paper: 12 years Wood: 23 years		

be concurrently implemented on the landscape – to visualize the cumulative potential of Pennsylvania's forests to provide climate mitigation benefits.

Various scenarios reference targets from Maryland's Greenhouse Gas Emissions Reduction Act (Maryland Department of the Environment 2021), a state law first passed in 2009 and updated in 2016 that sets a goal of 50% emissions reductions by 2030 for Maryland. Since Pennsylvania did not, at the time of our analysis, have a comparable policy or emissions reduction targets for forestry, we scaled up

Table 3. Scenario parameters for Pennsylvania. All carbon measurements are in metric tons (t C). Scenarios marked with * are included in the Portfolio scenario.

Forest management scenarios

Changes in rotation length

Scenario name	Objective	Parameter to change	Parameter value change	Scenario impact
Altered Rotations*	Increase average harvest age of hardwood stands	Minimum age of allowable harvest	+30 years on all hardwoods to 2170	Hardwood rotations: 70-80 years→100-110 years
	Decrease average harvest age of aspen stands for wildlife habitat		-10 years on aspen to 2170	Aspen rotations: 40 years→30 years

Tree planting

Scenario name	Objective	Parameter to change	Parameter value change	Scenario impact
Afforestation GGRA 2030	Increase afforestation, following GGRA targets, to 2030	Annual afforestation rate	+2,376 acres/year to 2030; then return to BAU rate	+23,760 acres afforested
Afforestation GGRA 2050*	Increase afforestation, following GGRA targets, to 2050	Annual afforestation rate	+2,376 acres/year to 2050; then return to BAU rate	+70,280 acres afforested
Afforestation Scale Up 2030	Increase afforestation, scaled up 10x GGRA targets, to 2030	Annual afforestation rate	+23,760 acres/year to 2030; then return to BAU rate	+237,600 acres afforested
Afforestation Scale Up 2050	Increase afforestation, scaled up 10x GGRA targets, to 2050	Annual afforestation rate	+23,760 acres/year to 2050; then return to BAU rate	+712,800 acres afforested
Silvopasture*	Increase silvopasture adoption (low-density planting of trees in pastureland; does not remove land from productive pasture use)	Annual silvopasture planting rate	+15,250 acres/year (0.5% of eligible acreage) to 2170	+2,287,500 acres in silvopasture system

Maintaining forest health and regeneration

Scenario name	Objective	Parameter to change	Parameter value change	Scenario impact
Restocking*	Increase supplemental planting to restocking understocked stands	Annual supplemental planting rate	+4,508 acres/year to 2170	+626,200 acres restocked
Timber Stand Improvements*	Increase TSI and wildlife habitat treatments, following GGRA targets	Annual thinning rate	+14,892 acres/year to 2170	+2,223,800 acres thinned
		Annual prescribed fire (Rx fire) rate	+25,000 acres/year to 2170	+3,750,000 acres treated with Rx fire
Reduced Deforestation*	Decrease rate of permanent forest loss (deforestation), following GGRA targets	Annual deforestation rate	-5,149 acres/year to 2170	+772,450 acres conserved
Reduced Diameter Limit Cuts*	Eliminate diameter limit cutting (DLC, i.e., high grading) on private lands; transition to sustainable selective harvests (modeled as seed tree cuts)	Annual DLC removals	-30,559 t C/year (15% of DLC in BAU) until DLC=0 in 2027; DLC removals remain at 0 to 2170	203,833 t C/year (27,960,055 cu ft/year) transitioned to sustainable selective harvests
		Annual seed tree removals	+30,559 t C/year until 2027 (transitioning removals from DLC to seed tree cut); seed tree removals remain at 485,078 t C/year to 2170	
Control Deer Browse*	Increase rates of successful deer browse control (i.e., fencing) to encourage better natural regeneration	Annual deer browse control rate	+14,459 acres/year to 2170	+1,985,496 acres controlled

Climate change

Scenario name	Objective	Parameter to change	Parameter value change	Scenario impact
Climate Change Growth	Project impacts of climate change on future forest growth	Annual growth rate	+0.3% average increase in growth (ranges by forest type, 0.05-0.6%) to 2170	-

Climate change, cont.

Scenario name	Objective	Parameter to change	Parameter value change	Scenario impact
Climate Change Disturbance	Project impacts of climate change on future natural disturbances	Annual disturbance rate (applies to natural disturbances in **Table 1**)	+10% acres/year to 2170	–
		Annual disturbance severity	+10% severity/year to 2170	

No harvest activities

Scenario name	Objective	Parameter to change	Parameter value change	Scenario impact
No Harvest	Reduce all harvest and thinning activities on all lands	Annual harvest rate	-100% acres/year to 2170	-100% acres/year of harvesting and thinning management practices
		Annual thinning rate	-100% acres/year to 2170	
		Annual DLC rate	-100% acres/year to 2170	

Wood utilization scenarios

Scenario name	Objective	Parameter to change	Parameter value change	Scenario impact
Bioenergy 1	Diversion of mill residues from pulpwood (from mill residues) to bioenergy	Proportion of mill residues used for pulpwood	-10% of pulpwood (from mill residues) diverted to pulpwood	Softwood mill residues to pulpwood: 46.2%→41.6%
				Hardwood mill residues to pulpwood: 58.7%→52.9%
		Proportion of mill residues used for bioenergy	+10% of pulpwood (from mill residues) diverted to bioenergy	Softwood mill residues to bioenergy: 32.0%→36.6%
				Hardwood mill residues to bioenergy: 24.9%→30.7%
Bioenergy 2	Diversion of all mill residues from pulpwood to bioenergy	Proportion of mill residues used for pulpwood	-10% of all mill residues diverted to pulpwood	Softwood mill residues to pulpwood: 46.2%→36.2%
				Hardwood mill residues to pulpwood: 58.7%→48.7%
		Proportion of mill residues used for bioenergy	+10% of all mill residues diverted to bioenergy	Softwood mill residues to bioenergy: 32.0%→42.0%
				Hardwood mill residues to bioenergy: 24.9%→34.9%

Portfolio scenario

Scenario name	Objective	Parameter to change	Parameter value change	Scenario impact
Portfolio	Ensemble of concurrent scenarios (marked with * above) to illustrate potential for Pennsylvania to fully leverage its forests as a natural climate solution	Minimum age of allowable harvest	+30 years on all hardwoods to 2170	Hardwood rotations: 70-80 years→100-110 years
			-10 years on aspen to 2170	Aspen rotations: 40 years→30 years
		Annual afforestation rate	+2,376 acres/year to 2050; then return to BAU rate	+70,280 acres afforested
		Annual silvopasture planting rate	+15,250 acres/year (0.5% of eligible acreage) until 2170	+2,287,500 acres in silvopasture system
		Annual supplemental planting rate	+4,508 acres/year to 2170	+626,200 acres restocked
		Annual thinning rate	+14,892 acres/year to 2170	+2,223,800 acres thinned
		Annual prescribed fire rate	+25,000 acres/year to 2170	+3,750,000 acres treated with prescribed fire
		Annual deforestation rate	-5,149 acres/year to 2170	+772,450 acres conserved
		Annual DLC removals	-30,559 t C/year (15% of DLC in BAU) until DLC=0 in 2027; DLC removals remain at 0 to 2170	203,833 t C/year (27,960,055 cu ft/year) transitioned to sustainable selective harvests
		Annual seed tree removals	+30,559 t C/year until 2027 (transitioning removals from DLC to seed tree cut); seed tree removals remain at 485,078 t C/year to 2170	
		Annual deer browse control rate	+14,459 acres/year to 2170	+1,985,496 acres controlled

GGRA targets proportionally to Pennsylvania's forest area and developed these scenarios to help state agency staff scope potential practices for influencing carbon in the forest and forest products sector. In keeping with the IPCC special report on global warming of 1.5 °C (IPCC 2018) and US federal emissions targets (The White House 2021) – both of which call for net-zero emissions by 2050 – some scenarios have also been extended to 2050 to represent sustained action towards these national and global goals.

Once modeled, all scenarios are compared and evaluated for their alignment with CSF principles. Climate-smart scenarios can be compiled to identify a target path for Pennsylvania reflecting the state's priorities for forest management and climate action.

Results and Discussion

Results of our analysis show that both the forest ecosystem and the forest products sector currently provide climate mitigation benefits in Pennsylvania, though the forest ecosystem is projected to transition from net carbon sink to net carbon source under future BAU management. Certain management approaches have the potential to slow or even reverse this trend to maintain Pennsylvania's forest carbon sink and its climate mitigation potential. As discussed in the **Forest Carbon Science** section above, this mitigation potential can be influenced by both carbon sequestration and carbon storage dynamics across the landscape, and climate-smart practices strive to balance both factors. Our results indicate that favoring one of these attributes over the other comes with important tradeoffs that can significantly impact future forest health, resilience, and climate mitigation potential.

Business-as-Usual Results

In the BAU scenario, Pennsylvania's forests remain a net carbon sink until 2025 and become a net carbon source with a declining rate of change through 2100, as represented by net ecosystem sequestration (**Figure 4**). *Net ecosystem sequestration* here refers to the net yearly sequestration of carbon by forests after accounting for decomposition and wood product removals. Ecosystem carbon stocks also decrease by 11.5% from 2020 to 2100 (**Figure 4**), indicating that declines in both carbon sequestration and storage contribute to the transition from net carbon sink to source under BAU.

The supply of wood to HWP remains relatively constant to 2100, assuming a static future HWP demand (**Figure 4**). Carbon stocks in HWP subsequently increase steadily over time in various products and
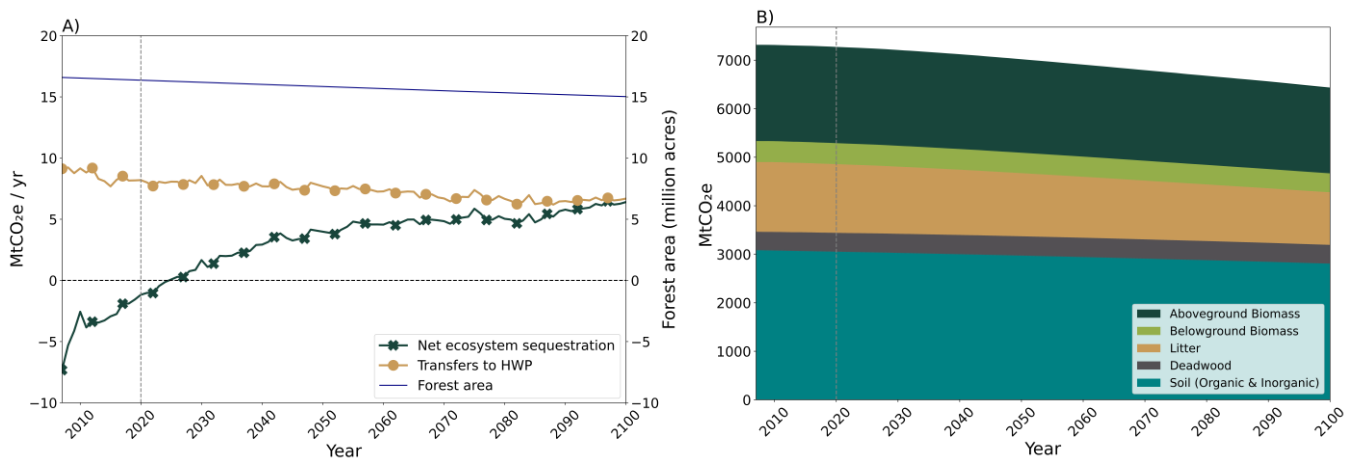

Figure 4. BAU scenario results showing A) annual net ecosystem sequestration and transfers to HWP (both in MtCO₂e/yr), forest area (million acres) and B) carbon stocks (MtCO₂e) in IPCC reporting pools from 2007-2100. Net ecosystem sequestration refers to the net yearly sequestration of carbon by forests after accounting for decomposition and wood product removals. Negative numbers for net ecosystem sequestration in Panel A) represent a net carbon sink, and positive numbers for transfers to HWP in Panel A) and positive numbers in Panel B) represent accruing carbon stocks.

more than double by 2100 (**Figure 5**). This transfer of carbon from the forest to the forest products sector outweighs emissions from current wood products in use and inherited products (those produced prior to simulation start in 2007 and either still in use or in landfills), making HWP a growing carbon storage pool for Pennsylvania (**Figure 5**).
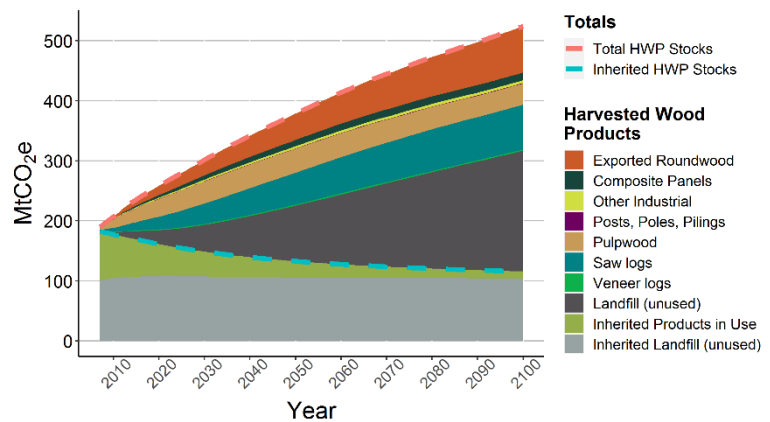
Forest area in Pennsylvania declines with time in the BAU scenario, dropping 7% from 16.2 million acres in 2020 to 15 million acres in 2100

Figure 5. BAU scenario HWP carbon stocks (MtCO₂e), 2007-2100. Positive numbers denote accruing carbon stocks.

(**Figure 4**). This trend is largely driven by projected land-use change rates comprised of 25,829 acres of mature forest loss coupled with an 8,535-acre gain of new forest, leading to a net average 17,294 acres of forest loss per year (**Table 1**). This decrease in forest area, especially the loss of typically carbon-dense mature forest acres, has a strong influence on both carbon sequestration and storage dynamics (Hansis et al. 2015; Williams et al. 2021): when forestland is cleared, some carbon stocks in existing trees are transferred to HWP or emitted over time through decomposition, and future carbon sequestration from the growth of those trees is lost. Through its influence on declining carbon sequestration and storage capacities as noted above, this trend of forest loss significantly affects the transition from net forest carbon sink to source under BAU.

70% of forestland in Pennsylvania is currently between 60 and 120 years old, distributed among 16 forest type groups (**Table 4**, **Figure 6**). This pattern is due to the land use legacy of the Northern US where a majority of forest was harvested over a century ago, and some land not later used for agriculture or development was allowed to regenerate back to forest naturally. Combined with relatively low rates of stand-replacing disturbances (like timber harvests or wildfires) in Northern forests over the last 50-60 years, most forestland in Pennsylvania was established between these two time periods. (Shifley et al. 2012)

This amount of mature forest is higher than the rest-of-US proportion of 40.4% for these forest type groups, leaving Pennsylvania with a lower share of young and old forests (<10 years old and >120 years old, respectively, per Shifley and Thompson 2011) of these types compared to the rest of the country (**Table 4**). This age class distribution reflects a relative lack of diversity across the state compared with a more even age distribution, limiting wildlife habitat for young- and old-forest dependent species, limiting the provision of certain timber products from younger trees, and limiting the carbon sequestration and storage capabilities of forestland (Shifley et al. 2012; Shifley and Thompson 2011). The small amount of young forest in particular reflects the concerns about natural regeneration and the need for age class redistribution noted in the **Identifying Forest Management Priorities** section.

To maintain or improve age diversity across the landscape, a stated priority for our state partners, forest management practices will need to both allow for aging into the old forest (>120 years old) category and establishment of additional areas of young forest (<10 years old). This process can take many years to realize notable changes in the age distribution of the forest at a regional scale (Shifley and Thompson 2011). By 2100, the age class distribution under BAU has shifted substantially, with 66% of the landscape in the old forest category, 16% between 60-120 years old, and just 6% in the 0-20 year age class (**Figure 6**). The large shift of forestland out of the 60-120 year age classes and into older age classes

may affect timber supply, especially in key HWP producing forest types like oak/hickory since these hardwood forests are most often harvested at 70-80 years old (**Table 3**). However, this modeled age class distribution is influenced by the harvest conditions of the model, which adhere to minimum and/or maximum harvest ages determined by forest type. Forest managers would have more flexibility in their harvesting decisions than our model can capture and could reasonably make management decisions to sustain their HWP supply more than is indicated by these results.

Table 4. Age class distribution of forest type groups from Figure 6, Pennsylvania compared to rest of the United States, 2020. Data from FIA.

Age Class (years)	Percent of Forestland	
	Pennsylvania	Rest of US
0-20	4.2	19.1
21-40	7.5	16.1
41-60	15.8	17.5
61-80	24.4	21.4
81-100	31.0	13.8
101-120	14.7	5.2
121-140	2.0	2.3
141-160	0.3	1.3
161-180	0.03	0.8
181-200	–	0.6
200+	0.01	1.7
Unknown	0.2	0.1

Meanwhile, the severe projected dearth of young forests under BAU supports state partners' expressed concerns about a lack of natural regeneration across the landscape. This may be in some way related to the potential drop in timber supply (and implicit drop in timber harvests) mentioned above – if timber harvests are not occurring as the forest grows beyond typical harvest ages, there will be few opportunities for young forest to appear through natural regeneration or reforestation to replace harvested stands. Deer browse also presents a significant natural regeneration challenge – surveys of FIA plots in Pennsylvania indicate that 83% of plots show evidence of medium or heavy deer browse (Albright et al. 2017). These results highlight the opportunity for climate-smart management practices to help establish additional young forest area in an effort to rebalance the age-class distribution of forests in Pennsylvania.

Figure 6. BAU scenario age class distribution by forest type group in A) 2020 and B) 2100.

Alternative Management Scenario Results

Annual Mitigation Potential in Forests and the Forest Products Sector

Under all scenarios modeled in this analysis, Pennsylvania forests and forest products become a yearly
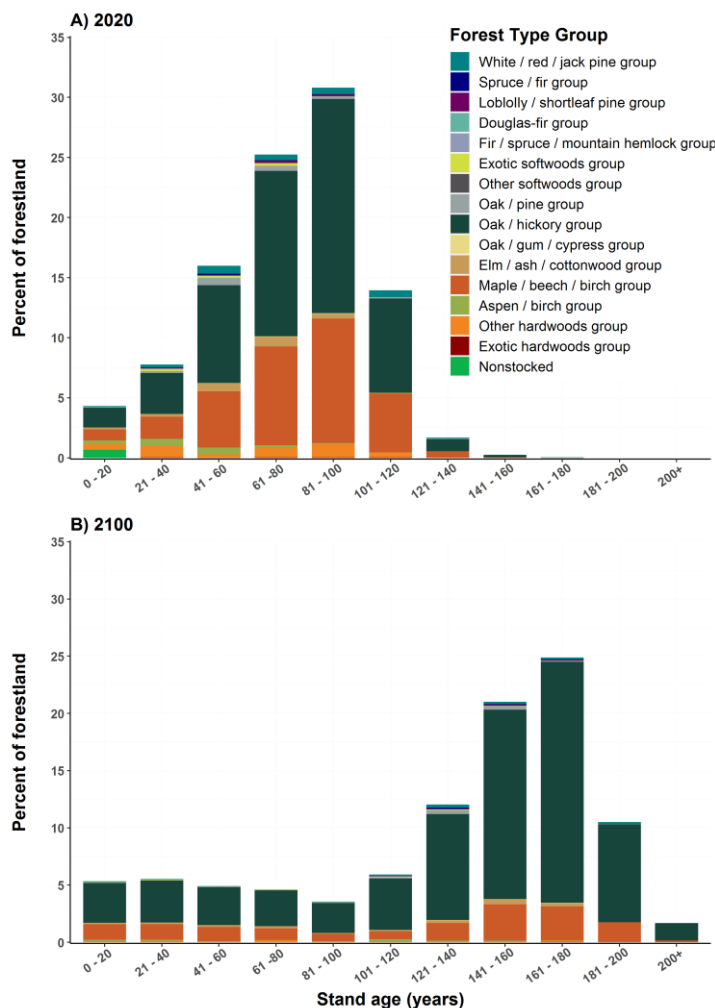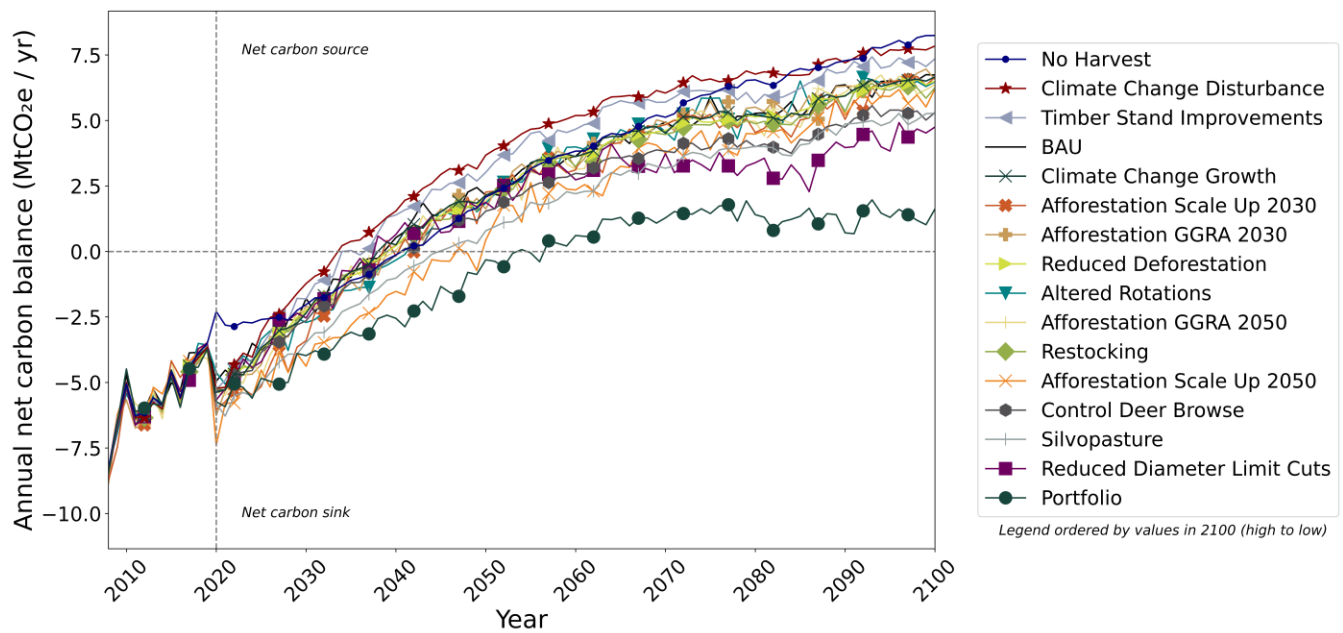
Figure 7. *Annual net carbon balance for all scenarios, 2007-2100. Net carbon balance includes net ecosystem sequestration in the forest, transfers to HWP, emissions from wood products in use and in landfills, substitution benefits in years where harvest is different than BAU, and leakage in years where harvest is less than BAU. Negative values denote carbon sequestration (a net carbon sink). Positive values denote carbon emissions (a net carbon source).*

net carbon source by 2057, indicated by an annual net carbon balance above zero (**Figure 7**). *Net carbon balance* here includes net ecosystem sequestration in the forest, transfers to HWP, emissions from wood products in use and in landfills, substitution benefits (which can be positive or negative) in years where harvest is different than BAU, and leakage in years where harvest is less than BAU. This is presented from the atmospheric perspective, where negative values indicate CO_2 sequestered from the atmosphere and captured as carbon in forests and wood products.

In the *Climate Change Disturbance* scenario, increased emissions from stronger and more frequent natural disturbances tip the scales to make forests a net carbon source by 2034 with a continuation of current (BAU) management practices (**Figure 7**). In the *No Harvest* scenario, harvesting levels are consistently lower than BAU (assuming constant future HWP demand), so negative substitution benefits and an increase in leakage drive forests and the forest sector to become a net carbon source by 2041 (**Figure 7**). Increased emissions from thinning and prescribed fire in the *Timber Stand Improvements* scenario outweigh the additional growth in the remaining trees as result of these treatments, leading to a net carbon source from forests and the forest sector in 2035 (**Figure 7**). Encouragingly, the remaining management scenarios considered in this analysis perform better than BAU, presenting viable climate-smart management practices in Pennsylvania despite a variably declining carbon sink. Several scenarios help to minimize this decline in the future, a capacity that may be increasingly important given the potential for climate-induced carbon losses indicated by the *Climate Change Disturbance* scenario.

The *Portfolio* scenario presents the best opportunity for minimizing this forest carbon sink decline, with an annual net carbon balance averaging 38% stronger than BAU by 2030, 233% stronger by 2050 and 124% stronger by 2100 (**Figure 7**). These values help keep the annual net carbon sink at 80% of its current capacity in 2030 and 6% of its current capacity in 2050 – still exhibiting a declining forest carbon sink but to a lesser degree than under BAU, which reaches 6% of current sink capacity in 2037.

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The *Portfolio* scenario also counteracts the forest loss trend exhibited under the BAU scenario, with a forest area of 16.4 million acres in 2030 and 16.7 million acres in 2100 (**Figure 8**). The *Silvopasture, Reduced Deforestation*, and *Afforestation Scale Up 2030* and *2050* scenarios also reduce the rate of forest loss relative to BAU, though not enough to keep forest area steady through the end of the century (**Figure 8**). For the *Silvopasture* and *Afforestation Scale Up 2050* scenarios, minimizing forest loss leads to better annual net carbon balances than most other scenarios and BAU (**Figure 7**).
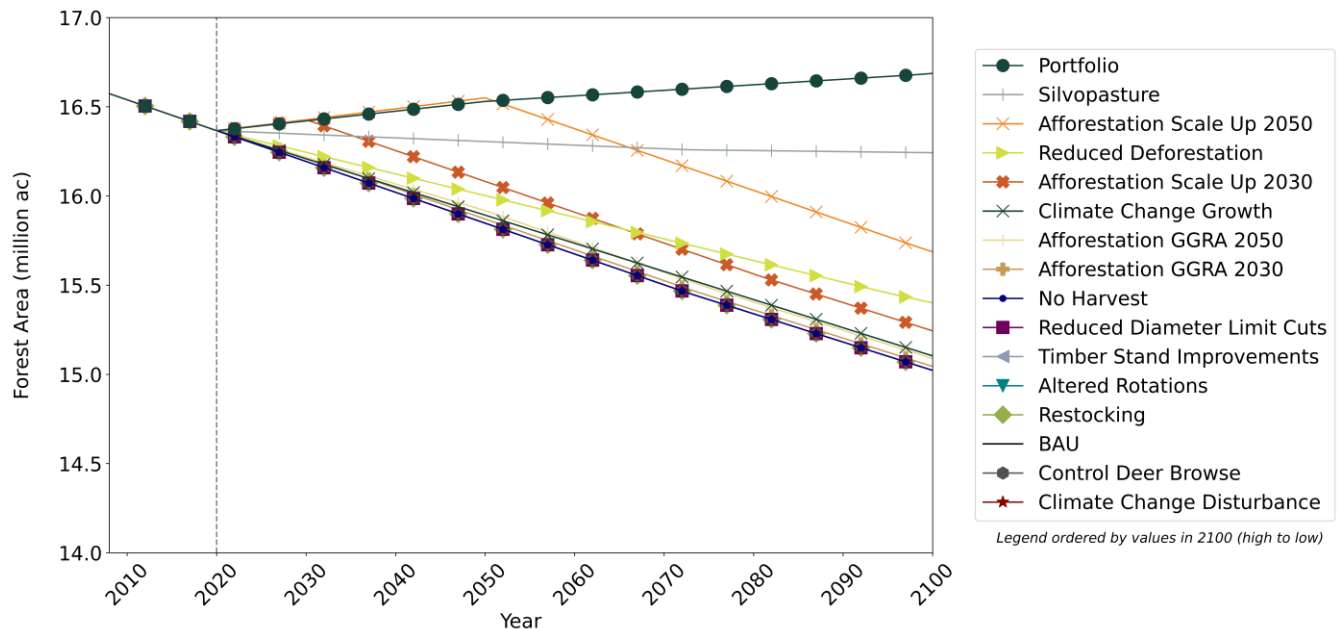

Figure 8. Total forest area by scenario, 2007-2100.

To better illustrate the differential impact of each scenario when compared to BAU, further results will be discussed in *standardized* terms, where BAU values are subtracted from each scenario (essentially setting BAU to 0). This allows for a more direct assessment of the relative strengths of each alternative management practice when compared to current conditions and will highlight the most promising climate-smart approaches for Pennsylvania's future forest management and climate action goals.

Cumulative Mitigation Potential in Forests and the Forest Products Sector

When considering carbon fluxes in forests and forest products and changes in carbon fluxes due to product substitution and leakage, most scenarios result in additional cumulative carbon sequestration and storage compared to BAU (**Figure 9**). *Cumulative carbon sequestration and storage* in this case is calculated as the sum of the annual net carbon balance values in **Figure 7**, standardized to BAU as described above.

By 2100, the *Climate Change Disturbance* scenario sequesters and stores over 97 million tons of carbon dioxide equivalent (MtCO₂e) less than BAU, while the *Portfolio* scenario sequesters and stores -265 MtCO₂e more than BAU over this time frame (**Figure 9**). This range illustrates the potential spread of carbon outcomes for Pennsylvania's forests, depending on future management decisions and climate impacts. The *Portfolio* scenario also demonstrates the potential additional climate benefits from implementing a wide range of concurrent climate-smart forest management practices in Pennsylvania. Only two other scenarios capture and store less carbon than BAU: the *Timber Stand Improvements* scenario (63 MtCO₂e less than BAU by 2100) and the *No Harvest* scenario (45 MtCO₂e less than BAU by 2100) (**Figure 9**). The remaining scenarios modeled range from an additional -4 to -114 MtCO₂e

carbon sequestered and stored relative to BAU by 2100, indicating more modest impacts of these scenarios when implemented alone (**Figure 9**).

We can further examine the components of cumulative carbon sequestration and storage for each scenario to understand the relative impacts of each scenario on the forest ecosystem itself and on the forest products sector. For example, the *No Harvest* scenario accumulates the largest amount of additional carbon in the forest ecosystem relative to BAU each year, but also suffers from the highest rates of foregone HWP production, accompanied by high leakage and negative substitution benefits. The combination of these factors leads the *No Harvest* scenario to sequester and store less carbon than BAU in each year of the simulation. This difference amounts to +14.79 MtCO₂e, +5.6 MtCO₂e, and +44.65 MtCO₂e less carbon sequestered and stored in 2030, 2050, and 2100, respectively (**Figure 10**). Other scenarios affecting harvest levels exhibit similar tradeoffs between ecosystem and HWP carbon, though to a smaller degree. The *Altered Rotations* scenario gains carbon in the forest ecosystem and reduces carbon in HWP relative to BAU, accompanied by modest leakage and negative substitution benefits. Overall, this scenario sequesters and stores an additional -0.14 MtCO₂e carbon relative to BAU by 2030, -12.02 MtCO₂e by 2050, and -9.96 MtCO₂e by 2100 (**Figure 10**).
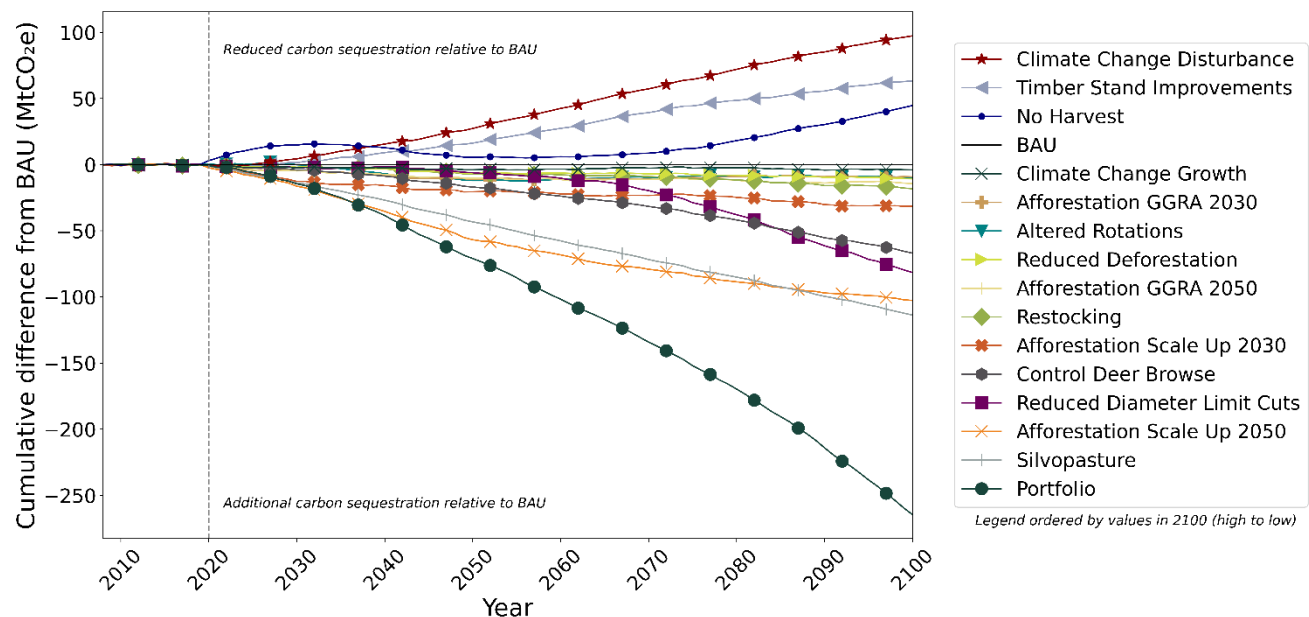

Figure 9. Cumulative carbon balance (MtCO₂e) standardized to BAU for both the forest ecosystem and forest products sector, including leakage and substitution benefits. Negative values denote additional carbon sequestration and storage compared to the BAU scenario. Positive values denote reduced carbon sequestration and storage compared to the BAU scenario.

Tree planting scenarios have the largest benefits for forest ecosystem carbon and especially soil carbon, which is not unexpected given the net increase in forested area under each scenario (Nave et al. 2019). The total increase in forest area ranges from 23,760 acres by 2030 for the *Afforestation GGRA 2030* scenario, which relies on tree planting on currently inactive land, and 2,287,500 acres by 2170 for the *Silvopasture* scenario, which relies on the integration of low-density tree cover on land that remains active pasture. The resultant carbon sequestration and storage impacts, including slight additional benefits from HWP production and substitution, range from -4.75 to -13.88 MtCO₂e by 2030, -11.21 to -43.28 MtCO₂e by 2050, and -9.27 to -113.73 MtCO₂e by 2100 for these scenarios, respectively (**Figure 10**).

Scenarios focused on forest health and regeneration have a range of largely modest carbon impacts compared to other scenarios when implemented alone, with all but the *Timber Stand Improvements* scenario managing to capture and store additional carbon relative to BAU each year. The *Timber Stand Improvements* scenario includes additional thinning and prescribed fire treatments, so the decrease in carbon relative to BAU is not unexpected. Additional thinning means a decrease in forest carbon stocks compared with BAU and additional material in pulpwood products, but the typical increases in growth rates following thinning and additional HWP stocks and substitution benefits do not outweigh the increase in carbon emissions from larger annual prescribed burn areas. This represents a necessary cost of business for the forest health benefits (that could result in greater carbon stability) and wildlife habitat co-benefits gained from these management activities. Of the remaining scenarios in this category, the *Control Deer Browse* and *Reduce Diameter Limit Cuts* scenarios are the most compelling climate-smart options. Both scenarios assume improved natural regeneration and forest health, and sequester and store an additional -4.13 to -2.47 $MtCO_2e$ by 2030, -16.96 to -6.1 $MtCO_2e$ by 2050, and -66.91 to -81.56 $MtCO_2e$ by 2100, respectively (**Figure 10**). Both scenarios also provide modest gains in HWP supply and subsequent substitution benefits, growing substantially between 2050 and 2100 in the *Reduce Diameter Limit Cuts* scenario. This scenario aims to improve health and vigor particularly in hardwood forests, which are typically harvested around 70-80 years of age (**Table 3**) – so the increase in wood products around 2100 from this scenario represents the first payoff from the DLC reductions implemented in 2020-2030. Finally, the *Control Deer Browse* scenario represents an earlier (within the first 25 years of growth) and more successful intervention (from a carbon perspective) to foster natural regeneration than the *Restocking* scenario, which occurs on maturing stands (25-70 years old). This contrast points to the importance of early and sustained action to enhance natural regeneration, rather than replacing it as the forest matures, for better climate mitigation benefits.

Other scenarios focused on wood utilization and substitution benefits – the *Bioenergy 1* and *Bioenergy 2* scenarios – have negligible impacts on carbon balance relative to BAU. These scenarios are constructed only to analyze additional use of mill residues for bioenergy, and not additional harvesting or use of other primary products. The pool of mill residues in Pennsylvania is relatively small, and most residues already go into uses with quick emissions back to the atmosphere (**Figure 3**). The tradeoff of quicker emissions from bioenergy than from pulpwood (0-year vs 3-year half-life, respectively) and small substitution benefits from bioenergy through 2045 leads to a difference from BAU of less than +/-0.2 $MtCO_2e$ sequestered and stored each year (**Figure 10**).

The *Climate Change Growth* and *Climate Change Disturbance* scenarios have variable impacts on forest ecosystem carbon relative to BAU. The *Climate Change Growth* scenario, based on literature data showing an average 0.3% increase in productivity in Pennsylvania's forests due to climate change by 2100 (Duveneck et al. 2017; Wang et al. 2017; Matala et al. 2005), captures and stores an additional -2.5, -3.94, and -3.97 $MtCO_2e$ relative to BAU by 2030, 2050, and 2100, respectively (**Figure 10**). Meanwhile, the *Climate Change Disturbance* scenario represents a 10% increase in the frequency and severity of natural disturbances in Pennsylvania and yields a carbon sequestration and storage decrease of +4.3 $MtCO_2e$ by 2030, +27.3 $MtCO_2e$ by 2050, and +97.34 $MtCO_2e$ by 2100 relative to BAU.

Representing a concurrent suite of climate-smart forest management actions, the *Portfolio* scenario provides the best climate benefits of all scenarios modeled, sequestering and storing an additional -14.53 $MtCO_2e$ by 2030, -70.97 $MtCO_2e$ by 2050, and -264.61 $MtCO_2e$ by 2100 relative to BAU while supporting a sustainable timber supply (**Figure 10**). As noted in the **Annual Mitigation Potential in Forests and the Forest Products Sector** section above, this scenario presents the best opportunity for maintaining a forest carbon sink in Pennsylvania, highlighting the importance of ambitious state action on a wide range of forest management practices to minimize future carbon losses.
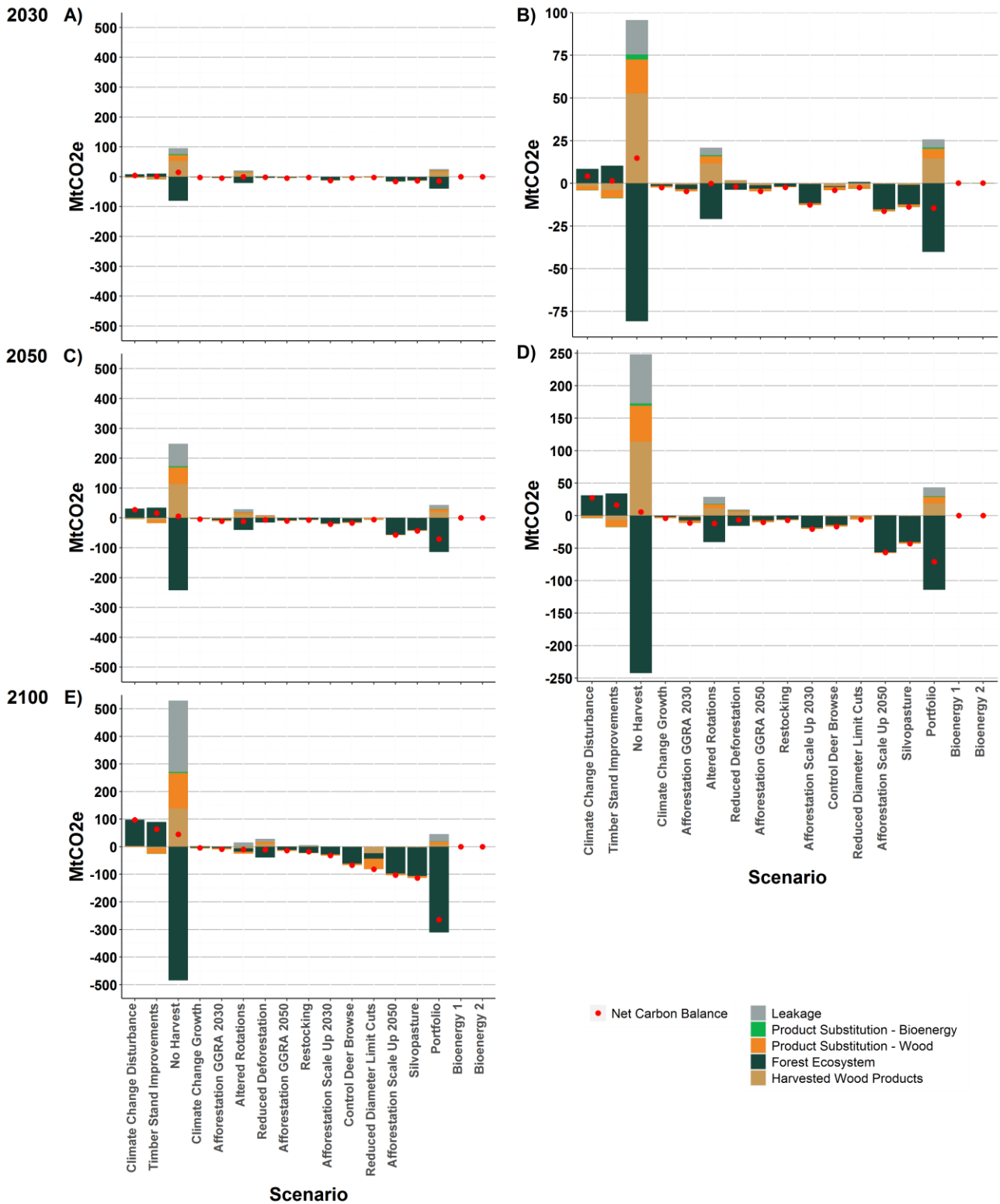
Figure 10. Snapshot of cumulative carbon flux (MtCO2e) standardized to BAU for both the forest ecosystem and forest products sector, including leakage and substitution benefits, in A-B) 2030, C-D) 2050, and E) 2100. Panels A), C), and E) share a common y axis scale, while Panels B) and D) are zoomed in versions of their annual counterparts. Red dots represent net carbon balance (the sum of all components) for each scenario. Negative values denote additional carbon sequestration and storage compared to the BAU scenario. Positive values denote reduced carbon sequestration and storage compared to the BAU scenario.

It is critical to note that these components of net carbon balance shift with changing assumptions about leakage, particularly for the proportions of substitution benefits realized by each scenario. Results in **Figure 10** use our 63.9% leakage assumption for years when harvest is lower than BAU, discussed in the **Harvested Wood Products Model** section. However, for different leakage assumptions we cannot simply subtract from or add to the leakage bar – leakage and substitution benefits interact with each other in a more complicated way. For example, if using a 0% leakage assumption, negative substitution benefits from decreased harvest are 200-300% higher than in **Figure 10**, and 50% lower under an 84.4% leakage assumption (data not shown). This occurs because a higher leakage rate assumes that a higher proportion of wood product demand in the state will be met by imported products, decreasing the need for other products to be used in place of wood. This dynamic assumes a static demand for wood products even with decreased in-state supply of HWP.

The Influence of Age Class on Mitigation Potential

Like with the BAU scenario, age class distribution plays an important role in determining the mitigation potential of each scenario modeled in this analysis. As discussed in the **Business-as-Usual Results** section, age class distribution under BAU shifts significantly over time, with 66% of the landscape in the old (>120 years old) forest category, 16% between 60-120 years old, and just 6% in the 0-20 year age class in 2100 (**Figure 6**). The average forest age subsequently changes from 79 to 125 from 2030-2100 (**Figure 11**).

Per-acre carbon storage and annual sequestration rate values – or *carbon stock density* and *carbon flux density* values, respectively – vary by age class, depending on the respective biomass volumes and growth rates exhibited by forests as they mature. These density values account for growth and decomposition in the forest ecosystem prior to harvest removals, therefore including the growth of wood that will later transfer to the HWP pool. At a stand or landscape scale, aging forests often exhibit slowing rates of growth and productivity, stemming from interacting competition and resource-use dynamics of individual trees (Binkley et al. 2002), leading to a declining forest carbon sink (Sleeter et al. 2018). In the BAU scenario, average carbon stock densities drop from 443.4 tCO_2e/ac in 2030 to 402.9 tCO_2e/ac in 2100, while average carbon flux densities decrease from -0.45 $tCO_2e/ac/yr$ in 2030 to -0.12 $tCO_2e/ac/yr$ in 2100 (**Figure 11**). Aggregated across the state, these trends lead to the diminishing net carbon sink over time shown in **Figure 4** and **Figure 7**.

A few scenarios deviate notably from this BAU trend. In the *No Harvest* scenario, average age increases from 81 to 148 from 2030-2100, with just 1% of forestland in the 0-20 year age class, 14% between 60-120 years old, and 83% in the >120 year age classes in 2100 (**Figure 11**). Though this scenario has allowed more mature forest to age into the old forest category, it comes at the cost of dwindling young and medium-aged forest representation on the landscape, a dynamic at odds with the balancing act needed to improve forest age diversity (Shifley and Thompson 2011). This trajectory also inherently prioritizes carbon storage over carbon sequestration, indicated by average carbon stock densities 0.8%-7.2% higher than BAU and carbon flux densities ranging from +26% higher to -199% lower than BAU from 2030-2100 (**Figure 11**).

By contrast, *Portfolio* scenario carbon stock densities change by -0.1% to +0.8% relative to BAU from 2030-2100, paired with an increase in carbon flux densities ranging from 27%-897% over BAU for the same time period (**Figure 11**). This initial drop in carbon stock densities is driven by modest forest area gains over this period, rather than the losses projected under BAU (+266,379 acres by 2100, or a 1.6% increase from current acreage; **Figure 8**). This forest gain, largely through tree planting activities, creates a larger proportion of younger forest on the landscape (22% of forest is less than 60 years old in 2100 in the *Portfolio* scenario, compared with 18% under BAU). These younger forests have higher carbon flux densities (**Figure 11**), which helps boost carbon flux density averages for this scenario. These
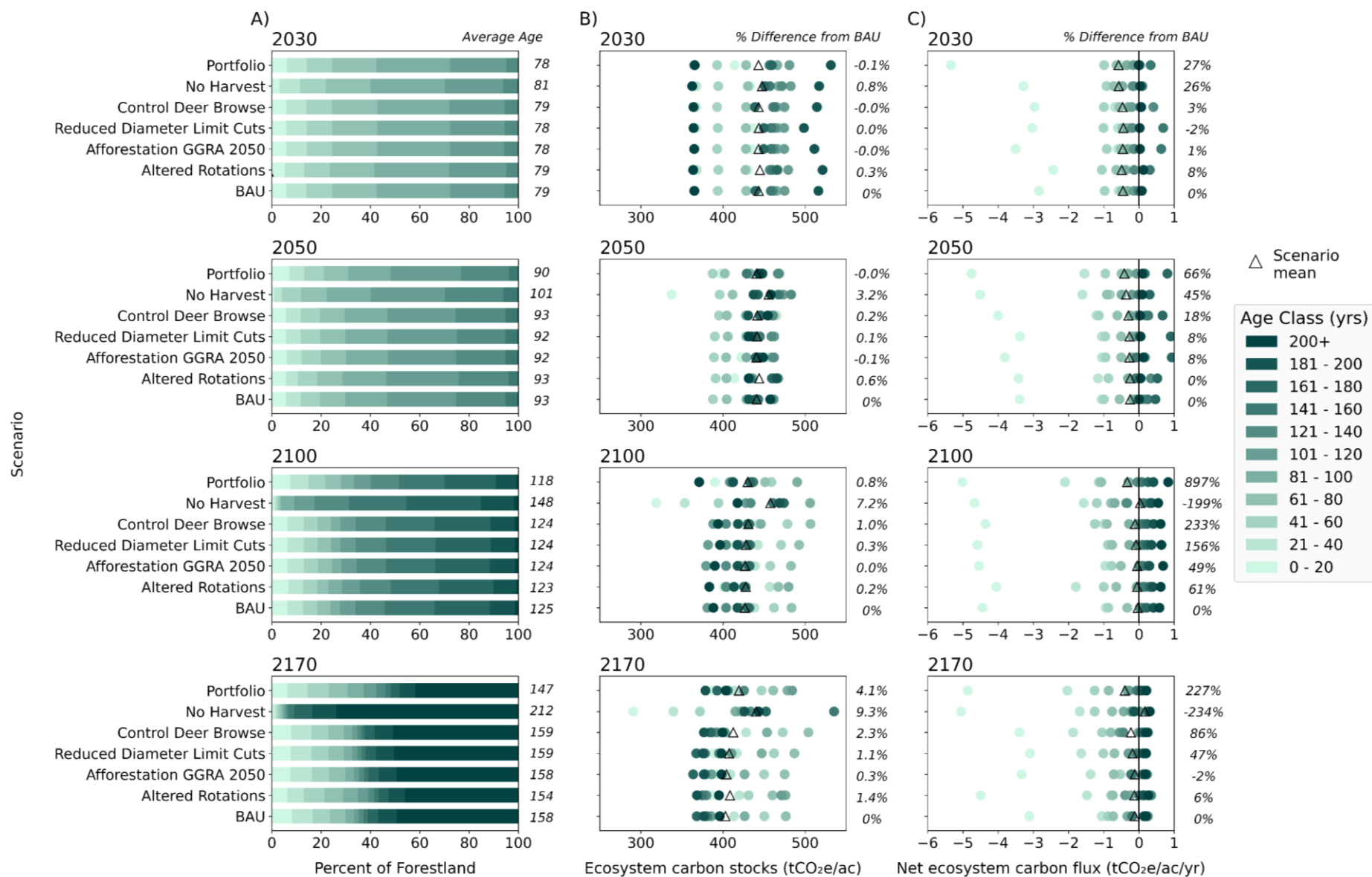
Figure 11. A) Age class distribution, B) carbon stock density (tCO₂e/ac), and C) carbon flux density (tCO₂e/ac/yr) for selected scenarios in 2030, 2050, 2100, and 2170. In Panel B), positive values denote accruing carbon stocks. In Panel C), negative values denote carbon sequestration and positive values denote carbon emissions.

dynamics lead to an average age ranging from 70-118 from 2030-2100, with 7% of forestland in the 0-20 year age class, 18% between 60-120 years old, and 60% in the >120 year age classes by 2100 (**Figure 11**).

Other promising climate-smart scenarios like *Altered Rotations, Afforestation GGRA 2050, Reduced Diameter Limit Cuts,* and *Control Deer Browse* (components of the *Portfolio* scenario and representative of the remaining forest management categories encompassed by our scenarios) have similar age class trends to BAU, with comparable average ages and age class distributions over time. Of this group, the *Altered Rotations* scenario generates the best early carbon storage gains relative to BAU by allowing trees to grow larger and store more carbon before harvest, ranging from 0.3% higher carbon stock density in 2030 to 0.6% higher in 2050 (**Figure 11**). Over a longer timeframe, the *Reduce Diameter Limit Cuts* scenario provides better carbon storage gains, with 0.3% higher carbon stock density over BAU in 2100 (**Figure 11**). The *Control Deer Browse* scenario provides the greatest increase in carbon sequestration by protecting natural regeneration and encouraging young forest growth, with carbon flux densities rising from 3%-233% over BAU from 2030-2100 (**Figure 11**). These differences demonstrate the additional potential of CSF management practices to increase forest carbon sequestration and storage in Pennsylvania even without altering current age class trajectories.

A final consideration for age class impacts on mitigation potential is the link to forest resilience. *Forest resilience* here refers to the capacity of a forest to respond to disturbance by withstanding permanent damage or change and recovering quickly (Ferrare et al. 2019). Larger trees are more susceptible to disturbance- or climate-driven mortality, and regeneration processes may become increasingly vulnerable to future climate conditions, especially following insect and disease disturbances (McDowell et al. 2020) which are expected to increase in Pennsylvania. Diversity of species composition and forest structure at a stand scale is key to facilitating ecosystem resilience (Ferrare et al. 2019; Seidl et al. 2016). Creating and maintaining a diversity of age classes at a landscape scale, already a priority for our state partners, can further support forest resilience to future disturbances. Forest age diversity, in turn, supports the resilience and stability of Pennsylvania's forest climate mitigation potential.

Limitations
The models and assumptions used in this analysis introduce a few key limitations:

1. The aspatial nature of the CBM-CFS3 means that scenarios do not provide information about the location of predicted carbon sequestration and storage over time. Our full classifier list does include a spatial reference (FIA survey units in Pennsylvania), which can be used to filter results to certain areas. However, the results in these spatial units are based on historical trends and not predictions of future management activities or natural disturbance. The aspatial nature of the model works in our favor in some cases: for long-range projections out to 2170, it would be nearly impossible to predict the location of all future events on the landscape, as would be required by a spatially explicit model. Instead, we are able to simulate general landscape trends and allow for some flexibility in where those trends occur, to reflect the flexibility in decision making held by forest managers.

2. The extended simulation timeframe, from 2020-2170, introduces increasing uncertainty as simulations move further into the future. Uncertainties may stem from factors like future forest management decisions, future policies, future market dynamics, or climate change. For example, despite inclusion of an overall increase in forest growth in the *Climate Change Growth* scenario, changes in forest growth will likely be dependent on individual species responses to changing climate conditions, which data specifically for Pennsylvania were not available. For this reason, most results here are reported only to 2100, though this 80-year period is not

without its own uncertainties. We have not conducted a sensitivity analysis for these scenarios, so our results here represent one set of possible outcomes. However, even with uncertainty around the quantified climate mitigation benefits presented in this report, we can reasonably have confidence in the trends and directionality indicated by these results.

3. The assumptions made in constructing each scenario represent one of many possible ways to implement each forest management practice. Where these assumptions are inaccurate for local conditions, actual climate mitigation results will vary. Our scenarios represent simplified versions of likely future dynamics intended to support forest management and policy decision makers in understanding the climate mitigation potential of forests in Pennsylvania. We do not make assumptions based on the feasibility of implementing each modeled management practice; rather, we focus on our state partners' objectives for forest management and land use and offer our assessment of the climate benefits of certain implementation levels. Each practice should be further examined for biophysical, political, and economic feasibility by land managers and decision makers in planning and policymaking processes.

Takeaways and Policy Opportunities

Forest ecosystems are an integral part of nature-based climate solutions (Griscom et al. 2017; Fargione et al. 2018), sequestering and storing carbon from the atmosphere each year while also supporting a vibrant bioeconomy through the provision of wood products (Skog 2008; Smyth et al. 2014; Lemprière et al. 2013). Results of this analysis indicate that several forest management practices represented by our scenarios have the potential for additional climate mitigation benefits beyond BAU in Pennsylvania, reducing the projected decline of the state's forest carbon sink. These practices generally follow CSF principles, balancing forest resilience, adaptation, and mitigation capacity with the continued supply of HWP and ecosystem services. Key factors for success in these scenarios include reducing forest loss, establishing a diverse age structure, and balancing carbon storage and sequestration rates across the landscape. Based on these criteria, climate-smart forest management strategies in Pennsylvania include (in no particular order):

- Maintain and increase forest area through *reducing deforestation, afforestation,* and s*ilvopasture.*

- Protect natural regeneration and foster age class diversity by *controlling deer browse* and *restocking understocked stands.*

- Encourage sustainable management practices on private lands, e.g., by *reducing diameter limit cuts.*

- Increase forest carbon stocks while sustaining timber supply by *extending rotations.*

- Prepare for potential negative impacts of *climate change*, especially from increasing pests and diseases.

When implemented concurrently across the landscape, these practices and others like *timber stand improvements* can help accomplish up to a 38% increase in Pennsylvania's forest carbon sink over BAU by 2030. This could help significantly on the state's path to 80% emissions reduction from 2005 levels by 2050, a goal recently established by the Pennsylvania Climate Action Plan 2021 (Pennsylvania Department of Environmental Protection 2021). The state may work to achieve these outcomes by adjusting management priorities and interventions on public lands and through education, incentives, and engagement with consulting forestry professionals to reach private actors.

While most of these climate-smart practices are familiar in Pennsylvania, *silvopasture* represents a substantial new opportunity for the state, both for its potential scale of climate benefits and the ability of silvopastoral systems to integrate with existing grazing operations (Nair 2014). This integration of trees into active pastureland helps farmers and ranchers diversify their income, reduces the potential for heat stress in livestock, and produces additional feedstock for pasture animals (Smith et al. 2022; Garrett et al. 2004). Adoption of silvopasture in the US has so far been limited and would likely require technical assistance for landowners to implement at scale. However, there are 3.47 million acres of pasture in Pennsylvania with the potential for tree planting (Cook-Patton et al. 2020), representing untapped potential as a climate mitigation strategy.

Wood products also comprise an important piece of the forest-climate puzzle. Certain wood product uses and demands are baked into our BAU scenario, so achieving BAU or other scenario results depends in part on steady future market conditions. Under these steady conditions, changes to harvesting (and therefore to in-state HWP supply) have notable carbon impacts, demonstrated by the negative substitution benefits and leakage in the *Extended Rotations* and *No Harvest* scenarios. Conversely, scenarios with increased wood utilization or available timber, such as the *Timber Stand Improvements, Reduced Diameter Limit Cuts,* or *Afforestation* scenarios, provide positive substitution benefits which help strengthen the overall forest carbon sink.

The eight practices listed above are considered climate-smart because they balance both carbon storage and sequestration rates with other important forest management goals – but not all scenarios modeled in this analysis find the same balance. The *No Harvest* scenario provides an example of the carbon outcomes from focusing primarily on ecosystem carbon storage, and our results do not show lasting climate mitigation benefits from this strategy. This carbon storage focus ignores three key factors: 1) carbon storage is only one of the ecosystem services forests provide, and it is possible for carbon stocks to reach a saturation point beyond which climate benefits diminish, 2) a climate mitigation approach that relies solely on long-term ecosystem carbon storage is exposed to risks of natural disturbance and climate change, and 3) to make the necessary progress in mitigating climate change, we must both maintain our current carbon stores and sequester as much additional carbon from the atmosphere as possible (Verkerk et al. 2020). While the *No Harvest* scenario does manage to store additional ecosystem carbon, carbon sequestration rates and HWP supply are severely diminished relative to BAU, posing constraints on the overall climate mitigation benefits of the scenario. Note this is largely dependent on the scale assumed by this scenario – a complete reduction in all harvest activities state-wide – and this approach could yield better climate outcomes when applied in more targeted areas. As is the case with climate-smart forestry, it's all about balance.

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Appendix

Modeling Methodology

This section describes our modeling methodology in more detail, including data inputs, assumptions, and calculation factors for both the forest ecosystem (CBM-CFS3) and harvested wood product (CBM-HWP-PA) models as well as scenario parameterization.

Forest Ecosystem Model Methodology

The forest ecosystem model (CBM-CFS3) requires 7 input tables for each scenario: 1) classifier list; 2) age class categories; 3) forest inventory; 4) volume-age curves, also called yield curves; 5) disturbance types; 6) disturbance event schedule; and 7) post-disturbance transition rules. Additionally, we used customized volume-to-biomass conversions and disturbance matrices using US-specific data rather than keep CBM-CFS3 defaults developed for Canada. Data and assumptions for each input table are described below. Models were run in Jupyter notebooks (Kluyver et al. 2016) using code provided by and adapted from the CBM-CFS3 Python GitHub repository (Morken et al. 2022; DeLyser and Papa 2022).

1. Classifier List

Classifiers are used to define relevant characteristics of the forest landscape (i.e., forest type, ownership, or stocking class) or reference spatial units within the study area (i.e., counties or ecoregions). These classifiers are used as categories in the forest inventory inputs and are used to develop specific volume-age curves so that growth and yield trends can be linked to appropriate inventory records during model runs. When running scenarios, classifiers can be used to direct management practices to certain categories (i.e., in this study, we distinguish between the management activities on private, federal, and state lands listed in **Table 1** using the OWNGRPCD classifier in Table S1). Classifiers also serve as filters for scenario results. We used 7 classifiers in this study (Table S1), most derived from FIA data (USDA Forest Service 2019) and one added as a custom code to tag forest undergoing a thinning treatment. Each unique combination of classifiers (e.g., STATE_UNIT 42_0 + OWNGRPCD 30 + ... + ALSTKCD 2, etc.) is used to structure the remaining model input tables, with input values required for each unique combination.

2. Age Class Categories

This input table defines the number of age classes and age class size (in years) for growth and yield data. Age classes can also be used in inventory, though they may be replaced with actual stand ages if available. For this analysis, we determined age class categories from FIA data (USDA Forest Service 2019) using 5-year age classes.

3. Forest Inventory

Forest inventory in the CBM-CFS3 is spatially referenced rather than spatially explicit, meaning that exact locations of inventory records are not known or tracked. Instead, inventory data are categorized using the classifiers mentioned above, and total area (in hectares) is estimated for each unique combination of classifiers. Additionally, the CBM-CFS3 requires information for each inventory record on UNFCCC land class (the default is 0, which represents forest), historic disturbance type (the most common disturbance type over the last 500+ years), and last disturbance type that created the current forest stand.

For this analysis, we used methodologies derived from Bechtold & Patterson (2005) and Pugh et al. (2018) to estimate each state's forest inventory from population estimates by pooling data from the most recent survey cycle (2014-2020). Doing so reduces estimate variation due to the pooling of panels

Table S1. List and descriptions of classifiers for Pennsylvania used in this study.

Classifier	Description	Values	
STATECD	FIA condition code to indicate state in which plots are located	42	Pennsylvania
STATE_UNIT	FIA condition code to identify FIA survey unit (groupings of counties within each state)	42_0	Pennsylvania: South Central
		42_5	Pennsylvania: Western
		42_6	Pennsylvania: North Central/Allegheny
		42_7	Pennsylvania: Southwestern
		42_8	Pennsylvania: Northeastern/Pocono
		42_9	Pennsylvania: Southeastern
OWNGRPCD	FIA condition code to delineate stand ownership	10	US Forest Service
		20	Other Federal
		30	State and Local Government
		40	Private and Native American
RESERVCD	FIA condition code to denote reserve status for public lands, where reserved land is permanently prohibited from being managed for wood products; however, logging may occur to meet other management objectives	0	Not reserved
		1	Reserved
TYPGRPCD	FIA reference code indicating forest type group	0	Nonforest
		100	White / red / jack pine group
		120	Spruce / fir group
		160	Loblolly / shortleaf pine group
		170	Other eastern softwoods group
		200	Douglas-fir group
		260	Fir / spruce / mountain hemlock group
		380	Exotic softwoods group
		390	Other softwoods group
		400	Oak / pine group
		500	Oak / hickory group
		600	Oak / gum / cypress group
		700	Elm / ash / cottonwood group
		800	Maple / beech / birch group
		900	Aspen / birch group
		960	Other hardwoods group
		990	Exotic hardwoods group
		999	Nonstocked
ALSTKCD	FIA condition code indicating stocking code for all live trees including seedlings	1	Overstocked (100+%)
		2	Fully stocked (60-99%)
		3	Medium Stocked (35-59%)
		4	Poorly Stocked (10-34%)
		5	Non-stocked (0-9%)
THIN	Binary code to denote whether a stand has undergone a thinning treatment to signal transition to post-thinning yield curve	0	Stand has not been previously thinned
		1	Stand has been previously thinned

across the survey cycle (Bechtold and Patterson 2005). We used the rFIA package (Stanke et al. 2020) in the R programming environment (R Core Team 2020) to run spatio-temporal queries on the FIA database and format data inputs. Historic disturbance and last disturbance data for each inventory record were derived from LANDFIRE (USGS 2016) and FIA (USDA Forest Service 2019), respectively.

4. *Volume-Age Curves and Volume-to-Biomass Conversions*

Volume-age curves, or yield curves, are used to determine carbon stocks and sequestration rates by age class for the study area in the CBM-CFS3. To estimate empirically derived yield curves, we utilized a Gompertz growth equation to model the relationship between merchantable volume (excluding bark, in cubic meters per hectare) and average stand age from FIA data (USDA Forest Service 2019). This growth model is a common exponential function used to estimate various forest attributes while not assuming symmetry within the curve unlike other logistic functions (Fekedulegn et al. 1999). The Gompertz growth curve takes the following form:

$$y(t) = \alpha \exp\left(-\beta \exp(-k^t)\right)$$

where α is the upper asymptote, β is the growth displacement, and k is the growth rate at time t. We derived yield curves for each unique combination of classifiers as data allowed (see Figure S1 for an example). For some rare forest type groups or stocking codes, we aggregated similar plots or expanded our spatio-temporal FIA queries using EPA Level II ecoregions to increase plot sample size sufficient for yield curve estimation.
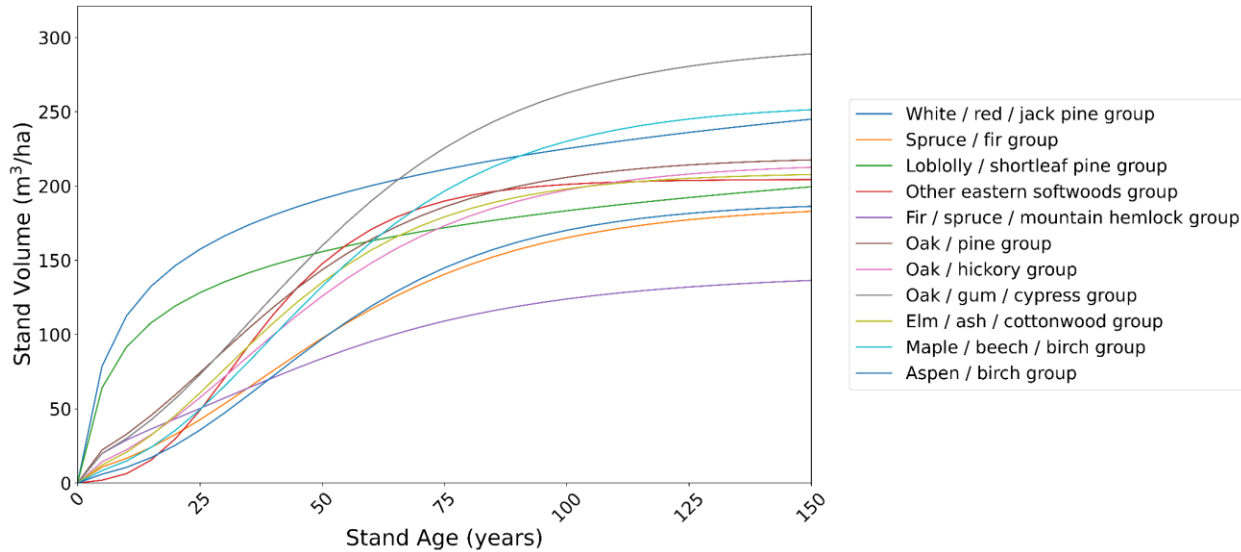

Figure S1. Example of empirically derived yield curves for forest type groups in Pennsylvania with full stocking (ALSTKCD=2).

Due to limitations of using stand age to estimate merchantable volume in uneven-aged stands following harvest events, we derived modified yield tables following Pilli et al. (2013), specifically focused on annual growth increments of uneven-aged systems following commercial thinnings conducted at an early stand age. This methodology outlines that following the removal of a specific proportion of merchantable volume, stand volume will continue to approach the same asymptote as unthinned stands, representing an anticipated bump in growth in response to the thinning. Using merchantable volume as a function of stand age, the rate of change k of the post-thinning yield curve can be modified using a basic exponential function to then reapproach the original asymptote α, based on the assumption that younger cohorts of trees move more quickly towards canopy dominance once patches are created through harvesting. Specific considerations and assumptions should be accounted for when deriving modified yield curves such that:

(a) Stand age is a product of selective removal of groupings of trees (i.e., partial cutting) of the dominant canopy dominant class.

(b) The removal of biomass allows for the faster accumulation of biomass from younger age cohorts becoming more canopy dominant in the stand.

(c) For simplicity, harvest age of tree cohorts is lumped into large age classes where, following the removal of biomass, the remaining tree cohorts accumulate biomass more quickly.

We created modified yield tables for growth following thinning treatments using an exponential function (Sit and Poulin-Costello 1994):

$$y = ab^t$$

where y is the percentage increase in merchantable volume for year t, a is the asymptote or maximum value for the y-axis, and b is a value between 0 to 1 that controls the rate of the curve as it approaches the asymptote on the x-axis. Modified yield curves were assigned to stands undergoing thinning treatments proportionally to the original area of each age class being treated.

Since these yield curves only consider merchantable volume, the CBM-CFS3 uses allometric equations to predict wood volume-to-biomass relationships during model runs to convert yield curves into carbon values. These volume-to-biomass relationships also account for the non-merchantable portions of trees (tops and limbs, stumps, bark, and foliage). The allometric equations are specific to forest type and environmental conditions, such that equations for Canadian species (used as defaults in the CBM-CFS3) are not applicable to similar species or forest types in Pennsylvania. We replaced existing default allometric equations for relevant forest types with recalibrated equations for Eastern US conditions, calculated by applying coefficients from Boudewyn et al. (2007) to volume and biomass values from FIA (USDA Forest Service 2019) following this equation:

$$b_m = a \times volume^b$$

where b_m is total biomass in metric tons per hectare, $volume$ is merchantable volume in cubic meters per hectare, and a and b are model coefficients calculated using Canadian forest inventory data. Using FIA inputs by forest type group for b_m and $volume$, we chose the best-fit coefficients from Boudewyn et al. to recalibrate allometric equations for each forest type group in Pennsylvania.

5. *Disturbance Types and Disturbance Matrices*
Once inventory and growth data have been determined, forest management, natural disturbance, and land-use change events (collectively termed *disturbances*) must be defined for use in the CBM-CFS3. We determined the list of disturbances for Pennsylvania using information provided by our state partners during our discussions Identifying Forest Management Priorities and by collecting historical data. See **Table 1** for the list of disturbances included in the BAU scenario, and **Table 3** for the list of disturbances included in the alternative management scenarios.

Forest management disturbances
In the forest management category, harvest removal data were from FIA (USDA Forest Service 2019) and prescribed fire data was provided by the Pennsylvania DCNR Bureau of Forestry. We estimated harvest removals from 2007-2019 (in terms of average annual removal of merchantable timber in cubic feet) per Bechtold and Patterson (2005) by forest type group, ownership, and age class. We then converted cubic volume to metric tons of carbon using methodologies and specific gravities reported by Smith et al. (2006) with the following equation:

$$C = \left(\left(volume \times SW_{proportion} \times SW_{sg}\right) + \left(volume \times HW_{proportion} \times HW_{sg}\right)\right) \times 0.5$$

where carbon (C) was calculated individually for both softwood (SW) and hardwood (HW) portions of the stand by multiplying harvest volume by the representative $SW_{proportion}$ and $HW_{proportion}$ and then by the respective specific gravity (sg) for each portion of the stand. A carbon fraction of 0.5 was then applied to convert from biomass to carbon.

This method of estimating total volumetric harvest removals does not allow for attribution to specific management practices (i.e., clearcut, shelterwood cut, commercial thinning, etc.) because the FIA database does not contain this information. To assign a harvest type and intensity to each record of volumetric removal, stand age at the time of removal was calculated by taking the mid-point average between time t_1 and t_2 (Bechtold and Patterson 2005) where t_1 is the year the unharvested stand was

measured (from the 2007-2013 survey cycle) and t_2 is the repeat interval measurement year post-harvest (from the 2014-2020 survey cycle). Stand age at the time of harvest can then be calculated by taking the time between t_1 and t_2 divided by 2 added to the stand age in t_1. These harvest ages from FIA data were binned into 20-year age classes to reduce uncertainty around stand age, especially for uneven-aged management systems. Then, we used information on typical management practices provided by our state partners and state-level management documents such as the 2016 State Forest Resource Management Plan (Pennsylvania Department of Conservation and Natural Resources 2016) to estimate the average age and harvest intensity (in terms of percent merchantable biomass removed) corresponding to each harvest type for each forest type group. Finally, we attributed volumetric removals from FIA for those age+forest type group combinations to a certain harvest type (Table S2)

Table S2. Harvest type and intensity by forest type group and average stand age in Pennsylvania. Harvest intensity refers to the proportion of merchantable biomass removed during harvest.

Harvest type	Average stand age at harvest	Harvest intensity
White / red / jack pine group		
Thinning	<70 years	30%
Clearcut	>80 years	85%
Oak / pine group		
Shelterwood cut	>40 years	50%
Oak / hickory group		
Thinning	<60 years	30%
Diameter limit cut	>80 years	70%
Seed tree cut	>80 years	70%
Shelterwood cut	>80 years	50%
Group cut/overstory removal	>100 years	30%
Elm / ash / cottonwood group		
Thinning	<80 years	30%
Shelterwood cut	>80 years	50%
Group cut	>100 years	30%
Maple / beech / birch group		
Thinning	<60 years	30%
Diameter limit cut	>80 years	70%
Seed tree cut	>80 years	70%
Shelterwood cut	>60 years	50%
Group cut/overstory removal	>100 years	30%
Aspen / birch group		
Thinning	<40 years	30%
Clearcut	<70 years	85%
Shelterwood cut	>80 years	50%

following harvest frequencies for Pennsylvania from Canham et al. (2013), whereby percent basal area (%BA) harvested from Canham et al. was mapped to harvest intensity from our state partners, and the corresponding percentage of plots for each %BA level from Canham et al. was used to apportion volumetric harvest removals from FIA for each harvest type.

Harvest intensity is modeled through *disturbance matrices* – tables that describe the movement of carbon between various ecosystem pools in response to a disturbance, including treatment of harvest residues and removals for HWP (see **Figure 1** for the carbon pools included in the CBM-CFS3). The CBM-CFS3 provides default disturbance matrices for over 200 disturbance types; following accuracy assessments with our state partners, we used defaults for all harvesting practices except for diameter limit cuts (DLC).

Attribution of DLC removals and determining DLC intensity required additional literature review, as our state partners and documents did not have immediate information about this practice. Since DLC occurs exclusively on private lands, we used survey data on private landowner behavior from Metcalf et al. (2012) stating that 42% of private forest owners engaged in harvesting activities chose to "only cut a few select, large trees" – a practice we and our state partners interpreted to mean DLC. We estimated harvest intensity based on literature review, which showed that DLC harvests led a 76% reduction in basal area, residual stocking reduced by over 40%, and residual stand growth around 18% of previous capacity (Ward et al. 2005; Kenefic et al. 2005). We correlated this data to roughly 70% harvest intensity – the same intensity as our seed tree cuts (Table S2) – and assumed that 42% of removals from the seed tree cut harvest type on private lands are in fact DLC instead. We reassigned these harvests accordingly and implemented a post-harvest transition to a depressed yield

curve (represented by a poorly-stocked stand, ALSTKCD=4) to capture the decrease in stocking and future growth. Furthermore, our state partners indicated that this practice only occurs in hardwood forests with large and valuable trees, so we applied DLC removals only to oak/hickory and maple/beech/birch forest type groups.

Prescribed fire information provided by the Pennsylvania DCNR Bureau of Forestry included total annual acres of prescribed fire applied from 2010-2019, across all land ownerships and land-cover types. We used the overall percentage of forestland in Pennsylvania to scale total fire acres to those treatments applied only on forestland. We created a custom disturbance matrix for prescribed fire, since it has a lower intensity than the default stand-replacing wildfire matrices in the CBM-CFS3. Based on literature review, we determined that prescribed fire in Pennsylvania consumes roughly 40% of understory material with no significant impact on the overstory, though impacts differ by carbon pool (see Table S3; Clark et al. 2015; Elliott and Vose 2010; Hubbard et al. 2004; Waldrop et al. 2010; Hartman 2004; Hutchinson et al. 2005). Proportions of greenhouse gas emissions from prescribed fire follow CBM-CFS3 defaults (burned material emissions are 90% CO_2, 9% CO, and 1% CH_4).

Table S3. Impacts of prescribed fire on carbon pools in the CBM-CFS3 in Pennsylvania, based on literature review.

Pool	Description	Impact
Aboveground Very Fast DOM*	1-hr fuels, leaf litter, herbaceous material	60% consumed 4% gain from Other pool
Aboveground Fast DOM*	10-hr fuels, small wood	35.5% consumed 17% gain from Other pool
Branch Snags	All snags excluding the merchantable stem wood portion	12% consumed
Other	Nonmerchantable stem wood and all branches, tops, stumps, and bark	40.5% consumed
Foliage	Foliage	40.5% consumed
Coarse Roots	Coarse roots	40.5% consumed
Fine Roots	Fine roots	40.5% consumed

Natural disturbances

Natural disturbance data were collected from the National Interagency Fire Center (NIFC; National Interagency Fire Center 2021), National Insect and Disease Detection Surveys (IDS; USDA Forest Service 2020), and LANDFIRE (USGS 2016). The LANDFIRE Historical Disturbance dataset relies on a publicly reported disturbance database and change detection from Landsat imagery and includes a large list of natural disturbances, but tends to underreport on insect/disease events or other slow disturbances processes (Joshua Picotte, personal communication, December 23, 2020). We therefore combined LANDFIRE with IDS data to expand insect/disease event coverage. We also used recent fire data from NIFC to verifying wildfire estimates from LANDFIRE.

We combined these geospatial datasets in ArcGIS Pro (Esri Inc. 2021) and overlayed them with maps of forest type group (Ruefenacht et al. 2008) and forest ownership (USGS Gap Analysis Project 2018; Sass et al. 2020). We combined these two ownership datasets to preserve private landowner categories from Sass et al. and integrate more detailed public land manager information from the USGS Protected Areas Database. As the forest ownership data are newer than the forest type group map (based on MODIS imagery from the 2002-2003 growing seasons), we used current forest type group distributions from FIA (USDA Forest Service 2019) to gap fill data for pixels with forest ownership information but no mapped forest type group. We then extracted disturbance information for these classifiers and aggregated specific events into more general disturbance categories (e.g., all insect disturbances noted to cause defoliation were combined into an "Insect – Defoliation" disturbance type). Where multiple disturbances occurred in a given pixel, we followed LANDFIRE's data hierarchy, selecting for disturbances with greater influences on vegetation and therefore carbon (wildfire > abiotics > insects >

disease; USGS n.d.). Final natural disturbance types included: low-intensity fire, insect-caused defoliation, insect-caused mortality, disease, and abiotic events.

We determined appropriate disturbance matrices for these events using severity information from IDS and LANDFIRE where available, and otherwise relying on literature review. Pennsylvania wildfire events were generally recorded as low in intensity in LANDFIRE and NIFC data, so we applied the same low-intensity disturbance matrix developed for prescribed fires. Insect-caused defoliation events had moderate severity (~50% of trees affected) in IDS and LANDFIRE data, so we applied a medium-severity (45% defoliation) disturbance matrix chosen from the CBM-CFS3 defaults and differentiated for softwood and hardwood forest type groups. Insect-caused mortality was recorded at an average of 30% mortality in our geospatial datasets, so we used insect disturbances from the CBM-CFS3 to match this mortality level, again differentiated for softwoods and hardwoods. Disease events were generally low in intensity per IDS and LANDFIRE, so we created a generic disturbance matrix with 5% mortality and 20% defoliation, based on other low-intensity disease matrices in the CBM-CFS3. Windthrow is the most common abiotic event in Pennsylvania and typically affects 10-15% of trees in the disturbed area (Ulanova 2000; Gresham et al. 1991; Rich et al. 2007; Hedden et al. 1995), so we applied a generic 15% mortality matrix from the CBM-CFS3 to abiotic events.

Land-use change
We assessed land-use change trends from a time-series comparison of the National Land Cover Database (NLCD; Wickham et al. 2021) from 2001 versus 2016. We chose this period to match as closely as possible with the IPCC Guidance threshold of 20 years for classifying land-use change (Aalde et al. 2006) while working within the constraints of available data. Although 1992 and 1996 NLCD products exist, they are not comparable to the more recent datasets and cannot be used for change detection. The 2019 NLCD product, released in June 2021, was not available at the time of our analysis. This longer timeframe avoids temporary land cover changes (such as temporary loss of trees from a clearcut harvest followed by reforestation) that do not constitute permanent land-use change.

Annual averages of land-use change by ownership and forest type group were derived by overlaying the forest type group and forest ownership maps mentioned above (Ruefenacht et al. 2008; Sass et al. 2020; USGS Gap Analysis Project 2018) with NLCD products from 2001 and 2016. We assessed land cover classification changes between the two NLCD years, focusing on transitions to and from forest, shrub/scrub, and woody wetlands (NLCD codes 41, 42, 43, 52, 90). We included shrub/scrub in this category because recently harvested forests are often misclassified under this code before regeneration is visible via satellite. Shifts between these codes were not counted as land-use change events. Changes were categorized as forest loss if moving from one of these cover types in 2001 to non-forest in 2016, and categorized as forest gain if newly classified as one of these cover types in 2016. We applied CBM-CFS3 default disturbance matrices for deforestation and afforestation, respectively, to these change categories.

6. Disturbance Event Schedule
The CBM-CFS3 does not independently predict future events, but instead follows a user-determined schedule of annual disturbances for each simulation period. While gathering data on disturbance types for Pennsylvania, we also collected data on the historical occurrence (in terms of volumetric removals per year for harvesting, or acres per year for natural disturbances and land-use change) of these events from 2007-2019. We used these historical values to calibrate our model during spinup and applied annual averages based on the historical period for each disturbance type in our BAU scenario from 2020-2100 (see **Table 1** for BAU event schedule values).

7. Post-Disturbance Transition Rules

This final input table defines model behavior after each disturbance event. For stand-replacing events such as clearcut harvest, the CBM-CFS3 assumes that stand age resets to zero, all other classifiers remain the same, and the forest begins to grow again in the next model timestep. For events that are not stand-replacing, the model assumes that no changes occur post-disturbance aside from the movements of carbon determined by the disturbance matrix. If these assumptions are inaccurate, they can be changed using transition rules, allowing for changes to new classifiers, yield curves, or stand ages, as well as regeneration delays if necessary.

To more accurately model carbon dynamics after certain harvest disturbances, we adopted three distinct strategies for transition rules. For thinnings in both uneven and even-aged stands, the modified yield curves mentioned above were applied using the THIN classifier (records transitioned from THIN=0 to THIN=1) to represent the anticipated bump in growth from remaining trees. Following harvest disturbances with at least 50% volume removed such as shelterwood cuts or seed tree cuts (Table S2), forest records were split where the harvested area stand age was reset to zero to simulate natural regeneration, and unharvested trees continued on their original growth and age trajectory (i.e., for a shelterwood cut at 50% removal, 50% of the stand reset to age zero and 50% continued as before). Following DLC harvest, we transitioned stand records to depressed yield curves using the stocking classifier (transition to ALSTKCD=4) representing the decrease in growth of residual trees as mentioned above. We also utilized transition rules to implement forest loss (transition to nonforest) and forest gain (transition from nonforest to other forest type group) events.

Harvested Wood Products Model Methodology

The harvested wood products model (CBM-HWP-PA), built using the ANSE framework, requires data inputs on 1) harvested wood volume; 2) exports; 3) mill efficiency and use of mill residues; 4) primary product ratios; 5) domestic end-use consumption and half-lives; and 6) product retirement and landfills. Data sources and assumptions for each are described below. Models were run using Excel and R (Microsoft Corporation 2016; R Core Team 2020).

1. Harvested Wood Volume

Because carbon makes up approximately half of the dry weight of wood, much of the carbon that is harvested from the forest ecosystem continues to be stored in harvested wood products (HWP). The CBM-HWP-PA tracks carbon going into the HWP stream, including where it goes, its path to get there, and how long it spends in different pools before ultimately being retired (**Figure 3**). It is a closed system, meaning that all carbon that enters the stream eventually comes out (i.e., is emitted); there is no additional or lost carbon over time. From a carbon accounting perspective, it is most relevant to know what percent of harvested carbon is stored or emitted at any given time; as such, rather than track specific carbon molecules over time, the model works by tracking proportions of carbon as they move through the HWP stream. For example, a certain proportion of merchantable timber entering the stream will first be exported; a proportion of what remains domestically will go toward commodity production, with a certain proportion of that carbon going toward mill residues, where some will be burned and some will go toward additional commodity production.

Input data on carbon entering the HWP stream in each year of our simulation came from two sources. Carbon entering the stream after 2006 came directly from harvest disturbances in the CBM-CSF3, equal to the amount of carbon transferred to HWP in disturbance matrices. Carbon entering the stream between 1950 and 2006 representing *inherited carbon* (i.e., carbon entering the HWP stream before the start of our BAU scenario) was calculated using estimates of total US commodity production (Howard and Liang 2019, Tables 6b and 7b). We assumed that Pennsylvania's historic share of total US production was equal to its share in 1997, 2002, or 2007, calculated using production data from

Resource Planning Act (RPA) assessments (USDA Forest Service 2021) and applying state-specific bark expansion factors from RPA and conversions from carbon to product volumes such as board feet (Smith et al. 2006). These carbon conversions differ by state and wood type according to harvested species and their associated specific gravities. Converted product volumes were also provided to Penn Soil RC&D for the associated project assessing economic tradeoffs from our BAU and alternative management scenarios.

2. Exports

We calculated HWP exports at two stages: raw roundwood exports before commodity production, and commodity exports after production. We used Pennsylvania roundwood export data from US Commodity Flow Surveys (US Department of Transportation and US Department of Commerce 2021) and the US International Trade Commission trade database (2021) to determine both proportions of harvested material exported and destination countries, and found that Pennsylvania exported 1.34% of roundwood harvested in 2012 (**Table 2**). We relied on the FAOSTAT statistical database (FAO 2021) to determine the proportions of commodities produced from exported roundwood, categorized as fuel, paper, or wood commodities (Figure S2). Destination countries were binned into three categories based on their weighted-average HWP half-life (Table S4; FAO 2021; Pingoud et al. 2006). We assumed all exported logs were stripped of their bark prior to shipment so no bark was exported; instead, we modeled it as a domestic mill residue.

Table S4. Export destination country bins based on product-weighted average HWP half-life.

Bin	Half-Life Range	Average Half-Life	Major Countries
1	2-5 years	3 years	China
2	5-15 years	9 years	Brazil, Mexico, Vietnam, Italy, India
3	15-30 years	20 years	Canada, Germany, Malaysia

We used data from Howard and Liang (2019) for US-level commodity exports and found that an average of 6% of softwood commodities and 8% of hardwood commodities were exported annually from 1965-2017. We utilized national numbers here rather than state-specific ones due to a lack of data on intrastate trade and subsequent difficulty determining which commodities were traded within the US rather than internationally. Commodity exports again binned by destination country based on average HWP half-life as described above (Table S4).

3. Mill Efficiency and Use of Mill Residues

We assumed that all harvested wood not exported entered domestic commodity pools, either as primary products (see below) or mill residues. Mill residues have different uses than other primary products, so they need to be tracked separately in the CBM-HWP-PA. We used mill efficiency data from RPA (USDA Forest Service 2021) for 1997-2012 to estimate mill residues as a proportion of total harvest volume after export for domestic HWP. We found that Pennsylvania mills have an average mill efficiency of 61.4% for softwoods and 54.4% for hardwoods, meaning that the remaining material – 38.6% and 45.6% of total harvest after export for softwoods and hardwoods, respectively – becomes mill residue during the commodity production process. We differentiated between softwood and hardwood inputs, as these wood types differ in their exports and commodities produced, as well as their associated product half-lives and displacement factors (described below). We then assigned mill residues, including bark from exported roundwood, to four commodity pools using proportions from RPA for 1997-2012: pulpwood, composite panels, bioenergy, and unused residues (see **Table 2** for proportions for softwoods and hardwoods).

4. Primary Product Ratios

As noted above, the CBM-HWP-PA works by tracking proportions of carbon as they move through the HWP stream. These proportions come from *primary product ratios*, which partition harvest volume

inputs into various commodities based on their relative historic production. Upon entering the CBM-HWP-PA model, a certain amount of carbon was immediately partitioned to roundwood exports as described above. We then apportioned the remaining carbon into various domestic commodity pools and mill residue uses (as noted above) following primary product ratios for Pennsylvania from RPA data, 1997-2017 (**Table 2,** Figure S2; USDA Forest Service 2021). Again, we differentiated between softwood and hardwood inputs.

5. Domestic End-Use Consumption and Half-Lives

Once we had calculated exports, mill residues, and primary products from annual harvest volumes, we determined

Figure S2. Primary product ratios for commodities produced in Pennsylvania, differentiated between softwood and hardwood inputs.

end-uses for those products and their associated half-lives. We used end-use product half-life (Dymond 2012) and product use data (Howard et al. 2017) to calculate softwood- and hardwood-specific half-lives for Pennsylvania sawn wood and veneer products, weighted by wood product market share for each product following the IPCC approach (Pingoud et al. 2006). We relied on literature estimates for other products (Smith et al. 2006; Skog 2008). We estimated these half-lives based on averages from 2012-2017. See **Table 2** for half-life assumptions for both domestic and international product use.

6. Product Retirement and Landfills

Finally, we estimated product retirement proportions for each commodity in use, dividing retired products between landfills, waste incineration (energy recovery), and recycling streams based on values from 1960-2018 (EPA 2022c; 2022b; Howard and Liang 2019). Due to data limitations, we assumed recycling and energy recovery occurred only for sawlogs and pulpwood – all other commodities were assumed to retire exclusively to landfills. Recycled products were moved back into the appropriate commodity pool and stayed there according to the half-life determined for that commodity (see **Figure 3** for recycling pathways modeled). Energy recovery pathways were assumed to result in immediate emissions to the atmosphere.

To accurately model landfill dynamics, we utilized information on biodegradable proportions of landfilled material (Zhao 2019) to determine that 50% of carbon in landfilled HWP could eventually be emitted. We then applied IPCC default landfilled material half-lives for wet, temperate climates (Pipatti et al 2006); half-lives were assumed to be 23 years for wood and 12 years for paper. We determined the appropriate landfill climate zone based on mean annual temperature and a calculated ratio of mean annual precipitation and potential evapotranspiration for Pennsylvania from 1981-2010 (Northeast Regional Climate Center 2022a; 2022b; 2022c). Finally, we used IPCC default methane generation (k) rates for wet, temperate climates using the same data sources listed above to determine methane emissions of 0.03 m³/yr from wood and 0.06 m³/yr from paper.
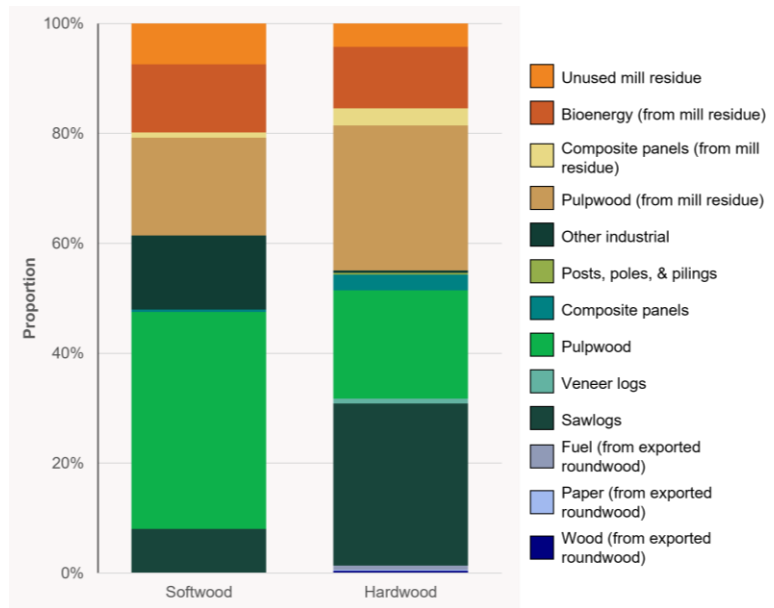
The data sources and methodologies above largely apply for business-as-usual (BAU) scenario parameterization for the forest ecosystem and HWP models. We created our alternative management scenarios in consultation with our state partners, and some scenario parameters were given to us directly while some scenarios required additional data and assumptions to parameterize (see **Table 3** for all scenario parameters). Scenario assumptions and additional data sources are described below.

Altered Rotations

Changing rotation lengths, specifically extending the average length of rotations before harvesting, is a popular management tool for increasing forest carbon storage (D'Amato et al. 2010; 2011; Fargione et al. 2018). State partners had a unique interest in the effects of extending rotation lengths by 30 years for forest type groups except for aspen/birch, which was modeled with a 10-year reduction in rotation length to provide wildlife habitat, one of our state partners' management objectives. These altered rotations were implemented from 2020-2170 in this scenario, with no ramp-up or gradual transition to the new harvesting schedule.

Afforestation (GGRA 2030, GGRA 2050, Scale Up 2030, Scale Up 2050)

Given the regional nature of this analysis, some scenarios were co-created with state partners from both Maryland and Pennsylvania. The Maryland legislature adopted the Greenhouse Gas Emissions Reduction Act (GGRA; Maryland Department of the Environment 2021) in 2009 (updated in 2016) to set a goal of 50% emissions reductions state-wide by 2030. Implementation planning for the GGRA includes several goals for forest management programs on both public and private lands, tree planting, biomass for energy production, increasing urban tree cover, and improving soil health (Maryland Department of the Environment 2021). Since Pennsylvania did not have a comparable state policy at the time of our analysis, our state partners instructed us to use GGRA targets for Maryland, scaled up proportionally to Pennsylvania's forest area. GGRA targets extend only to 2030, so in keeping with the IPCC special report on global warming of 1.5 °C (IPCC 2018) and US federal emissions targets (The White House 2021) – both of which call for net-zero emissions by 2050 – we also extended GGRA-related implementation to 2050 to represent sustained action towards these national and global goals.

Using this approach, we defined two afforestation scenarios following GGRA implementation rates (2,376 acres/year) to 2030 and 2050, respectively. Our state partners were also interested in scenarios representing greater ambition in tree planting, so we created two additional Scale Up scenarios to quantify the benefits of 10 times the afforestation rates of the GGRA targets (23,760 acres/year) out to 2030 and 2050. This 10x figure was chosen for illustrative purposes and does not necessarily represent a concrete policy goal for Pennsylvania, though it is significantly lower than the total reforestation potential identified by Cook-Patton et al. (2020). These planting targets were applied on top of BAU rates of forest gain, and once the planting period for each scenario ended only the BAU rate continued to 2170. Acreage targets were distributed among ownership groups based on historical accomplishments as estimated by our Maryland state partners (95% on private lands, 3.5% on local lands, and 1.5% on federal lands) and scaled to Pennsylvania forest acreage. Federal lands targets were applied to other federal lands (OWNGRPCD=20) only, as we assumed that US Forest Service land is already forested or classified as such in land cover data for Pennsylvania.

Silvopasture

Silvopasture is the purposeful integration of low-density tree cover in pastureland and does not remove land from productive pasture use (Nair 2014). In fact, this practice helps farmers and ranchers diversify their income, reduces the potential for heat stress in livestock, and produces additional feedstock for pasture animals (Smith et al. 2022; Garrett et al. 2004). Silvopasture is receiving increasing attention

as a potential natural climate solution (Fargione et al. 2018; Cook-Patton et al. 2020), but adoption in the US has so far been limited due to a lack of available information and successful case studies (Smith et al. 2022; Garrett et al. 2004). Silvopasture implementation at scale would likely require outreach and technical assistance for landowners. Since the purpose of this analysis is to examine a broad range of potential climate-smart forestry practices, our state partners decided to include a silvopasture scenario in our model to assess its relative climate benefits against the work required to establish new silvopasture sites and programs.

Silvopastoral systems are typically designed for low (10-40%) canopy density and are best implemented with tree species adapted to regional conditions (Garrett et al. 2004; Nair 2014; Natural Resources Conservation Service 2016). In consultation with our state partners, we assumed that hardwood trees like oaks would be best-suited for planting in the hardwood-dominated landscape of Pennsylvania. We therefore modeled silvopasture as an afforestation event increasing the area of oak/hickory forest at poorly-stocked stand density (10-34% stocking, ALSTKCD=4).

There are 3.47 million acres of pasture in Pennsylvania with the potential for tree planting (Cook-Patton et al. 2020). To represent low current rates of silvopasture adoption, our state partners asked us to model the practice on only 0.5% of available acreage each year (15,250 acres/year). We modeled this from 2020-2170 to illustrate the potential of sustained efforts to increase silvopasture adoption; note that this is a much longer timeframe than the other afforestation scenarios, so the silvopasture scenario has a larger impact on total forest gains (in terms of both acreage and carbon) in the state.

While some silvopasture systems can also be established by removing trees from existing forests and integrating livestock grazing, we chose not to model this method to prioritize maintaining current forest acreage in the state and to illustrate the potential of adding trees to pastureland.

Restocking
Generally, restocking of temperate forest stands occurs through successful natural regenerative processes. However, evidence indicates that many naturally regenerated forests are understocked (Vickers et al. 2019), supporting our state partners' concerns about declining natural regeneration in Pennsylvania forests. Oak/pine and oak/hickory forests are of special focus for our state partners, as the pine component of oak/pine stands has been decreasing and oak/hickory forests cover nearly half the understocked acres in the state (USDA Forest Service 2019).

Restoration practices in these understocked forests include manual restocking through direct seeding or underplanting, targeting stands between the ages of 25 to 70 where natural regeneration has already failed. We modeled restocking on 0.2% of understocked acres each year (4,508 acres/year) from 2020-2170, representing sustained focus on optimizing stocking levels across the state. Restocked stands in the model were transitioned from poorly-stocked status to medium stocking levels (ALSTKCD=4 to ALSTKCD=3).

Timber Stand Improvements
Timber stand improvements (TSI) are defined here as management interventions that improve the future quality of timber within a stand. Here, we model them as a combination of additional thinning and prescribed fire to reduce competition and increase the growth of residual trees. These actions can also have wildlife habitat benefits, and they may be implemented for habitat purposes rather than timber production purposes. Since both thinning and prescribed fire lead to the removal of carbon from the forest, we did not model these practices for their carbon sequestration benefits; rather, the inclusion of a TSI scenario in this analysis acknowledges the importance of these practices for meeting other forest management goals and a desire to understand the necessary carbon cost of business.

We modeled the TSI scenario based on both TSI and wildlife habitat improvement targets from the GGRA, adjusted for Pennsylvania management goals. As directed by our state partners, we divided total TSI targets to represent two-thirds treatment by prescribed fire (25,000 acres/year) and the remaining third treatment by thinning (14,892 acres/year) and modeled all TSI treatments from 2020-2170. Prescribed fire treatments were targeted to oak/hickory, maple/beech/birch, aspen/birch, and oak/pine forest type groups, while thinning treatments were targeted to all forest types currently thinned under BAU management (Table S2).

We assumed that any of this thinned wood material would not be of merchantable size or quality, so we directed all additional harvest from TSI treatments to the domestic pulpwood commodity and bioenergy pools only in the CBM-HWP-PA model. Proportions of this additional harvest going each pool were based on 2012 mill residue to commodity production rates (hardwood: 62% pulpwood and 38% bioenergy; softwood: 68% pulpwood and 32% bioenergy; USDA Forest Service 2021).

Reduced Deforestation

Under the Reduced Deforestation scenario, we modeled a permanent decrease in the annual rate of forest loss on private lands from 2020-2170. This decrease (-5,149 acres/year) was calculated based on GGRA targets and scaled to Pennsylvania forest area, but it is not enough to reverse the overall trend of forest loss occurring in the state (a net average 17,294 acres of forest loss per year; **Table 1**).

Reduced Diameter Limit Cuts

The Reduced Diameter Limit Cuts (DLC) scenario was created in response to state partners' concerns about the prevalence of this practice on the landscape and our subsequent inclusion of DLC in our BAU management practices, as described in the **Forest management disturbances** section. Also known as high grading, DLC is practice on private lands that encourages landowners to harvest the largest and most valuable trees from their forests and leave only smaller or stunted trees behind. DLCs are not considered a long-term sustainable harvesting practice, as they leave the forest in a degraded ecological state with unpredictable regeneration and diminished future growth (Kenefic et al. 2005; Ward et al. 2005; Nyland et al. 2016).

To counteract this management trend, we modeled this scenario as a 15% reduction in annual DLC removals in Pennsylvania until reaching a rate of zero DLC harvest in 2027, after which point DLC rates remained at zero through 2170. Rather than assume this harvest would not happen at all, we transitioned DLC harvests to seed tree harvests instead – a practice with similar harvest intensity but assumed to be done in a more sustainable way and therefore not subject to the depressed growth rates observed after DLC harvests. Since our annual harvest events are measured in terms of volumetric removals rather than acres, this scenario transitions removals of 30,559 tC/year from DLC to seed tree until reaching a new seed tree removal equilibrium in 2027 and does not transition these stands to a depressed post-harvest yield curve.

Control Deer Browse

Deer overabundance is a long-standing issue in Pennsylvania and can have severe consequences for forest regeneration, as deer browse can kill seedlings and smaller saplings (Côté et al. 2004; Rooney and Waller 2003). Long-term effects of deer browsing can drastically reduce forest stand characteristics such as biomass, carbon, and basal area (White 2012; Bressette and Beck 2013), as well as reducing the number of trees that can ascend to the canopy (Kain et al. 2011). Deer exclosure and fencing is the most common way to combat these effects, but it is difficult and expensive, and therefore is not currently widespread across the state.

In consultation with our state partners, we assumed that the majority of young and poorly stocked forest have been subject to deer browse, as there is often heavy browsing pressure in younger stands without a canopy where new growth is abundant. We further assumed that successful deer exclusion in these areas would allow natural regeneration processes to continue such that the forest would reach full stocking. We modeled this scenario by targeting stands under 25 years old that were considered poorly stocked (ALSTKCD=4) and transitioning them to fully-stocked status (ALSTKCD=2). Note that this transition does not change the carbon stocks in each stand, but instead uses the growth increment for a fully stocked stand to simulate faster forest growth with successful control of deer browse. We applied this transition to 10% of eligible acres annually (14,459 acres/year) from 2020-2170.

Climate Change Growth and Disturbance

As noted in the **Identifying Forest Management Priorities** section, state partners identified climate change as a key future forest management concern. Future climate trends for Pennsylvania are projected to bring hotter, wetter weather (but with drier summers) and longer growing seasons (Butler-Leopold et al. 2018). We assessed and modeled potential future climate impacts in two ways: through changes in forest growth and changes in natural disturbance.

We compiled data on projected future growth for Pennsylvania tree species under RCP 8.5 (Duveneck et al. 2017; Wang et al. 2017; Matala et al. 2005) and summarized decadal changes in growth from 2020-2100 for each. We calculated these changes as growth multipliers, representing the projected percent change in growth relative to expected future growth under current climate conditions. We then aggregated species-specific multipliers to the forest type group level using the relative abundance of each species within each forest type group (USDA Forest Service 2019). We found that overall, forests in Pennsylvania will experience an average 0.3% bump in growth by 2100, ranging from 0.05%-0.6% for various forest type groups (Table S5).

Table S5. Projected changes in future growth for key forest type groups in Pennsylvania under RCP 8.5. Positive numbers denote additional growth compared with current climate conditions.

Forest Type Group	Average Change, 2020-2110	Annual % Change in Growth									
		2020	2030	2040	2050	2060	2070	2080	2090	2100	2110
White/red/jack pine	0.25%	0.19%	0.19%	0.21%	0.29%					0.30%	0.34%
Spruce/fir	0.60%	0.39%		0.40%	0.49%		0.82%			0.88%	
Loblolly/shortleaf	0.10%	0.11%		0.15%	0.07%					0.08%	0.11%
Other Eastern softwoods	-	-									
Douglas-fir	-	-									
Fir/spruce/mtn hemlock	-	-									
Exotic SW	0.41%	0.32%	0.32%	0.36%	0.40%		0.51%				0.53%
Other SW	0.05%	0.05%									
Oak/pine	0.32%	0.20%	0.21%	0.24%	0.38%	0.36%				0.39%	0.47%
Oak/hickory	0.39%	0.11%	0.11%	0.15%	0.40%	0.42%				0.61%	0.91%
Oak/gum/cypress	0.24%	0.04%		0.06%	0.33%	0.34%				0.35%	0.35%
Elm/ash/cottonwood	0.18%	0.02%	0.03%	0.06%	0.26%	0.27%				0.31%	0.34%
Maple/beech/birch	0.32%	0.04%	0.05%	0.17%	0.52%					0.57%	0.59%
Aspen/birch	0.39%	0.08%	0.22%	0.25%	0.38%		0.41%			0.42%	0.99%
Other hardwoods	0.41%	0.26%		0.28%	0.43%	0.44%				0.50%	0.58%
Exotic hardwoods	0.18%	0.18%									
Non-stocked	0.35%	0.04%		0.18%	0.51%	0.52%					0.52%

To construct the Climate Change Growth scenario, we created a modified set of yield curves by applying our calculated growth multipliers for each forest type group and decade, resulting in 544 separate curves. For model years from 2100-2170, we continued to apply the 2100 growth multipliers, as no growth predictions went beyond end of century. For this scenario, we added an additional classifier (CC_Phase) in the CBM-CFS3 to force transitions between our modified yield curves for each decade. All disturbance events in this scenario followed BAU trends – management was not changed in response to future climate conditions.

We also compiled data from the literature for projected future natural disturbances for Pennsylvania under RCP 8.5 (Lucash et al. 2018; Butler-Leopold et al. 2018; Guyette et al. 2014; Del Genio et al. 2007), yielding a wide range of possible values. Acknowledging that climate futures are numerous and difficult to predict, we opted for a simple 10% increase in natural disturbance frequency and severity. This 10% increase is not outside the realm of possibilities and may in fact represent the lower bound of future disturbance impacts. All natural disturbances were equally amplified with 10% more acres in the disturbance event schedule each year, and we created new disturbance matrices causing 10% more defoliation or mortality for each event type. All management and land-use change events continued under BAU trends. We modeled this new disturbance regime from 2020-2170.

These two climate change scenarios were run independently of one another and of all other scenarios. They represent possible bounds of a climate envelope around our BAU scenario, but do not represent future interactions between growth and altered natural disturbance or harvesting events. While this bounding of climate change impacts is informative, for future modeling efforts we plan to better incorporate future climate conditions with each other and with alternative management scenarios.

No Harvest

The No Harvest scenario was included at the request of our state partners, who have come under increasing pressure to consider a complete reduction in harvest practices as a climate mitigation strategy. Though this approach can increase forest carbon stocks, it comes with tradeoffs in carbon sequestration rates and the forest products sector as forests age and wood supply declines. Our use of linked forest ecosystem and HWP models makes our analysis well-suited to explore these sector-wide tradeoffs and their relative climate impacts. To parameterize the No Harvest scenario, we simply removed all harvesting activities from our event schedule. Other forest management activities such as prescribed fire were modeled as normal under BAU conditions from 2020-2170, as were natural disturbances and land-use change. This 100% reduction in harvesting is an extreme example of the potential impacts of this approach, and does not represent a stated goal of either our state partners or climate advocates in the state – instead, it serves as an illustration of the anticipated sector-wide tradeoffs made more clear by its exaggerated nature and helps to establish an upper bound on the potential impact of harvest reductions.

Bioenergy 1 and 2

A stated goal in the GGRA is the use of woody biomass for energy production, so we constructed two bioenergy scenarios. In consultation with state partners, we limited these scenarios to changing the use of mill residues only – we did not consider diverting material from other primary products or harvesting additional material for bioenergy feedstocks. The Bioenergy 1 scenario diverted 10% of only the portion of mill residues destined for pulpwood into bioenergy uses; the Bioenergy 2 scenario diverted 10% of all mill residues to bioenergy uses.

Substitution Benefits and Leakage

For any scenarios changing harvest frequency or volume relative to BAU, we calculated *substitution*

benefits and *leakage* for this change in HWP supply. Substitution benefits, or *displaced emissions*, were estimated following Smyth et al. (2017), with positive substitution benefits when additional wood products are manufactured and used in place of alternative emissions-intensive materials, and negative substitution benefits when wood supply falls short and other emissions-intensive materials are assumed to be used instead. We applied substitution benefits only to saw log, composite panel, and bioenergy products.

Substitution benefits calculations rely on assumptions made about the emissions associated with the extraction, raw material transport, and manufacture of both the wood products and the assumed alternatives. To calculate substitution benefits associated with wood product substitution, we coupled Pennsylvania-specific production data (USDA Forest Service 2021), US consumption rates (Howard et al. 2017), product weights (Smyth et al. 2017), and LCA data (Bala et al. 2010; Dylewski and Adamczyk 2013; Hubbard et al. 2020; Puettmann 2020; Puettmann and Salazar 2018; 2019; Puettmann et al. 2020b; 2020c; 2020a; Athena Sustainable Materials Institute 2019; Meil and Bushi 2013), following the calculation methods developed by Smyth et al. (2017). We calculated state-specific displacement factors for saw logs (softwood: 2.032; hardwood: 2.692) and composite panels (softwood: 2.794; hardwood: 1.932), as each is associated with a different commodity and end-use mix. These values represent the amount of carbon reduction from other products per unit of carbon used in additional wood products.

To account for substitution benefits associated with bioenergy, we applied the lower and more conservative displacement factor estimate for bioenergy (0.47) from Smyth et al. (2017) starting in 2022; we applied a linearly decreasing displacement factor in each subsequent year until it reaches zero in 2040, balancing Maryland's net-zero ambitions by 2045 (Climate Solutions Now Act of 2022) as well as the Biden Administration's aim of reaching a carbon pollution-free power sector by 2035 (The White House 2021) and setting that target for Pennsylvania. As noted above, wood products, including bioenergy, displace emissions associated with more emissions-intensive products. If the alternative products can achieve zero emissions in their production, the counterfactual scenario is zero emissions, meaning there are no longer any emissions to displace.

For any scenarios resulting in less harvest relative to the BAU in a given year, we applied a leakage factor to represent an assumed increase in out-of-state harvest activity compensating for the decrease in harvesting in-state. We assumed demand for wood (or substitute) products will remain constant despite reductions in harvest (e.g., due to continued construction demand) and assumed a portion of that demand would be met via additional wood imports from increased out-of-state harvest (i.e., leakage). We assumed all remaining product demand (that which is not met by in-state harvest or out-of-state imports) would be met by product substitution (i.e., increased use of non-wood materials in place of wood). Determination of leakage rates in the United States depends in part on the degree of assumed regional collaboration (e.g., less leakage occurs when neighboring states or regions are engaging in similar harvest reduction activities) and estimates in the literature range from 63.9% with regional collaboration (Gan and McCarl 2007) to 84.4% without (Wear and Murray 2004). In this analysis, we applied a leakage factor of 63.9% given the multi-state nature of this project, meaning that 63.9% of reduced harvest relative to the BAU was assumed to leak out-of-state and the remaining 36.1% of reduced harvest relative to the BAU was subject to additional emissions from product substitution, as noted above. In all cases, leakage was only assumed to result from reduced in-state harvest; any additional in-state harvest relative to BAU was assumed to result in increased in-state wood use rather than reductions in out-of-state harvest.