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Modeling climate-smart forestry and wood utilization for climate mitigation potential in Minnesota

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Summary and Implications for Decision-Makers

Forests as Natural Climate Solutions

Climate change presents unprecedented global challenges to society and the ecosystems society relies on. Forests have become increasingly important in the 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) to help reach net zero greenhouse gas (GHG) emission targets. Further, there is increasing consensus of forests' importance as a nature-based solution to climate change, or natural climate solution (NCS) through their mitigative and adaptive potentials (Drever et al. 2021; Griscom et al. 2017; Fargione et al. 2018).

Forests in the United States (US) and the forest products sector already play an important role in mitigating climate change, a benefit which can be significantly impacted through forest management, land use change, and climate change. The overall mitigation potential of the forestry sector is determined not only by the carbon captured from tree growth, but also by the carbon stored in harvested wood products (HWP) and how HWPs are ultimately retired (e.g., sent to the landfill, recycled, or combusted for energy recapture). In 2020, land use, land use change, and forestry captured and stored an additional 758.9 million metric tons of carbon dioxide equivalency (MMT CO_2e), offsetting 13.6% of total GHG emissions that same year (EPA 2022a). Almost 90% of this climate benefit was provided by existing forests and forest products. Assessments of natural climate solutions potential indicate that we could significantly increase the carbon-capturing potential of forests through management and policy actions (Fargione et al. 2018). However, this carbon savings potential is expected to decrease throughout the 21st century due to forest loss, declines in productivity, and forest health challenges 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 and policy, implementing climate-smart practices on state-owned lands, and providing technical and financial support for other forest landowners. Determining the role of forests, forestry, and wood products in mitigating climate change is complex and requires holistic and rigorous analytical methods to describe accurately. Increasingly, states such as Minnesota, Wisconsin, and Michigan are taking steps to build this foundational knowledge in order to integrate climate considerations into existing sustainable forest management regimes. This report is designed to provide important insights into potential climate mitigation actions for Minnesota's forests which can help inform forest management and policy decisions. Here, we present the results of a modeling exercise for estimating climate mitigation potential across a selection of forest management and wood utilization scenarios using a systems-level forest carbon accounting framework, the Carbon Budget Model of the Canadian Forest Sector v3 (CBM-CFS3).

Modeling Forest Management and Wood Utilization in Minnesota

Following similar assessments in Papa et al., 2023; Davidson et al., 2026; DeLyser et al., 2025; 2022a; 2022b; and Dugan et al., 2018; 2019; 2021, we assess carbon trends and management scenarios in the forest ecosystem and forest products sector for Minnesota using 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 optimize forest ecosystem carbon stocks, harvested wood products, and the net exchange of CO_2 between the forest and atmosphere over time (Dugan et al. 2018). Our modeling process includes:

1) Consultation with state agency staff and forestry experts to understand opportunities and challenges related to climate mitigation and adaptation in Minnesota's forests;

2) Development of business-as-usual (BAU) and alternative forest management scenarios – including forest management, natural disturbance, land-use change, and wood utilization – 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 Minnesota, ii) a harvested wood products dynamics model for Minnesota (CBM-HWP-MN) utilizing the Abstract Network Simulation Engine (ANSE) framework, iii) potential leakage factors applied to changing harvest rates, and iv) 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 connections with forest management programs and policies statewide, and inform engagement in state climate policy work.

Box 1. MODELED SCENARIOS

- Extended rotations
- No harvest
- *Increased harvest levels
- Increased reserve size
- *†Avoided conversion
- *†Tree planting
- *Enrichment planting
- *Climate change impacts
- *Insect vulnerability transition
- †Increased production of long-lived wood products
- Logging residue utilization (BAU, bioenergy, biochar, or transportation fuels)
- Portfolio (concurrent implementation of scenarios marked with *)

†Scenarios that include multiple levels

Through a series of meetings with staff from Minnesota's Department of Natural Resources Division of Forestry, we identified several questions, opportunities, and challenges related to the role of public and private forests in climate mitigation and adaptation. Several key high-level themes emerged from these discussions including: **management of working forestlands**, **climate change impacts and adaptive silviculture**, **wood utilization and markets, and land-use change**. Many of these themes are common across the Lake States as well as are relevant nationally. From these high-level themes, we developed 19 modeling scenarios to represent a broad range of concepts grouped into five categories: 1) forest management; 2) climate impacts and adaptive silviculture; 3) harvested wood product utilization; 4) tree planting; and 5) avoided forest conversion (**Box 1**). For full scenario descriptions and parameters, see **Table 3**.

The forest management and climate policy themes outlined above align well with the core principles 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 ecosystem services such as timber supplies (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 to enhance forest carbon sinks in support of GHG emission reduction goals. CSF directly addresses long-term forest health and resilience to sustain forest productivity in the face of climate change. Importantly, CSF aims to achieve these climate mitigation and adaptation objectives while continuing to provide wildlife habitat, clean water, timber and other forest products, and scenic beauty.

Climate mitigation potential from Minnesota's forests

Forests and the forest products sector already contribute strong climate mitigation benefits in Minnesota, and are a net carbon sink (e.g., they sequester and store more carbon each year than they emit). The results presented in this analysis suggest that Minnesota's forests are expected to continue to provide those benefits through 2100 based on the continuation of recent levels of management, disturbance, and land use change (*Business-as-usual*). The results also highlight

Box 2. CLIMATE-SMART FORESTRY IN MINNESOTA

- ✓ **Continued sustainable management of working forestlands** to support the balance between harvest removals and forest growth into the future as represented in the *Business-as-usual* scenario

- ✓ **Maintain and increase forest area** by accelerating the rate of *tree plantings* and *avoiding conversion* of forests to other land uses such as development and agriculture

- ✓ **Bolster climate mitigation potential of the forest products sector** through wood utilization strategies including *increasing use of longer-lived wood products* and *innovative uses of logging residues*

- ✓ **Prepare for the impacts of climate change** and related stressors by maintaining a diversity of forest ages and species across the landscape while considering targeted efforts to maintain biological legacies through *increasing reserve size* retention following harvest and *transition insect-threatened forest types* and *plant understocked forests* with potentially climate-adapted species several strategies that may potentially increase climate mitigation benefits over time relative to business-as-usual. Key factors for generating climate mitigation benefits over the timeseries include establishing and maintaining a diverse, productive forest landscape that balances the two key mechanisms– *carbon sequestration* (removal of carbon from the atmosphere and converting it into wood through photosynthesis) and *carbon storage* (storing carbon in forest ecosystems and wood products). This study quantifies these two mechanisms across a wide range of scenarios pointing towards important priorities to potentially support long-term climate mitigation benefits (**Box 2**).

The potential benefits of climate-smart forestry in Minnesota

The results from this analysis suggest that the continuation of recent levels of forest management, natural disturbance, and land use change in Minnesota through 2100 (as reflected in the *Business-as-usual (BAU)* scenario) will lead forests in Minnesota to sequester and store an average of -5.1 MMT CO_2e yr^{-1} through 2100. This means that by maintaining the balance between harvest and growth, Minnesota forests are projected to remain a net carbon sink through 2100, while still being able to provide a steady supply of HWPs. When considered in terms of *net carbon balance* - a metric which includes net ecosystem flux in the forest, transfers to HWP, emissions from HWP 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* - the stable rate of annual carbon sequestration, combined with an average of 6.3 MMT CO_2e yr^{-1} transferred to HWP, mean that Minnesota's forests and forest product sector are projected to provide on average -5.4 MMT CO_2e yr^{-1} of climate mitigation over the period from 2021-2100.

Other alternative forest management and wood utilization scenarios are expected to provide similar levels of climate mitigation as the *BAU* scenario. All scenarios tested in this analysis result in a cumulative net carbon balance below zero, meaning that the forest and forest products sector will remain a net carbon sink until the end of the century. That said, only a few scenarios provide substantially different cumulative climate mitigation benefits than *BAU*. Of these, the *Tree planting (high)* scenario generates the greatest climate mitigation benefits relative to the *BAU* scenario. In the *Tree planting (high)* scenario, the rate of intentional tree planting on non-forest open lands is increased by 22,375 acres yr^{-1}, which leads to an average increase in sequestration and storage of -3.3 MMT CO_2e yr^{-1} from 2021-2100 relative to *BAU*. However, this increase is not uniform, with the magnitude of additional mitigation increasing through time from an average of -0.9 MMT CO_2e yr^{-1} more than *BAU* from 2021-2030 to an average of –5.1 MMT CO_2e yr^{-1} more than *BAU* from 2091-2100. Cumulatively, under the *Tree planting (high)* scenario, Minnesota's forests and forest product sector are projected to provide -700.6 MMT CO_2e of climate mitigation by 2100, over 61% (-226.4 MMT CO_2e) more than in the *BAU* scenario.

The second greatest level of climate mitigation benefit comes from the *BAU – 50% LLP* scenario. In this scenario, half of harvested wood fiber destined for short-lived products (e.g. pulp and paper) is diverted into longer-lived products such as composite panels. This shift increases overall carbon storage in the HWP sector, as longer-lived products have longer in-use half-lives and a lower decomposable fraction in landfills. This scenario also benefits from positive product substitution, where an increase in the production of longer-lived products relative to *BAU* is assumed to lead to a reduction in more emissions-intensive alternative products, thereby displacing sector wide emissions. This scenario leads to an average increase in carbon sequestration and storage of -3.2

MMT CO_2e yr^{-1} from 2021-2100. Cumulatively, this amounts to −690.5 MMT CO_2e of carbon climate mitigation by 2100, or 59% (-256.4 MMT CO_2e) more than in the *BAU* scenario.

Forest managers are also interested in understanding how changes in the intensity of active forest management—specifically timber harvest—affects the provision of climate mitigation benefits over time. This study modeled several variations of active forest management and wood utilization concepts to illustrate that relationship in a rigorous and holistic way—including utilization of logging residues, increasing harvest rates on private lands, increasing reserve size, and extending rotations. We also assessed the impacts of two levels of avoided forest conversion, that is the prevention of permanent forest loss. Our results indicate that each of these scenarios generate a steady stream of annual climate mitigation benefits through 2100. However, the magnitude of benefits from these scenarios differed only minimally from *BAU*—falling within a range of +/- 1 MMT CO_2e yr^{-1} through 2100 compared to the *BAU* scenario.

The *No Harvest* scenario which consists of a total cessation in harvesting illustrates a "boom and bust" trend in climate mitigation benefits over time and therefore stands apart from all other scenarios. In this scenario, the annual harvest rate on all ownerships is reduced to zero, meaning that no timber harvest or thinning disturbances occur. This shift in management results in a significant increase in carbon sequestration and storage in the forest ecosystem relative to the *BAU* scenario in the early decades of the simulation, peaking at −4.1 MMT CO_2e yr^{-1} more than *BAU* in 2034. However, as the forest age-class distribution shifts towards older forests, the modeled annual net productivity of the forest begins to decline from 2035 onward. When accounting for this decline in productivity, negative substitution effects from non-wood alternatives used in place of HWPs, and leakage from the reduction in harvest volumes, the annual climate mitigation benefits of the *No Harvest* scenario are less than that of the *BAU* scenario starting in 2061, and by 2100 result in an annual net carbon balance +2.3 MMT CO_2e yr^{-1} (40%) greater than the *BAU* scenario, meaning over this period *No Harvest* provides less climate mitigation than *BAU*. That said, the *No Harvest* scenario still cumulatively (from 2021-2100) sequesters and stores −487.0 MMT CO_2e, which is 12% (-52.9 MMT CO_2e) more than the *BAU* scenario. Given that this increase in cumulative sequestration and storage is driven mainly by increased forest productivity in the first one to two decades of the simulation, harvest cessation could be seen as a short-term management strategy in the context of climate mitigation. However, adopting such a shift in management comes with longer-term downsides, such as increased emissions from decomposition of wood which could have otherwise been transferred to durable HWPs, and a shift in the forest age class distribution which limits the potential for future productivity and thus climate mitigation potential.

Climate change is expected to diminish the capacity of forests to sequester and store carbon due to increased levels of natural disturbance and mortality (Janowiak et al. 2017). One aspect of these impacts, higher levels of forest mortality due to more frequent and severe insect infestation, was incorporated into the *Climate Change Impacts* scenario. Due to this increase in mortality, the *Climate Change Impacts* scenario consistently produced fewer climate mitigation benefits each year compared to *BAU,* emitting + 0.4 MMT CO_2e yr^{-1} (7%) more carbon on average. Cumulatively, these increased emissions relative to the *BAU* scenario mean that the *Climate Change Impacts* scenario emits +31.1 MMT CO_2e (7%) more carbon than the *BAU* scenario by 2100. We also assessed two adaptive silviculture scenarios—reflecting intentional efforts to enhance the long-term resilience of forests to a changing climate. However, neither the *Insect Vulnerability Transition* nor the *Enrichment Planting* scenarios meaningfully impact climate mitigation benefits relative to the *BAU* scenario, with average annual emissions <0.1 MMT CO_2e yr^{-1} greater than *BAU* for both scenarios. Despite these scenarios providing marginal differences in mitigation potential as compared to *BAU*, enacting these treatments can lead to additional co-benefits including increases in forest resilience and adaptive capacity in the face of future climate regimes and growing conditions.

The *Portfolio* scenario illustrates the potential climate mitigation benefits of implementing several scenarios concurrently from 2021 through 2100. These practices include those from the *Avoided Conversion (low)*, *Tree Planting (mid)*, *Enrichment Planting*, *Climate Change Impacts*, and *Insect Vulnerability Transition* scenarios. These combined effects lead to an average annual increase of −1.5 MMT CO_2e yr^{-1} more climate mitigation than the *BAU* scenario between 2021 and 2100, demonstrating that various actions can be taken to counter additional emissions from climate change impacts and increase Minnesota's forest carbon sink relative to BAU. Like the *Tree Planting (high)* scenario, these effects are not uniform through time, increasing from an average of -0.3 MMT CO_2e yr^{-1} more than *BAU* from 2021-2030 to an average of −2.6 MMT CO_2e yr^{-1} more than BAU from 2091-2100. Cumulatively, this equates to -553.3 MMT CO_2e of climate mitigation from 2021-2100, 27% (-199.1 MMT CO_2e) more than the *BAU* scenario. However, despite the fact that the *Portfolio* combines multiple potential CSF management strategies, the inclusion of the *Climate Change Impacts*, and *Insect Vulnerability Transition* scenarios (which each result in less climate mitigation than BAU), means that the *Portfolio* only provides the fourth highest level of cumulative climate mitigation, behind the *Tree planting (high)*, *Tree planting (low)*, and *BAU – 50% LLP* scenarios.

Other Considerations

The *BAU* scenario does not incorporate future climate conditions or climate-driven disturbance regimes. Except for the *Climate Change Impacts* scenario, every scenario assumes that recent levels of natural disturbance (e.g. wind, fire, insects, wind damage) will persist through the end of the century. The analytical approach used in this report focuses more narrowly on climate mitigation potential, and the results are reported solely in those terms as assumptions related to shifts in growing conditions and subsequent alterations to albedo, hydrological conditions, belowground dynamics and other ecosystem processes introduce substantial uncertainties. The results of this study do not include explicit findings on the impacts of each scenario on other forestry objectives related to biodiversity, wildlife habitat, water cycling, recreation, or other vital services forests provide.

Conclusion

Forests are managed for multiple goals and objectives. Identifying strategies and policies that could optimize all forest benefits remains crucial to the health and stewardship of public and private forestlands. Scenarios that increase overall forest extent not only increase the future climate mitigation potential of forests but expand the provision of other forest benefits such as wildlife habitat, clean water, forest products, and recreation as well. The need to balance climate mitigation goals with future demands for resources is essential to the stewardship of natural and working forestlands. Further, proactively preparing for climate change by incorporating climate change considerations into management and planning will further support the health and stewardship of forests today and into the future.

Our modeling results suggest that the continuation of recent management levels, natural disturbances, and land use changes achieve a balance between harvest and forest growth that sustains a stable carbon sink over the 80-year study period. This analysis also estimated the climate mitigation potential of other management actions based on high-level themes identified by state agency staff. The results broadly indicate that increasing the area of forestland, maintaining forest health and regeneration, sustainable use of timber products, and managing for future impacts of climate change provide promising opportunities to increase climate mitigation benefits from Minnesota's forests. Furthermore, our results suggest that managing forests state-wide for age-class diversity allows for optimization of forest management, economic, and societal goals. This report only assesses the carbon implications of actions (or lack of actions), but many of the scenarios evaluated provide other forest co-benefits in support of forest stewardship. Our results do not suggest that Minnesota is currently at a critical point of a future weakened net carbon sink. However, our results do highlight several strategies that forest managers in Minnesota could consider to increase both the climate mitigation potential and future resilience of Minnesota's forests and forest products sector.

Introduction

Forests as a Natural Climate Solution

Climate change presents an unprecedented global challenge to society and the ecosystems society relies on. Forests have become increasingly important in international climate change dialogues, as seen in the Paris Agreement and the COP26 Glasgow Leaders' Declaration on Forests and Land Use (COP26 2021; Popkin 2019) to help reach net zero greenhouse gas (GHG) emission targets. Further, there is also increasing consensus of forests' importance as a nature-based solution to climate change, or natural climate solution (NCS) through their mitigative and adaptive potentials (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 durable longer-live wood products.

Forests in the United States (US) and the forest products sector already play an important role in mitigating climate change, a benefit which can be significantly impacted through forest management decisions and policies. The overall mitigation potential of the forestry sector is determined not only by the carbon captured from tree growth, but also by the carbon stored in harvested wood products (HWP) and how HWPs are ultimately retired (e.g., sent to the landfill, recycled, or combusted for energy recapture). In 2020, land use, land use change, and forestry captured and stored an additional 758.9 million metric tons of carbon dioxide equivalency (MMT CO_2e), offsetting 13.6% of total GHG emissions 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 significantly increase the carbon-capturing potential of forests through management and policy actions (Fargione et al. 2018). However, this carbon savings potential is expected to decrease throughout the 21st century due to forest loss, forest productivity declines, and forest health challenges fueled by climate change (Wear and Coulston 2015; Oswalt et al. 2019).

Assessing Forest Climate Benefits in Minnesota

State governments can leverage the climate benefits from forests, and protect them from future climate impacts, through their strong influence on forest management and policy, 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 economy-wide or multi-sector 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 power and potential of forests to reduce the concentration of carbon dioxide in the atmosphere, states are exploring measures to demonstrate, promote, and support an active sustainable forest industry and are incorporating forests, forestry, and HWPs in state climate policy and planning efforts.

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. State governments within the Lake States region (Minnesota, Wisconsin, and Michigan) desire to use this information to inform decision-making and shape policy regarding forests and climate action. Minnesota, Michigan, and Wisconsin collectively contain 54.66 million acres of forestland, and are currently taking steps to build knowledge about climate mitigation and adaptation opportunities in their forests. Understanding shifts in emissions and the role of forests and forest products at a regional level creates opportunities to address challenges through shared learning.

This report is designed to provide important insights into the key drivers of climate mitigation in Minnesota's forests—with the goal of building knowledge about the role of forests, forestry, and wood products in meeting statewide climate objectives. Here, we present carbon modeling results for a broad range of forward-looking scenarios including forest management, HWP utilization, climate impacts and adaptive silviculture, tree planting, and avoided conversion. This systems-level approach assesses the carbon sequestered in forests and stored in forests and HWP, along with an analysis of the substitution benefits from using wood in place of other emissions-intensive materials and shifting of harvest activities to other regions.

The Environmental Context of Minnesota's Forests

Minnesota's forests are a diverse arrangement of boreal coniferous forests in the north and east, temperate hardwoods to the southeast, and prairie parklands in the west. These 18.68 million acres of forestland (~34.6% of the total state area) were heavily shaped by economic and political forces in the 19th century, including widespread conversion of forests to agricultural lands and periods of extensive logging. Prior to European settlement, Minnesota's forests were an estimated 31.5 million acres (Marschner 1930). Land use policies in the 18th century that encouraged agricultural development resulted in the clearing of forestlands across large portions of the state. The footprint of Minnesota's forests are currently half of the pre-settlement area. More recent estimates of forested area in Minnesota through the USDA Forest Service FIA program suggest that this footprint is steadily growing despite continued pressure from agriculture and development (Hilliard et al, 2022).

Minnesota has a long history of forest management beginning prior to becoming a state in 1858. The 1800s was dominated by intensive logging centered on the use of eastern white pine for fueling rapid western expansion. However, the beginning of the 20th century saw a shift towards sustaining forest resources through development of more integrated forest management and planning. The establishment of federal and state forest lands—and the profession of forestry itself—during this period reflected a shift towards long-term sustainable forest stewardship (MN DNR 2020). The 2020 State Forest Action Plan established three priority areas being: 1) Conserve and manage working forest landscapes for multiple values and uses; 2) Protect forests from threats; and 3) Enhance public benefits from trees and forests.

45% of Minnesota's forest area is privately owned, where 4% of the total forest area are within Tribal reservation boundaries. 24% of forestlands are managed by state agencies as state forests, parks, and wildlife areas. The Federal government has jurisdiction over nearly 16% of forests in the state. Local governments (e.g. counties) own 15% of forests (USDA Forest Service 2020a). Minnesota's forests are diverse but are dominated by Aspen-Birch forest type groups (36% of forest area), Spruce-fir forest type groups (25% of forest area), and a variety of other deciduous species including oaks, hickory, elm, and maple (29% of forest area, USDA Forest Service, 2020a). The majority of forests (52%) are characterized as young or early successional (0-60 years old) with 42% being characterized as middle-aged (60-120 years old) (USDA Forest Service, 2020a). Current threats to forest land in Minnesota include forest fragmentation, high rates of insect-caused mortality, aging forests which may increase susceptibility to disease, insects, weather, and other damaging agents, and an overall decline in timber harvest since the early 2000s as a result of mill closures. Minnesota's forests are at a nexus where the continued maintenance of the forest carbon sink requires implementing continued forest stewardship strategies. Addressing key vulnerabilities in both economically and ecologically important forest types within Minnesota necessitates improved insights and information for decision-makers about the future ramifications of both management and policy decisions that may directly or indirectly influence forest carbon dynamics at a regional level.

Research and Modeling Process

Following methodologies developed in Papa et al. (2023); Davidson et al. (2026); DeLyser et al. (2025; 2022a; 2022b); and Dugan et al. (2018; 2019; 2021), we assessed carbon trends of several scenarios including alternative forest management, wood utilization, climate adaptation and impacts, tree planting, and avoided conversion. We estimated net emissions in Minnesota's forest ecosystem and forest products sector for each scenario using a systems-based approach. This systems-based approach accounts for the influence of forest management activities beyond the forest itself and allows us to evaluate the effects of each scenario in terms of the net exchange of carbon dioxide between forests, harvested wood products, and the atmosphere over time (Papa et al., 2023; Dugan et al., 2018). Our participatory modeling process included:

1) Consultation with state agency staff and forestry experts to understand opportunities and challenges related to climate mitigation and adaptation in Minnesota's forests;

2) Development of business-as-usual (BAU) and alternative forest management scenarios – including forest management, natural disturbance, land-use change, and wood utilization – 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 Minnesota, ii) a customized harvested wood products dynamics model for Minnesota (CBM-HWP-MN) utilizing the Abstract Network Simulation Engine (ANSE) framework, iii) potential leakage factors applied to changing harvest rates, and iv) 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 connections with forest management programs and policies statewide, and inform engagement in state climate policy work.

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 including deadwood and forest soils. In addition to growth of woody biomass, accrual of carbon in the forest ecosystem also depends on rates of accumulation of dead wood, leaf litter, and soil (Smith et al. 2006), as well as decomposition – all complex dynamics that affect the net carbon balance of the forest. 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. 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, accurate assessments of forest carbon dynamics and interactions with other sectors are needed. The systems-based 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, substitution effects of wood products in place of emissions-intensive materials, and leakage which occurs when emissions shift elsewhere due to a reduction in harvest. Excluding any one of these components would lead to an incomplete accounting of forest carbon, misrepresenting net forest emissions and climate mitigation potential (Smith et al. 2006; Papa et al. 2023; Dugan et al. 2018; Kurz et al. 2009; Nabuurs et al. 2007).

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 (Papa et al. 2023; 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 flexible 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 Database (FIADB, USDA Forest Service, 2020a) to ensure accuracy for Minnesota's forests. We use the CBM-CFS3 for this study of climate mitigation trends in Minnesota's forests and harvested wood products sector to expand on previous modeling efforts in Maryland, Pennsylvania, California, and Oregon (Dugan et al. 2018; Papa et al. 2023; DeLyser et al. 2022a; 2022b, 2025; Davidson et al. 2026).

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 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).

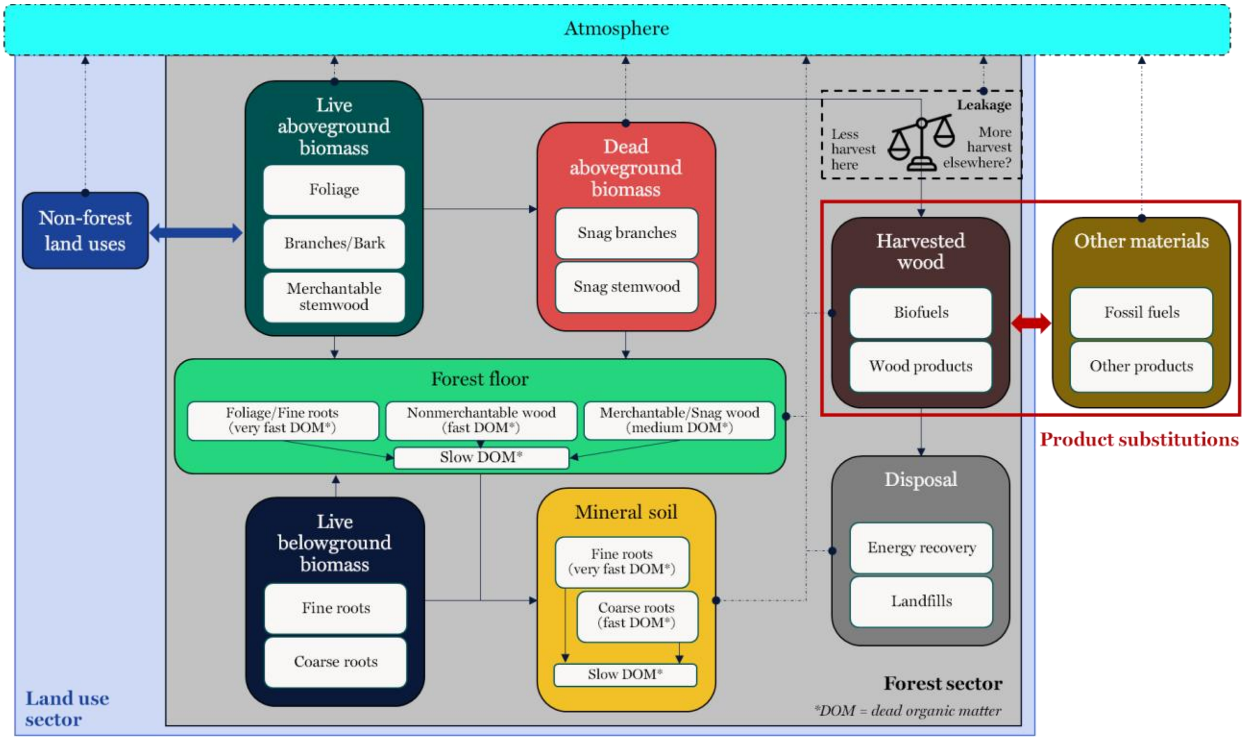

Figure 1. Simplified systems view of land uses and sectors influencing forest carbon stocks and sequestration. The Forest sector (gray box) provides a graphical representation of forest carbon pools and transfers in the CBM-CFS3 model and ANSE carbon accounting tool. For DOM pools, "very fast", "fast", "medium", and "slow" refer to the rate of decomposition among the various DOM pools. Transfers between the land-use sector (blue box) and the forest sector (gray box) represent land-use change (either forest loss or forest gain). Product substitutions (red outline) represent the use of harvested wood in place of other more carbon intensive materials. (Adapted from Kull et al., 2019; Nabuurs et al., 2007).

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** and **Table S1** 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 Lake States region 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).

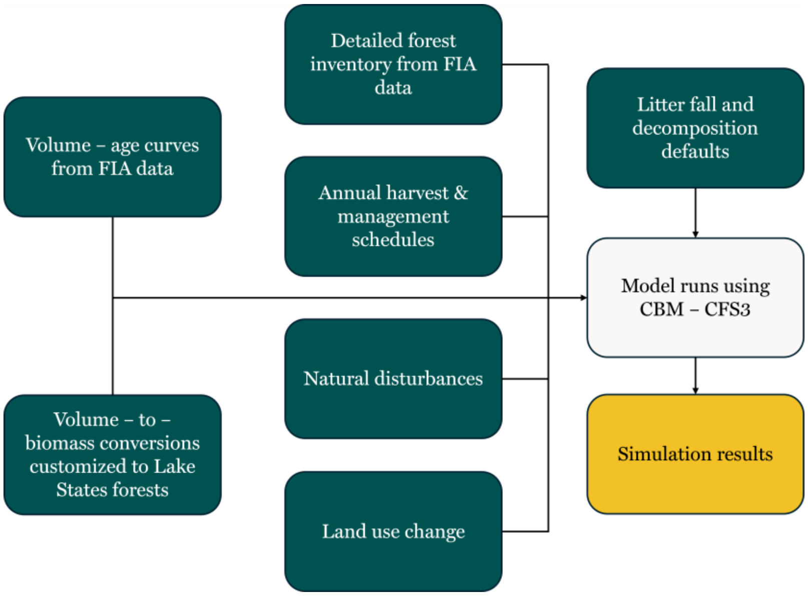

Figure 2. Modeling inputs and processes for CBM-CFS3. Adapted from Kull et al. 2019.

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, disturbance data come from FIA (USDA Forest Service, 2020a), USDA National Insect and Disease Detection Surveys (IDS; USDA Forest Service 2020b), the Monitoring Trends in Burn Severity (MTBS, Eidenshink et al., 2007), and the National Land Cover Databases (Wickham et al, 2021). Estimates for harvest data were derived from both USDA Forest Service FIA (USDA Forest Service, 2020a) and MN DNR planning documents. Harvest schedules on state managed lands were informed by both the MN DNR stand exam list (MN DNR 2020) and direct Division of Forestry consultation whereas private and federally managed harvest schedules were derived from the FIADB. 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 the **Appendix** for more information on data and assumptions used in model parameterization.

Harvested Wood Products Model

To calculate and assess carbon stored by, and GHG emitted from, forest products across diverse forest management scenarios, we employed the CBM-HWP-MN model. This model was built using the ANSE modeling framework, a carbon accounting tool developed by the Canadian Forest Service (CFS) and used for Canada's national GHG inventory reporting in tandem with CBM-CFS3 (CFS 2024). This framework facilitates tracking, modeling, and calculating carbon storage and emissions in the forest products sector associated with HWP from both historic and projected future harvest activities. Emissions from other related sectors, such as transportation and manufacturing of HWP, are not included in this framework. The CBM-HWP-MN model contains custom modeling flows and parameters, e.g., roundwood export proportions and destinations, commodity production proportions, product half-lives, wood recycling rates, and displacement factors, specific to Minnesota products and markets.

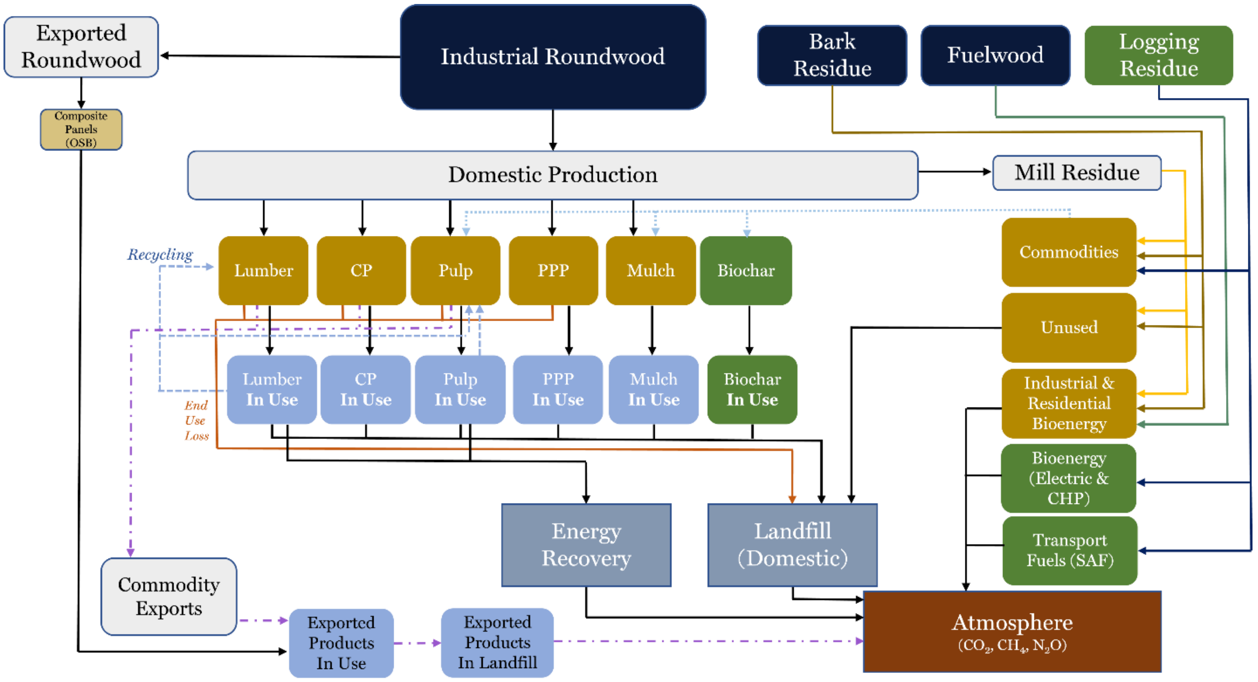

Figure 3. Pathways for carbon in harvested wood products in the CBM-HWP-MN model, used for analysis of the fate of harvested carbon in Minnesota. CP stands for composite panels; PPP stands for poles posts and pilings. Logging residue inputs, and Bioenergy, Biochar, and Transport Fuels categories are included for alternative wood utilization scenarios and do not represent current active industries in Minnesota.

Some *disturbance events* (particularly, though not exclusively, harvest events) in CBM-CFS3 transfer carbon to the wood products sector, providing annual wood removal volumes in units of carbon which in turn become the primary data input for the CBM-HWP-MN model. These carbon inputs are partitioned into various HWP streams based on current practices in the forest products sector in Minnesota (**Figure 3;** data sources provided below). Of that which enters into the industrial roundwood stream, a portion is first allocated to roundwood exports. 100% of exported roundwood is assumed to be sent to Canada for processing into oriented strand board (OSB), a type of composite panel. All remaining industrial roundwood carbon is allocated toward domestic commodity production, with a certain proportion going toward mill residues that either become fuel, feed into additional commodity production, or go unused. Other wood product streams include bark residue, which like mill residues can be used for fuel, additional commodity production, or remain unused, and fuelwood, which is burned for residential or industrial heating and energy production. Each domestic commodity produced from roundwood or other sources has a corresponding half-life that determines the longevity of the carbon in use before moving to a product retirement pathway (i.e., recycled, burned for energy, or sent to the landfill) and, eventually, being emitted back to the atmosphere. Emissions from landfilled wood and paper products are largely dictated by the proportion of their material assumed to be decomposable (we assume 10% for wood and 50% for paper) meaning the remaining material will not decompose or emit carbon to the atmosphere during our model timeframe (IPCC 2019; Zhao 2019).

For any scenario resulting in less harvest than 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 apply a leakage factor of 84.4% (Wear and Murray 2004), meaning that 84.4% of reduced harvest relative to BAU is assumed to leak out-of-state and the remaining 15.6% of reduced harvest relative to BAU is subject to additional emissions from product substitution from using other emissions-intensive materials instead of wood. In all cases, we assume leakage only results from reduced in-state harvest; we assume any additional in-state harvest relative to BAU results in increased in-state wood use and disposal (e.g., pile burning, recycling, or landfilling) rather than reductions in out-of-state harvest.

In cases where HWP substitute for alternative, more emissions-intensive products (e.g., concrete or steel), the difference in embodied emissions associated with those commodities relative to 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, bioenergy, and transport fuel production. 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; instead, 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 leakage and substitution benefit calculation methods.

To parameterize the CBM-HWP-MN model, we use state-specific harvest, commodity, and trade data from USDA Forest Service (2019b; 2023a; 2023b), Minnesota DNR (De Pellegrin Llorente et al. 2024), and Howard & Liang (2019). Softwood and hardwood products are parameterized and modeled separately, as the two wood types differ in exports and commodities produced, as well as their associated product half-lives and displacement factors. We incorporate commodity manufacturing efficiency data from Row & Phelps (1996), Franklin Associates (1998), and Skog & Nicholson (2000). We use end-use product half-lives from IPCC (2022), Skog (2008), Howard et al. (2017), Dymond (2012) and Smith et al. (2006) to calculate weighted softwood- and hardwood-specific half-lives for all commodities currently produced in Minnesota, and default IPCC half-lives for international wood, fuel, and paper (Pingoud et al. 2006). We assume a biochar half-life of 100, on the conservative (i.e., low) end of literature ranges (Zhang et al. 2022; Li and Tasnady 2023), based on state partner input. Displacement factors associated with wood product substitution and bioenergy are calculated according to Smyth et al. (2017) and Cabiyo et al. (2021) and include emissions from harvest, transport, and production but do not factor in building operational emissions. Landfill carbon dioxide and methane emissions calculations rely on IPCC defaults for methane generation (k) and landfill half-lives. See **Table 3** in the **Developing Modeling Scenarios** section for BAU HWP parameters and **Appendix** for more details on data and assumptions used in model parameterization.

Identifying Forest Management and Policy Priorities

Through a series of meetings with staff from the Minnesota Department of Natural Resources Division of Forestry, we identified several questions, challenges, and opportunities related to the role of Minnesota's public and private forestlands in mitigating climate change. Discussions were iterative and focused on how these pathways would relate to influences on future forest carbon dynamics. In 2023, the MN DNR published a legislative report identifying keeping forest as forest (avoided conversion), expanding forest cover (tree planting), and sustainable forest management as three key pathways for enhancing climate mitigation benefits (MN DNR, 2023). We used this information to translate these narratives into scenarios to model, both for a projected BAU scenario and a suite of scenarios representing a range of opportunities and challenges including:

- **Management of working forestlands** to maintain and enhance multiple co-benefits. This requires the balancing of goals to ensure the optimization of benefits from forests. Tools such as tree harvesting or cutting, prescribed fire, and other climate adaptive management techniques can be utilized now to address vulnerabilities to ensure forests remain productive today and into the future. Changes to current management regimes such as altering rotation lengths, altering harvest levels, and assisting the transition of ecosystems can be expected to affect forest carbon dynamics and therefore lend themselves well to sets of alternative management scenarios. There is significant interest in the relationship between timber harvest, harvested wood products, and atmospheric carbon. This interest includes discourse among differing perspectives and opinions about the climate mitigation consequences of timber harvesting. Technical dimensions of this discourse has oftentimes relied on incomplete assessments. Therefore, there is a strong need to build more rigorous and holistic understanding about the climate mitigation effects of sustained management of public and private forestlands—as well as the implications of timber harvest levels.

- **Climate change impacts and climate-adaptive forestry** to protect forests from current and future threats. Future forest management and planning will need to include adapting to and reducing climate impacts. Mortality events from insect-caused outbreaks and shifts in precipitation patterns are predicted to decrease the suitable habitat and biomass across northern areas of the state. This will subsequently impact species range and health of both ecologically and economically important species such as aspen, northern red oak, black spruce, tamarack, or eastern white pine (Handler et al, 2014). We utilized the Climate Change Response Framework (CCRF) that uses a continuum of resistance, resilience, and transition to serve as fundamental options for managers to consider when responding to climate change (Swanston et al., 2016). Quantifying the climate mitigation effects of climate impacts—and the strategies that enhance adaptive capacity—are important for understanding the relationship between adaptation and mitigation over the long term.

- **Wood utilization and markets** to ensure a healthy vibrant forest bioeconomy sustaining rural livelihoods and communities. Forests are both ecologically and economically important, but the viability of wood markets is contingent on sustaining forest productivity. In turn, wood markets provide vital resources and financing for forest management activities. Harvested wood products store carbon and substitute for more emissions-intensive materials. Identifying where climate benefits within the forest products sector can bolster the economic viability of working forest lands remains crucial to mitigating global climate change.

- **Maintain and expand forest cover** to generate multiple benefits—including climate mitigation. Each year, thousands of acres of Minnesota's forests are permanently converted to development and agricultural production. Reducing the rate of forest conversion into other land uses is a critical pathway for enhancing the role of forests in climate mitigation. Similarly, intentional tree planting on open ground where ecologically appropriate is another pathway for enhancing the strength of Minnesota's forest carbon sink. Past studies suggest that there are somewhere between 3.6 and 7.6 million acres of formerly-forested private open lands that can be converted to forests without compromising primary cropland (MN DNR 2023). Understanding the climate mitigation implications of maintaining and expanding forest cover in quantitative terms is an important aspect of integrating them into climate policy and planning work.

The forest management and policy themes outlined above align well with the three core principles 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 ecosystem services such as wildlife habitat, clean water supplies, forest products, and recreation, among others (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 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 directly addresses long-term forest health and resilience in the face of climate change as part of sustainability in forest management. Importantly, CSF aims to generate these climate mitigation and adaptation objectives while continuing to provide wildlife habitat, clean water, timber and other forest products, and scenic beauty.

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. They do not reflect direct specific intentions or plans. At least two scenarios—*No Harvest* and *Climate Impacts*—were developed for the purpose of testing extremes to better illustrate drivers, tradeoffs, and differences in climate mitigation benefits over time. In general, we developed modeling scenarios based on available data, modeling capabilities, and expected relevance for landscape-scale carbon dynamics. Other identified priorities may reasonably be expected to influence carbon on a landscape scale but were novel or unstudied enough that available data quantifying those carbon influences were limited. Thus, the final list of scenarios chosen had both sufficient data and carbon impact to incorporate into as scenario.

Business-as-Usual (BAU) Scenario

A core objective of this project is to estimate the differential carbon impacts of various forest management and wood utilization strategies in Minnesota. This requires the development 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 fire), land-use changes (afforestation and deforestation), and natural disturbances (i.e., wildfires, windthrow, and insect and disease outbreaks) at relatively steady rates based on a snapshot of recent conditions. As constructed, the *BAU* allows for the estimation and project of current practices and their collective effects on net carbon balance into the future. Though this does not account for changes in policies, climate, or economics, it is a useful exercise to explore how the continuation of average behaviors and disturbances in recent years may affect future forest dynamics and carbon cycling. It also allows for comparisons to scenarios with different assumptions than the *BAU*.

The analysis covers the period from 2021-2100 projecting historical averages starting in 2020 (**Tables 1 and 2**). This longer-term simulation period can capture multiple rotations of management through Minnesota forests. Doing so allows estimation of the effects of management decisions that may take years to decades to manifest. Similarly, HWP model results extend through 2100, and incorporate an initial spin-up period (1950-2020) to estimate inherited products and landfill carbon stocks from prior to year 2020.

Table 1. BAU ecosystem disturbance parameters. All areas are inputted targets (actual model response may vary by year). Tons of carbon and volumetric values are summarized based on the volume removed by each harvest or cutting regime in the BAU simulation. All values are reported as a rate (per year).

Land-use change			
Forest loss	28,808 ac yr^{-1}	Forest Gain	41,758 ac yr^{-1}
Natural disturbances			
Fire (Low Intensity)	7,888 ac yr^{-1}	Animal	79,803 ac yr^{-1}
Fire (Medium Intensity)	1,502 ac yr^{-}	Abiotic (Light)	50,822 ac yr^{-1}
Fire (High Intensity)	949 ac yr^{-1}	Abiotic (Severe)	39,835 ac yr^{-1}
Defoliator (light <10%)	9,392 ac yr^{-1}	Mortality (Light < 10%)	14,619 ac yr^{-1}
Defoliator (Moderate 10-50%)	41,417 ac yr^{-1}	Mortality (Moderate <10-50%)	5,291 ac yr^{-1}
Defoliator (Severe > 50%)	7,999 ac yr^{-1}	Mortality (Severe >50%)	3,934 ac yr^{-1}
Forest management practices			
Prescribed fire (~40% understory consumption)	10,971 ac yr^{-1}		
Federal forests			
Clearcut	8,451 ac yr^{-1} 116,753 tC yr^{-1} 43,034 MCF yr^{-1}	Thin	2,730 ac yr^{-1} 5,854 tC yr^{-1} 1,387 MCF yr^{-1}
Uneven-Aged	1,846 ac yr^{-1} 10,044 tC yr^{-1} 13,348 MCF yr^{-1}		

Table 1, cont. *BAU ecosystem disturbance parameters. All areas are inputted targets (actual model response may vary by year). Tons of carbon and volumetric values are summarized based on the volume removed by each harvest or cutting regime in the BAU simulation. All values are reported as a rate (per year).*

State forests			
Clearcut	31,241 ac yr^{-1} 179,621 tC yr^{-1} 71,248 MCF yr^{-1}	Thin	7,250 ac yr^{-1} 22,561 tC yr^{-1} 11,255 MCF yr^{-1}
Uneven-Aged	5,829 ac yr^{-1} 22,638 tC yr^{-1} 12,549 MCF yr^{-1}		
County / Municipal forests			
Clearcut	23,784 ac yr^{-1} 270,363 tC 92,754 MCF yr^{-1}	Thin	4,559 ac yr^{-1} 12,253 tC yr^{-1} 5,485 MCF yr^{-1}
Uneven-Aged	3,966 ac yr^{-1} 16,929 tC yr^{-1} 18,282 MCF yr^{-1}		
Private forests			
Clearcut	85,866 ac yr^{-1} 540,360 tC yr^{-1} 196,663 MCF yr^{-1}	Thin	20,789 ac yr^{-1} 56,788 tC yr^{-1} 20,907 MCF m^{3} yr^{-1}
Uneven-Aged	13,939 ac yr^{-1} 100,160 tC yr^{-1} 89,402 MCF yr^{-1}		

Alternative Management and Wood Utilization Scenarios

Within this analysis, we constructed alternative *scenarios* by changing BAU parameters beginning in 2020, representing potential changes in future decision-making, disturbances, or market dynamics. Scenarios relate to one specific practice or objective where only one BAU parameter is changed while all other parameters remain the same. This allows for the examination of the specific influence of each scenario on net ecosystem carbon balance and evaluation of its climate mitigation potential. Our 19 scenarios cover a broad range of themes and are grouped into five categories representing similar objectives: 1) forest management; 2) climate impacts and adaptive silviculture; 3) harvested wood product utilization; 4) tree planting; and 5) avoided forest conversion (**Table 3**; see the **Appendix** for additional scenario details). While each individual scenario represents a single management concept, these practices would rarely be implemented in isolation across the state. To better represent comprehensive forest climate action, we constructed a *Portfolio* management scenario – an ensemble of multiple scenarios that could be concurrently implemented across the state—to illustrate the cumulative potential of Minnesota's forests to provide climate mitigation benefits.

We developed four scenarios to assess the impacts of different **Forest Management** practices on carbon dynamics. The *Extended Rotation* scenario increases the modeled minimum harvest age (**Table S2**), increasing the average rotation age. We extended the rotation ages of key forest types of red pine, aspen, black spruce, and tamarack +15-30 years depending on the forest type as well as increased the reentry interval for uneven aged management systems and thinnings by +10 years. The *No Harvest* scenario ceases all harvesting, cutting, and thinning activities. This scenario does result in some carbon being sent to HWP from forestland being converted to other land-uses. The *Increased Harvest Levels* scenario increased the annual rate of harvest on private lands by +10% per year to assess how increased timber harvesting activity might impact forest carbon sink strength across the timeseries. The *Increased Reserve Size* increases the proportion of merchantable volume left standing following clearcutting or other even-aged silvicultural treatments.

Three scenarios were developed to assess potential carbon implications of **Climate Change Impacts and Climate Adaptive Silviculture**. The *Climate Change Impacts* scenario increases the extent of insect mortality disturbance events by +10% (acres per year) as well as increasing the severity, or mortality rate, by +10%. The remaining two scenarios use the idea of transition from the CCRF which refers to either actions or responses intentionally anticipated to accommodate a change in ecosystems of higher vulnerability to adapt to changing and new conditions. The *Insect Vulnerability Transition* scenario increases the rate of harvest of ash and tamarack stands, two forest types severely impacted by invasive disease and pests in the region, and regenerates them artificially as black spruce, northern white-cedar, and lowland hardwood forest types noting the scenario makes an assumption of successful regeneration of new forest types.

We developed six scenarios aimed at assessing the impact of **Harvested Wood Product Utilization** on carbon sequestration and storage, particularly in the HWP sector. Two of these scenarios used BAU ecosystem assumptions paired with alternate HWP assumptions where a proportion (20% or 50%) of roundwood that would normally be allocated toward pulp was instead allocated toward longer lived wood products (**Table 3**), thereby altering product retirement and landfill emissions, as well as substitution benefits. In the latter four scenarios, additional wood which would otherwise be left in the forest as coarse woody debris, is removed during the harvest process and sent to the HWP sector. All other ecosystem aspects of the scenarios, including the harvest intensity (acres per year), are identical to *BAU*. This logging residue is used in one of four ways (**Table 3**). In the *Logging Residue Utilization - BAU* scenario it is treated as any other HWP input (i.e. using the BAU HWP assumptions). In the *Logging Residue Utilization - Bioenergy* scenario, 100% of the logging residue is allocated to bioenergy production. In the *Logging Residue Utilization – Biochar* scenario, 100% of the logging residue is allocated to biochar production. Finally in the *Logging Residue Utilization – Transportation Fuels* scenario, 100% of the logging residue is allocated to the production of wood-based transportation fuels. In each of these three scenarios, novel product half-lives and/or substitution benefits are applied.

Four scenarios involved **Tree Planting**. The *Tree Planting (low)*, *Tree Planting (mid),* and *Tree Planting (high)* planted an additional +5,599, +11,275, and +22,398 acres per year for each respective scenario. New forests were established at a rate of 25% red pine, 20% white pine, 20% white spruce, 25% oak, and 10% walnut all of which are assumed to be fully stocked and to successfully regenerate following plantings. The *Enrichment Planting* uses an older forest management practice underplanting, in which tree saplings are planted in stands of low stocking and other high light environments without affecting the current growing stock as a means of either artificially regenerating a stand or increasing the success of natural regeneration (Paquette et al., 2006). Lastly, we constructed two scenarios to assess the carbon impacts of various **Avoided Conversion**. *Avoided conversion (low)* and *avoided conversion (high)* reduced the rate of deforestation by -10% and -30% annually which results in keeping more forest as forest over time.

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

Removals distribution (proportion of carbon inputs distributed to various modeling streams)			
Softwood removals		Hardwood removals	
Industrial roundwood	85.39% of all removals	Industrial roundwood	78.45% of harvest removals
Fuelwood	2.59% of all removals	Fuelwood	4.97% of harvest removals
Bark residue	12.02% of all removals	Bark residue	15.58% of harvest removals
Roundwood exports			
Softwood exports	0%	Hardwood exports	0.53%
Commodity distribution (proportion of carbon distributed to various commodities)			
Softwood commodities		Hardwood commodities	
Lumber	13.45%	Lumber	5.42%
Composite panels	3.21%	Composite panels	13.47%
Posts, poles, pilings	0.48%	Posts, poles, pilings	0%
Paper	36.69%	Paper	46.05%
Mulch	3.28%	Mulch	1.45%
Bioenergy from mill residue	10.67%	Bioenergy from mill residue	10.84%
Mulch from mill residue	14.96%	Mulch from mill residue	3.04%
Paper from mill residue	5.14%	Paper from mill residue	0.88%
Bioenergy from bark residue	8.89%	Bioenergy from bark residue	16.55%
Mulch from bark residue	3.26%	Mulch from bark residue	1.35%
Composite panels from exported roundwood	0%	Composite panels from exported roundwood	0.01%
Product half-lives			
Domestic use			
Softwood lumber	42.7 years	Pulp	2.6 years
Hardwood lumber	22.5 years	Mulch	2 years
Softwood composite panels	59.4 years	Biochar	100 years
Hardwood composite panels	59.4 years	Bioenergy	0 years
Posts, other industrial uses	12 years	Transportation fuel	0 years
International use			
Wood, composite panels, other industrial uses, poles	30 years	Fuel	0 years
		Paper	2 years
Product retirement (100% to landfill unless specified)			
Lumber	67.53% landfill 15.76% energy recovery 16.7% recycled (50% to paper, 50% to lumber)	Paper	26.59% landfill 6.49% energy recovery 66.98% recycled (100% to paper)
Landfills			
Decomposable materials	Paper: 50% Wood: 10%	Landfilled product half-lives, International	Paper: 13.5 years Wood: 26.5 years
Methane generation rate *k*	Paper: 0.06 m^3 yr^{-1} Wood: 0.03 m^3 yr^{-1}	Methane release	10.6% flared 56.8% energy recovery 32.6% unrecovered
Landfilled product half-lives, Domestic	Paper: 12 years Wood: 23 years		

Table 3. Scenario parameters for Minnesota. All carbon measurements are in metric tons (tC).

Forest management

Scenario Name	Objective	Parameter to Change	Parameter value change	Scenario impact
Extended Rotations	Increase average harvest age of stands	Minimum age of allowable harvest	+15-20 years to red pine plantation rotations	Average age of red pine plantation cutting: 81 years → 131 years
			+20 years to aspen rotations	Average age of aspen cutting: 45 years → 66 years
			+30 years to black spruce and tamarack rotations	Average age of black spruce and tamarack cutting: 105 years → 127 years
			+10 years on uneven-aged reentry interval rotations and thinnings	Average age of thinning and uneven-aged cutting: 87 years → 103 years
No Harvest	Reduce all harvesting and thinning activities to zero on all lands	Annual harvest rate	-100% ac yr^{-1}	-163,147 ac yr^{-1} of all harvests and cuttings from 2020-2100
†Increased Harvest Levels	Increase annual harvest targets on privately managed lands	Annual rate of harvest	+10% ac yr^{-1}	+6,860 ac yr^{-1} of harvest and cuttings from 2020-2100
Increased Reserve Size	Increase reserve size follow even-aged cuttings	Harvest intensity rate	+100% increase in merchantable volume left standing	Merchantable volume left standing: 5% → 10% following even-aged harvest from 2020-2100 compared to BAU

Climate change impacts and adaptive silviculture

Scenario Name	Objective	Parameter to Change	Parameter value change	Scenario impact
† Climate Change Impacts	Increase in futural insect mortality disturbances caused by climate change	Annual insect mortality rate and intensity	+10% ac yr^{-1}	+8,268 ac yr^{-1}affected by insect mortality events from 2020-2100 compared to BAU
			+10% severity	-
† Enrichment Planting	Increase supplemental planting to restock understocked stands	Annual rate of supplemental planting	+4,500 ac yr^{-1}	+360,000 ac of supplemental planting from 2020-2100 compared to BAU
† Insect Vulnerability Transition	Increase rate of insect-threatened forest types transitioning to other forest types follow clearcut harvests	Annual transition rate of ash and tamarack forest types following clearcut	+2,426 ac yr^{-1}of tamarack transitioning to black spruce and northern white-cedar forest type following clearcuts	+97,063 ac of tamarack transitioned to black spruce from 2020-2100 compared to BAU +97,063 ac of tamarack transitioned to northern white-cedar from 2020-2100 compared to BAU
			+3,996 ac yr^{-1} of ash transitioning to lowland hardwood forest type following clearcut	+319,655 ac of ash transitioned to lowland hardwoods from 2020-2100 compared to BAU

Table 3, cont. Scenario parameters for Minnesota. All carbon measurements are in metric tons (tC).

Harvested wood product utilization

Scenario Name	Objective	Parameter to Change	Parameter value change	Scenario impact
BAU- Long-lived Wood Products 20%	Increased proportion of harvested carbon sent to longer-lived or engendered wood products	Annual proportion of HWP allocated to longer-lived wood products	+20% of C sent to longer-lived products (composite panels) -20% of C diverted from pulp	
BAU- Long-lived Wood Products 50%	Increased proportion of harvested carbon sent to longer-lived or engendered wood products	Annual proportion of HWP allocated to longer-lived wood products	+50% of C sent to longer-lived products (composite panels) -50% of C diverted from pulp	
Logging Residue Utilization - BAU	Increased rate of logging residues sent to HWP. No change in HWP allocation.	Annual rate of logging residue sent to HWP	Novel logging residue stream, identical allocation to BAU	+0.356 MMT C yr^{-1} of harvest residues sent to HWP from 2020-2100 compared to BAU
Logging Residue Utilization - Bioenergy	Increased rate of logging residues sent to bioenergy production	Annual rate of logging residue sent to HWP	Novel logging residue stream, 100% allocation to bioenergy	+0.356 MMT C yr^{-1} of harvest residues sent to HWP from 2020-2100 compared to BAU
Logging Residue Utilization - Biochar	Increased rate of logging residues sent to biochar production	Annual rate of logging residue sent to HWP	Novel logging residue stream, 100% allocation to biochar	+0.356 MMT C yr^{-1} of harvest residues sent to HWP from 2020-2100 compared to BAU
Logging Residue Utilization – Transportation Fuels	Increased rate of logging residues sent to transportation fuel production	Annual rate of logging residue sent to HWP	Novel logging residue stream, 100% allocation to transportation fuels	+0.356 MMT C yr^{-1} of harvest residues sent to HWP from 2020-2100 compared to BAU

Tree plantings

Scenario Name	Objective	Parameter to Change	Parameter value change	Scenario impact
Tree Planting (low)	Increase rate of tree plantings per year	Annual rate of afforestation	+5,599 ac yr^{--1}	+447,952 ac planted from 2020-2100 compared to BAU
† Tree Planting (mid)	Increase rate of tree plantings per year	Annual rate of afforestation	+11,275 ac yr^{-1}	+895,904 ac planted from 2020-2100 compared to BAU
Tree Planting (high)	Increase rate of tree plantings per year	Annual rate of afforestation	+22,398 ac yr^{-1}	+1,791,998 ac planted from 2020-2100 compared to BAU

Avoided conversion

Scenario Name	Objective	Parameter to Change	Parameter value change	Scenario impact
† Avoided Conversion (low)	Decrease rate of permanent forest lass (deforestation)	Annual deforestation rate	-10% ac yr^{-1}	+2,881 ac yr^{-1} of forestland that avoided permanent conversion from 2020-2100 compared to BAU
Avoided Conversion (high)	Decrease rate of permanent forest lass (deforestation)	Annual deforestation rate	-30% ac yr^{-1}	+8,641 ac yr^{-1} of forestland that avoided conversion from 2020-2100 compared to BAU

Table 3, cont. Scenario parameters for Minnesota. All carbon measurements are in metric tons (tC).

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 Minnesota to fully leverage its forests as natural climate solutions	Annual rate of harvest	+10% ac yr^{-1}	+6,860 ac yr^{-1} of harvest and cuttings from 2020-2100
		Annual deforestation rate	-10% ha yr^{-1}	+2,881 ac yr^{-1} of forestland that avoided permanent conversion from 2020-2100 compared to BAU
		Annual rate of afforestation	+11,275 ac yr^{-1}	+895,904 ac planted from 2020-2100 compared to BAU
		Annual rate of supplemental planting	+4,500 ac yr^{-1}	+360,000 ac of supplemental planting from 2020-2100 compared to BAU
		Annual insect mortality rate and intensity	+10% ac yr^{-1}	+8,268 ac yr^{-1} affected by insect mortality events from 2020-2100 compared to BAU
			+10% severity	-
		Annual transition rate of tamarack forest types following clearcut	+2,426 ac yr^{-1} of tamarack transitioning to black spruce and northern white-cedar forest type following clearcuts	+97,063 ac of tamarack transitioned to black spruce from 2020-2100 compared to BAU
				+97,063 ac of tamarack transitioned to northern white-cedar from 2020-2100 compared to BAU
		Annual transition rate of ash forest types following clearcut	+3,996 ac yr^{-1} of ash transitioning to lowland hardwood forest type following clearcut	+319,655 ac of ash transitioned to lowland hardwoods from 2020-2100 compared to BAU

†Indicates alternative scenarios included in Portfolio

Results and Discussion

Results of our analysis show that under the continuation of current management practices, levels of disturbance, and land use change patterns, both the forest ecosystem and the forest products sector will contribute to climate mitigation benefits in Minnesota through the end of the century. Several of the alternative scenarios modeled in this analysis enhance forest ecosystem and wood products sector carbon sequestration and storage, with most providing additional climate mitigation benefits over BAU management through time. Our results indicate that there are important carbon storage and sequestration trade-offs to consider when assessing the near- and long-term impacts of traditional and climate-adapted management, and climate-smart practices strive to balance both factors while supporting long-term forest health. However, this study does not specifically evaluate tradeoffs between the social, environmental, and economic benefits associated with each management decision.

Impact of Business-as-Usual on Forest Age and Carbon

In the *BAU* scenario, Minnesota's forests are projected to remain a net carbon sink from 2021-2100 (**Figure 4a**), with the strength of this carbon sink remaining relatively stable through the end of the century. Across the 80 years of our simulation, *net ecosystem carbon flux*, the mean net yearly sequestration of carbon by forests after accounting for all emissions including decomposition and wood product removals, in Minnesota's forests was -5.11 MMT CO_2e yr^{-1} with +6.26 MMT CO_2e yr^{-1} transferred to HWP. Ecosystem carbon stocks per unit area of forest (e.g., carbon density) for this same period also increase slightly (**Figure 5**), indicating that the carbon density is relatively stable, and not expected to dramatically change. Importantly, forest extent increased by 14,868 ac yr^{-1} on average (**Figure 4b**) throughout the *BAU* scenario as annual rates of afforestation outpaced annual rates of permanent conversion of forests to other land uses. While this trend aligns with more recent statewide averages, it is important to note that forests may face additional future pressures to convert to other land uses which are not reflected in our *BAU* scenario.

The amount of carbon transferred to HWP also remained stable under the *BAU* scenario, despite initially decreasing through 2060 due to a decline in the area of forests within the harvest-eligible age range in our model (**Table S2**), before increasing again toward the end of the century (**Figure 4a**). Assuming static future HWP demand, Minnesota's forests will be able to maintain current timber supplies while staying a net carbon sink through 2100. Carbon stocks in both hardwood and softwood HWP increased over time in the *BAU* scenario (**Figure 6**), though substantially more for hardwood stocks (+82%) than for softwood stocks (+39%). By 2100, HWP carbon storage is dominated by the landfill categories, comprising 76% and 85% of hardwood and softwood stocks respectively (**Figure 6**). This shift is not representative of a reduction in HWP production, rather it is reflective of HWP retirement and durable landfill storage. Of the in-use categories, the largest components are composite panels (8% of total hardwood stocks in 2100), and sawlogs (6% of total softwood stocks in 2100). HWP carbon emissions mirror trends in HWP carbon transfers, with annual emissions from fuelwood (which are assumed to occur in the same year as the harvest) representing 33% and 19% of total hardwood and softwood emissions, respectively (**Figure 7**). Over the course of the simulation, HWP produced and in landfills prior to 2020 shift from being the dominant source of emissions (58% and 84% of hardwood and softwood HWP emissions, respectively, in 2021) to being the smallest source of emissions (4% and 6% of hardwood and softwood HWP emissions, respectively, in 2100), replaced by contemporary landfill emissions

(55% and 65% of hardwood and softwood HWP emissions, respectively, in 2100). Because the annual transfers of carbon from the forest to the forest products sector outweighs HWP emissions (both from current wood products in use and inherited products and landfills), net HWP carbon balance accrues additional carbon (-0.3 MMT CO_2e yr^{-1}on average from 2021-2100), meaning that HWPs represent a growing carbon storage pool for Minnesota.

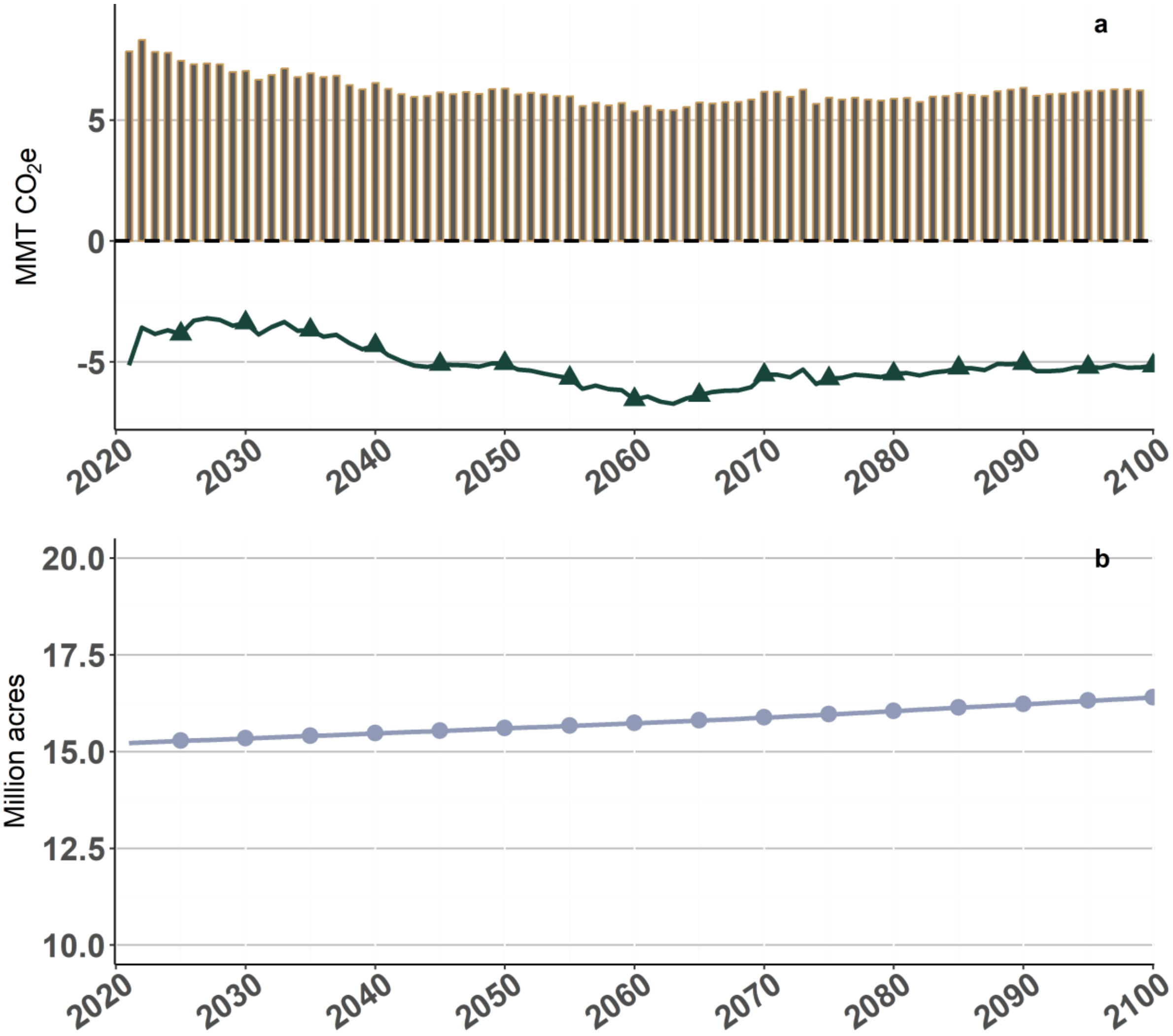

Figure 4. a) BAU scenario forest ecosystem results showing net ecosystem carbon flux (green line) and harvest removals (dark brown bars). Net ecosystem carbon flux represents all growth minus respiration, decomposition, and disturbance emissions (including carbon transfers to HWP). b) represents forest area (million acres) across the BAU simulation.

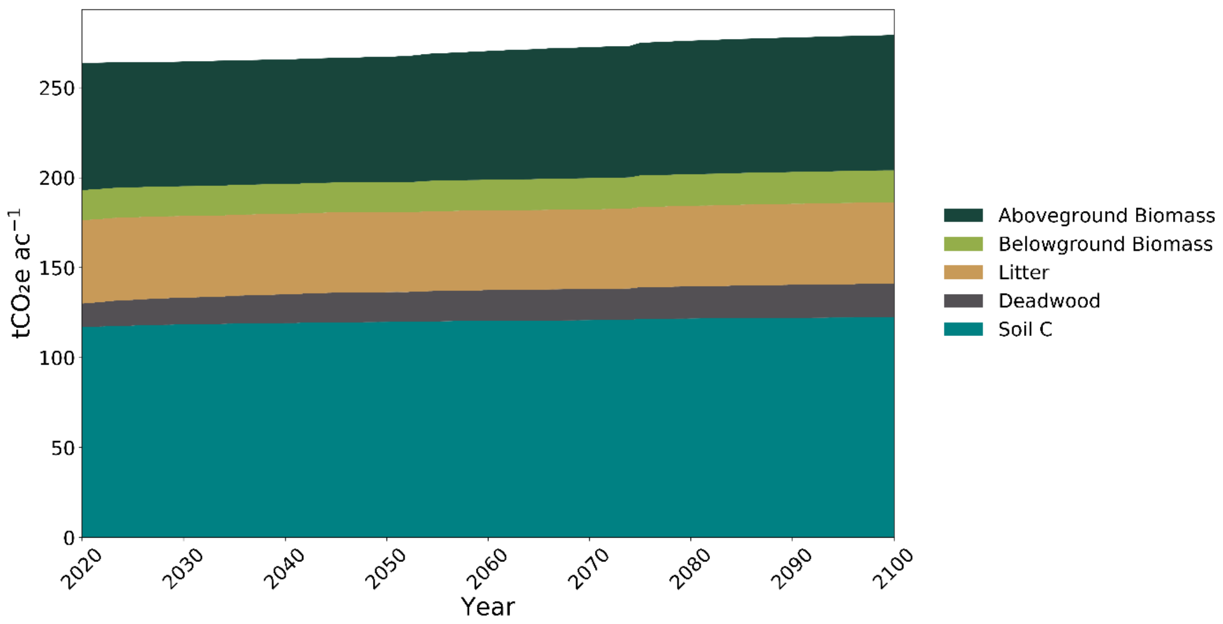

Figure 5. BAU scenario results for per acre carbon stocks ($tCO_2e\ ac^{-1}$) in IPCC reporting pools from 2007-2100. Positive numbers represent accruing carbon stocks. Litter layer includes carbon in the L horizon, fine and small woody debris including dead coarse roots in the forest floor, and carbon in the F, H, and O horizons (i.e., soil carbon above the mineral layer).

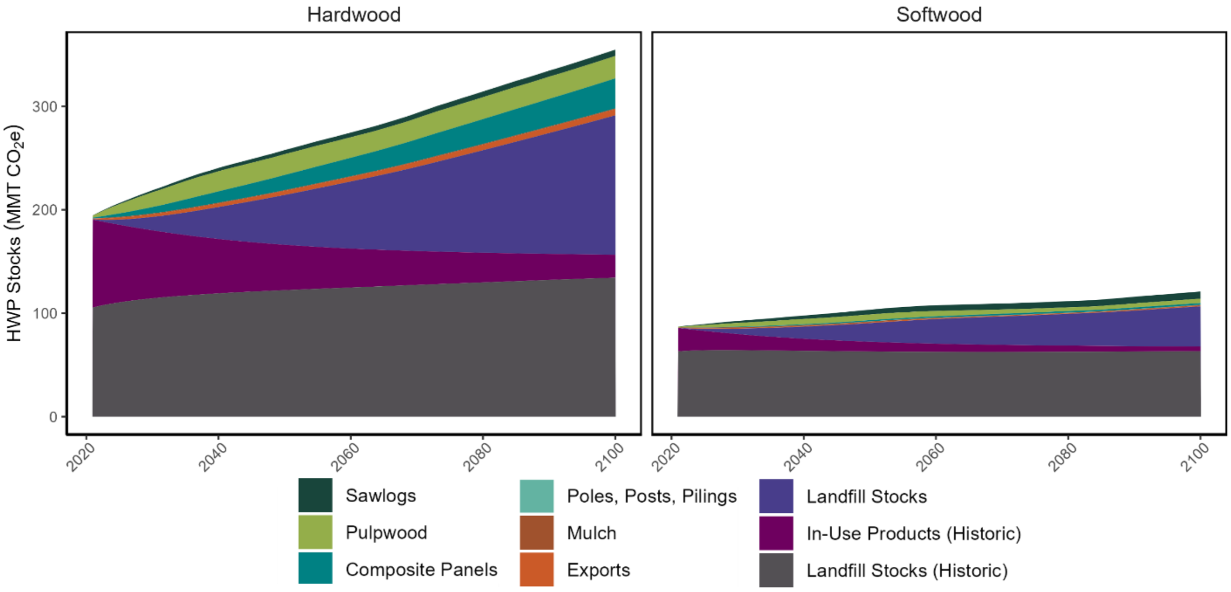

Figure 6. HWP carbon stocks (MMT CO_2e) by primary product for hardwood and softwood from 2021-2100. Positive numbers denote accruing carbon stocks. Historic in-use stocks and landfill stocks represent materials cut prior to the beginning of the simulation. Historic in-use stocks transfer to historic in-use landfill stocks when they reach end of life.

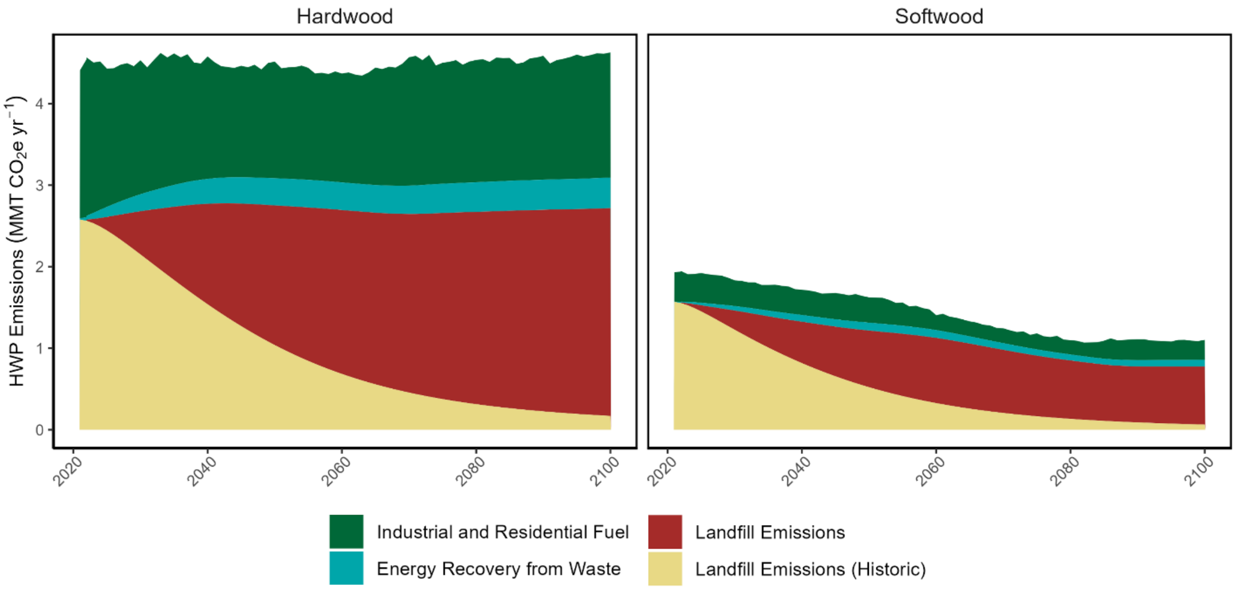

Figure 7. Annual HWP emissions distribution (MMT CO_2e yr^{-1}) for hardwood and b) softwood from 2021-2100 for the BAU scenario. Emissions are the result of woody material that is cut and removed from the forest and do not include any residues or other materials left on site. Historic landfill emissions come from materials cut prior to the beginning of the simulation and already in the landfill. Landfill and energy recovery emissions come from both historically produced products, and those produced from wood harvested during the simulation.

Forest age and age-dependent successional dynamics play an important role in determining current and future net carbon balances. According to our assessment of FIA data surveyed between 2014 and 2019 (USDA Forest Service, 2020a), in 2020, 54% of Minnesota's forests were under 60 years old (**Figure 8**) which suggests that Minnesota's forest should continue to provide strong mitigation benefits in the near future as younger forests generally provide future growth potential. However, as forests age, productivity tends to decline (Pothier et al., 2004; Coomes et al., 2012), meaning that if forests continue to age unabated, productivity is expected to decline toward the end of the century. Present observed age-class distributions in Minnesota are partly determined by legacies of previous management regimes—including both unsustainable timber harvesting in the 19th century and more recent up-and-down trends in total harvesting over the past few decades.

The sustainable management of working forest lands necessitates the careful maintenance of age-class diversity in forests to optimize the benefits received across the landscape. Our results suggest that the projected age distribution in 2100 under the *BAU* scenario (**Figure 8**) shifts into a bimodal distribution with substantial decrease in middle-aged forests (60-120 years old) and a proportional increase in both older forests (120+ years old) and younger early successional forests (<60 years old). Highlighting this phenomenon are aspen stands, which are the most common forest type, making up 28% of the forested landscape in Minnesota. In 2020, <1% of aspen stands are >120 years old. In 2100, the proportion of aspen stands >120 years old increases to 4% under the *BAU* scenario. The proportion of younger aspen stands (<60 years old) also increases by 4% with the proportional reduction coming from middle aged forests (60-120 years old). This shift in age distribution suggests current harvest levels can provide a sustainable amount of young and maturing aspen forests.

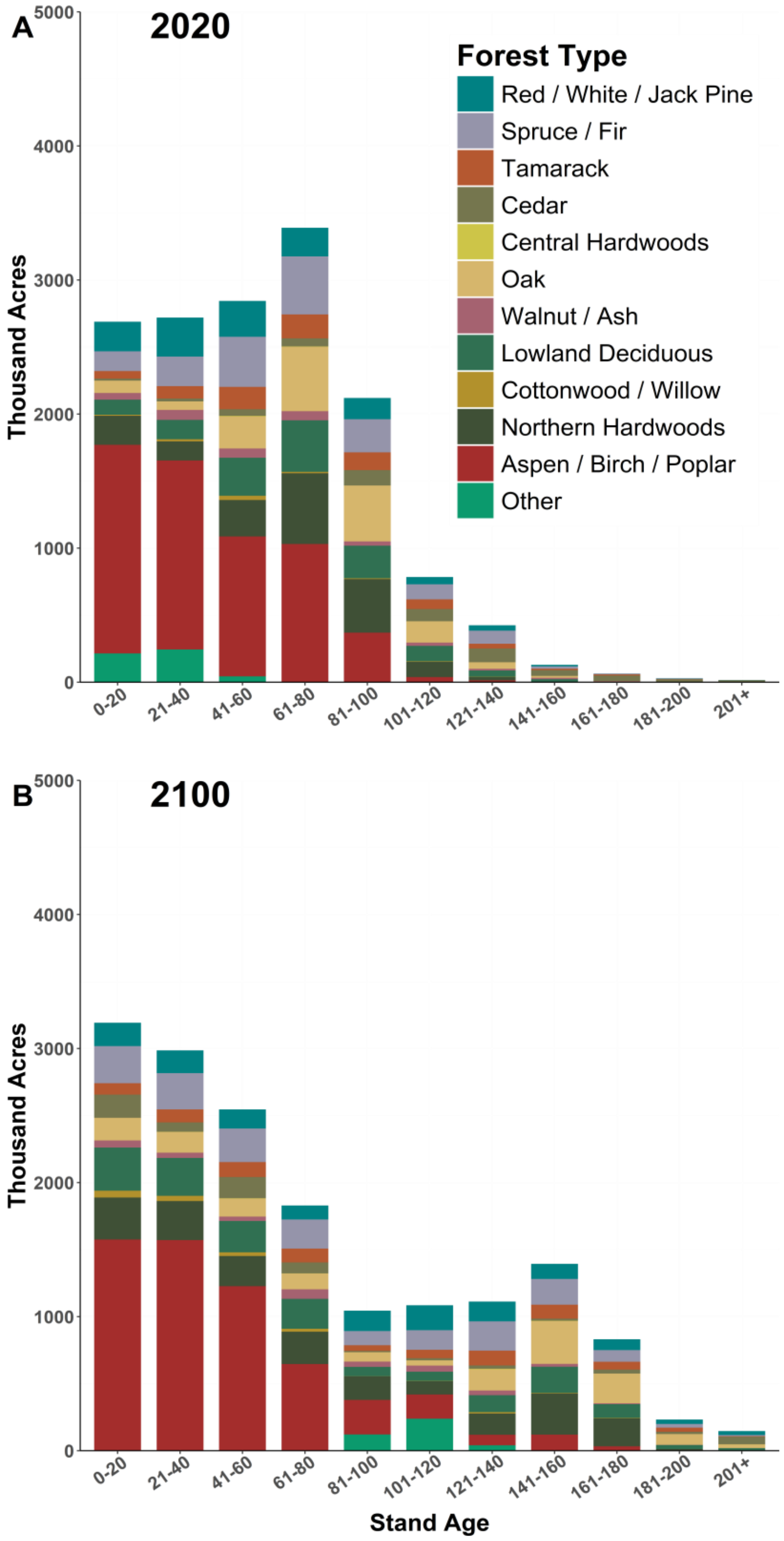

Figure 8. BAU scenario age class distribution by forest type in A) 2020 and B) 2100.

Projected trends in net ecosystem carbon flux by ownership, which does not account for HWP carbon storage or emissions, largely correspond to statewide trends where private forest lands—representing ~44% of forestland by area—provide the largest absolute annual net ecosystem carbon sink (**Table 4**). Under the *BAU* scenario, state-owned forestlands are projected to have high interannual variation in net ecosystem carbon flux that largely tracks annual harvest removals, where years with higher harvest allotments correspond with weaker net carbon sinks or even weak carbon sources. State managed forestlands begin the simulation as a weak source driven in part by harvest removals but also rates of forests recover. State managed forestlands shift primarily into a carbon sink throughout the latter half of the century except for a brief period between 2081-2090. Private and county and municipal forestlands increase in carbon sink strength throughout the *BAU* simulation (**Table 4**) whereas federally managed lands decrease in sink strength. These results are partially driven by changes in the distribution of forest age classes. The later section **The Influence of Age Class on Climate Mitigation Potential** describes in more detail variability across scenarios and potential driving factors.

Table 4. Average decadal net ecosystem carbon flux (MMT CO_2e yr^{-1}) by ownership for business-as-usual simulation and total annual average from 2021-2100. Net Ecosystem Carbon Flux represents all growth minus respiration, decomposition, and disturbance emissions (including carbon transfers to HWP). Negative numbers denote a net carbon sink.

Ownership	2021-2030	2031-2040	2041-2050	2051-2060	2061-2070	2071-2080	2081-2090	2091-2100	Total annual average
Forest Service	-1.43	-1.26	-1.07	-0.85	-1.07	-0.67	-0.50	-0.28	-0.80
Other Federal	-0.20	-0.18	-0.14	-0.12	-0.14	-0.10	-0.09	-0.07	-0.12
State	1.41	0.86	-0.06	-0.38	-0.06	-0.37	0.16	-0.56	0.1
County and Municipal	-0.27	-0.32	-0.52	-0.85	-0.52	-0.92	-0.80	-0.50	-0.60
Private and Native American	-3.17	-3.00	-3.28	-3.62	-3.28	-4.23	-4.37	-3.84	-3.70

Net Carbon Balance in Forests and Forest Products Sector

When considering both forests and the forest product sector, all scenarios remain a net carbon sink from 2021-2100, indicated by a net carbon balance less than zero. *Net carbon balance* includes net ecosystem carbon flux 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 atmospheric CO_2 sequestered and stored in forests and wood products (a net carbon sink), and positive values indicate atmospheric CO_2 emitted from forests and wood products (a net carbon source).

To illustrate the differential impact of each scenario when compared to *BAU*, results are presented in *standardized* terms. The standardized mitigation potential is calculated by subtracting the annual net carbon balance of the *BAU* scenario from the annual net carbon balance of each alternative scenario (**Figure 9**). This allows for a more direct assessment of the relative mitigation potential of each alternative management practice. We present these standardized values both as annual means and as cumulative totals (**Table 5**).

Annual Net Carbon Balance

The *Tree Planting (high)* scenario presents the best opportunity for increasing forest carbon sink strength, with an annual net carbon balance averaging 21% less (meaning greater sequestration and storage) than *BAU* from 2021-2030 (-0.9 MMT CO_2e yr^{-1}), 48% less than *BAU* from 2031-2050 (-2.3 MMT CO_2e yr^{-1}), and 72% less than *BAU* from 2051-2100 (-4.2 MMT CO_2e yr^{-1}; **Figure 9**, **Table 5**). These values help strengthen the annual net carbon balance, thereby creating a larger carbon sink, with annual values -24% of the current (2021) annual capacity in 2050 (-8.2 MMT CO_2e yr^{-1}) and -68% of the current annual capacity in 2100 (-11.1 MMT CO_2e yr^{-1}). This suggests that increasing the rate of afforestation efforts to convert non-forestland to forestland provides significant long-term mitigation potential but also highlights that the mitigation potential from tree planting can take years to decades to manifest, with the largest increases in annual net carbon balance relative to *BAU* occurring towards the end of the century (**Figure 9**). This dynamic of increasing relative mitigation through time is both the consequence of a growing forest area, allowing for more carbon sequestration across the state, and the fact that as the simulation progresses those trees planted early in the simulation reach maturity and peak productivity, contributing to higher carbon sequestration and storage and more climate mitigation. The other two tree planting scenarios (*Tree Planting (mid)* and *Tree Planting (low)*) each also result in increased annual mitigation relative to *BAU*, and like with the *Tree Planting (high)* scenario, each experience an increase in the magnitude of annual mitigation through time (-0.2 and -0.5 MMT CO_2e yr^{-1} from 2021-2030, -0.6 and –1.3 MMT CO_2e yr^{-1} from 2031-2050, and –1.0 and –2.1 MMT CO_2e yr^{-1} from 2051-2100, for the mid and low scenarios, respectively; **Figure 9, Table 5**).

Table 5. Comparison of mean annual standardized net carbon balance (MMT CO_2e yr^{-1}), and cumulative standardized net carbon balance (MMT CO_2e) for our 19 modeled scenarios. Net carbon balance includes net ecosystem carbon flux 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 numbers for net carbon balance represent a scenario which is a net carbon sink relative to BAU, and positive numbers represent a scenario which is a net carbon source relative to BAU.

Group	Scenario	Mean Annual Standardized Net Carbon Balance (MMT CO_2e yr^{-1})				Cumulative Standardized Net Carbon Balance (MMT CO_2e)		
		2021-2030	2031-2050	2051-2100	2021-2100	2021-2050	2021-2075	2021-2100
Forest management	Extended Rotations	-0.2	-0.5	-0.2	-0.3	-12.0	-16.1	-20.5
	Increased Harvest Levels	0.3	0.2	0.2	0.2	7.1	12.9	14.8
	Increased Reserve Size	-0.4	-0.4	-0.4	-0.4	-12.3	-21.8	-34.7
	No Harvest	-3.0	-3.1	0.8	-0.7	-92.4	-94.1	-52.9
Climate change impacts and adaptation	Climate Change Impacts	0.3	0.3	0.5	0.4	8.6	22.1	31.1
	Enrichment Planting	0.0	0.0	0.0	0.0	-0.3	1.2	0.2
	Insect Vulnerability Transition	0.1	0.1	0.0	0.0	2.6	3.9	2.9
Harvested wood product utilization	BAU - 20% LLP	-1.2	-1.2	-1.3	-1.3	-36.1	-68.4	-102.5
	BAU - 50% LLP	-2.9	-3.1	-3.3	-3.2	-90.2	-170.9	-256.4
	Logging Residue Utilization	-0.6	-0.8	-0.4	-0.5	-21.8	-31.2	-41.2
	Logging Residue Utilization - Biochar	-0.6	-1.0	-0.8	-0.8	-25.9	-45.1	-67.3
	Logging Residue Utilization - Bioenergy	0.4	0.0	0.0	0.0	3.6	4.3	2.9
	Logging Residue Utilization - Transport Fuels	0.0	-0.7	-0.6	-0.5	-13.5	-27.2	-44.1
Avoided conversion	Avoided Conversion (low)	0.0	-0.2	-0.1	-0.1	-2.9	-4.5	-7.3
	Avoided Conversion (high)	0.0	-0.3	-0.5	-0.4	-7.0	-17.2	-31.2
Tree planting	Tree Planting (low)	-0.2	-0.6	-1.0	-0.8	-13.3	-34.7	-63.2
	Tree Planting (mid)	-0.5	-1.3	-2.1	-1.7	-30.1	-75.4	-136.4
	Tree Planting (high)	-0.9	-2.3	-4.2	-3.3	-55.2	-143.2	-266.4
Portfolio	Portfolio	-0.3	-0.8	-2.0	-1.5	-19.4	-58.6	-119.1

Like the three tree planting scenarios, the *Avoided Conversion (high)* scenario also exhibits an increase in annual climate mitigation through time, though of a substantially smaller magnitude (**Figure 9**). In this scenario, the annual net carbon balance averages 1% less (meaning greater sequestration and storage) than *BAU* from 2021-2030 (-0.03 MMT CO_2e yr^{-1}), 7% less than *BAU* from 2031-2050 (-0.3 MMT CO_2e yr^{-1}), and 8% less than *BAU* from 2051-2100 (-0.5 MMT CO_2e yr^{-1}; **Table 5**). This increase in climate mitigation through time comes about as the result of two changes. First, since the *Avoided Conversion (high)* scenario reduces the rate of permanent conversion of forests to other land use types, less wood is transferred to the HWP sector, thereby reducing future HWP sector emissions. Second, like the *Tree Planting* scenarios, *Avoided Conversion* effectively increases the forest area and carbon sequestration and storage relative to the *BAU*, with this relative difference increasing through time.

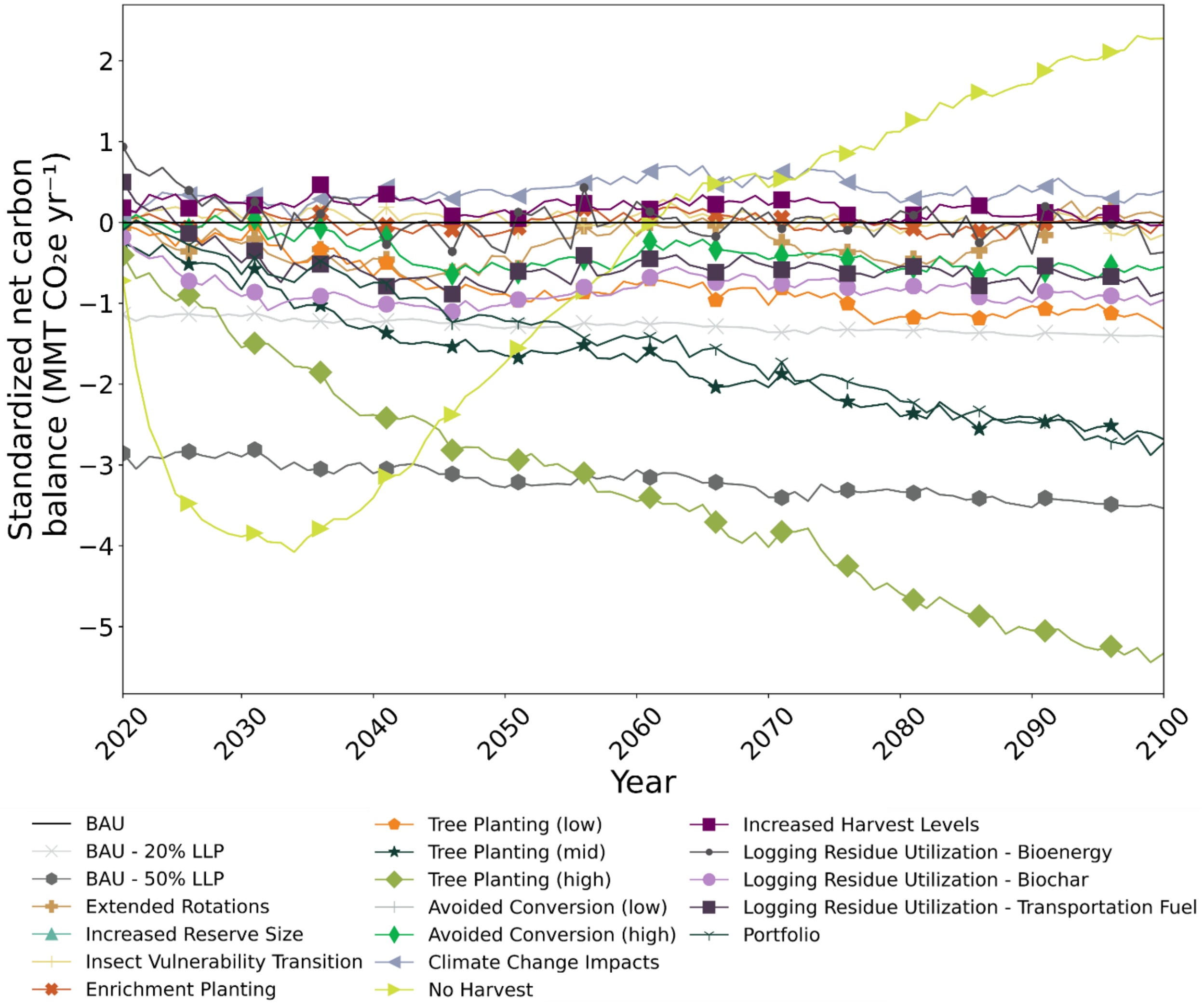

Figure 9. Annual net carbon balance for selected scenarios (2021-2100) standardized to BAU. Net carbon balance includes net ecosystem flux in the forest, transfers to HWP, emissions from wood products in use and in landfills, substitution benefits in years where harvest is different than BAU, and leakage 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).

Both *Long-Lived Products* scenarios also provide substantial and consistent additional annual climate mitigation relative to *BAU* (**Figure 9**). For example, the *BAU – 50% LLP* scenario has an annual net carbon balance which averages 62% less (meaning greater sequestration and storage) than *BAU* from 2021-2030 (-2.9 MMT CO_2e yr^{-1}), 66% less than *BAU* from 2031-2050 (-3.1 MMT

CO_2e yr^{-1}), and 57% less than *BAU* from 2051-2100 (-3.3 MMT CO_2e yr^{-1}; **Table 5**). Unlike other scenarios, the *Long-Lived Products* scenarios provide strong climate mitigation from the outset, as much of their benefit comes from product substitution where the production of additional composite panels displaces other more emissions-intensive non-wood products. Both scenarios also experience a slight increase in standardized annual net carbon balance through time, as composite panels have a longer in-use and in-landfill half-life than pulp products, meaning that compared with the BAU wood utilization assumptions, emissions in these scenarios are reduced in the near to long term.

Trends in annual net carbon balance for the *No Harvest* scenario provide an interesting case, highlighting the important tradeoff between ecosystem and HWP carbon dynamics. In this scenario, annual net carbon balance averages 67% less (meaning greater sequestration and storage) than *BAU* from 2021-2030 (-3.0 MMT CO_2e yr^{-1}), 69% less than *BAU* from 2031-2050 (-3.1 MMT CO_2e yr^{-1}), and 14% more than *BAU* from 2051-2100 (0.8 MMT CO_2e yr^{-1}; **Table 5**). However, these periodic trends do not tell the full story. The annual climate mitigation potential of the *No Harvest* scenario initially increases until 2034 before decreasing for the remainder of the simulation, and it is less than *BAU* from 2061 onwards (**Figure 9**). The initial improvement in annual net carbon balance is fueled by elevated annual ecosystem carbon sequestration and storage and reduced emissions from the HWP sector, indicative of the fact that when harvests are curtailed, the ecosystem can sequester and store substantially more carbon. However, as the simulation progresses, ecosystem emissions from decomposition increase, offsetting much of the additional carbon storage in the ecosystem, and reduced harvest transfers, leakage, and displaced emissions from negative product substitution mean that the *No Harvest* scenario begins to sequester and store less carbon annually than *BAU*, leading to a positive standardized annual net carbon balance (**Figure 9**).

Despite emitting more carbon than the *BAU* scenario early in the simulation (2021-2024), the *Portfolio* scenario also results in significant additional climate mitigation (**Figure 9**). The *Portfolio* scenario has an average annual net carbon balance 6% less (meaning greater sequestration and storage) than *BAU* from 2021-2030 (-0.3 MMT CO_2e yr^{-1}), 18% less than *BAU* from 2031-2050 (-0.8 MMT CO_2e yr^{-1}), and 34% less than *BAU* from 2051-2100 (-2.0 MMT CO_2e yr^{-1}; **Table 5**). As with the *Tree Planting (mid)* scenario, which is a component of the *Portfolio* scenario, the annual climate mitigation for the *Portfolio* scenario increases through time, and reaches its peak in the final decade of the simulation (**Figure 9**).

The remaining scenarios each fall within the range of −0.8 to +0.4 MMT CO_2e yr^{-1} of average annual net carbon balance relative to *BAU* (**Table 5**), with no clear or consistent trends in each year's annual value (**Figure 9**). Of these scenarios, *Logging Residue Utilization – Biochar, Logging Residue Utilization - Transport Fuels, Increased Reserve Size,* and *Extended Rotations* each provide additional climate mitigation relative to *BAU*, while *Enrichment Planting, Insect Vulnerability Transition, Logging Residue Utilization – Bioenergy, Increased Harvest Levels*, and the *Climate Change Impacts* scenario lead to reduced climate mitigation relative to *BAU* (**Table 5**). Despite this increased annual average net carbon balance relative to *BAU*, it is important to note that all scenarios modeled in this analysis have overall (non-standardized) annual net carbon balances less than zero, meaning that forests and the forest products sector remain a net carbon sink under all scenarios.

Cumulative Net Carbon Balance

To further illustrate the differential impact of each scenario when compared to *BAU*, results in this section are presented in *cumulative standardized* terms. As is the case when looking at annual standardized net carbon balance, cumulative standardized net carbon balance is calculated by subtracting the net carbon balance of the *BAU* from the net carbon balance of each scenario, and then summing all standardized annual net carbon balance values to a point in time (**Figure 10**). This allows for a more direct assessment of the relative mitigation potential of each alternative management practice totaled over the entire simulation.

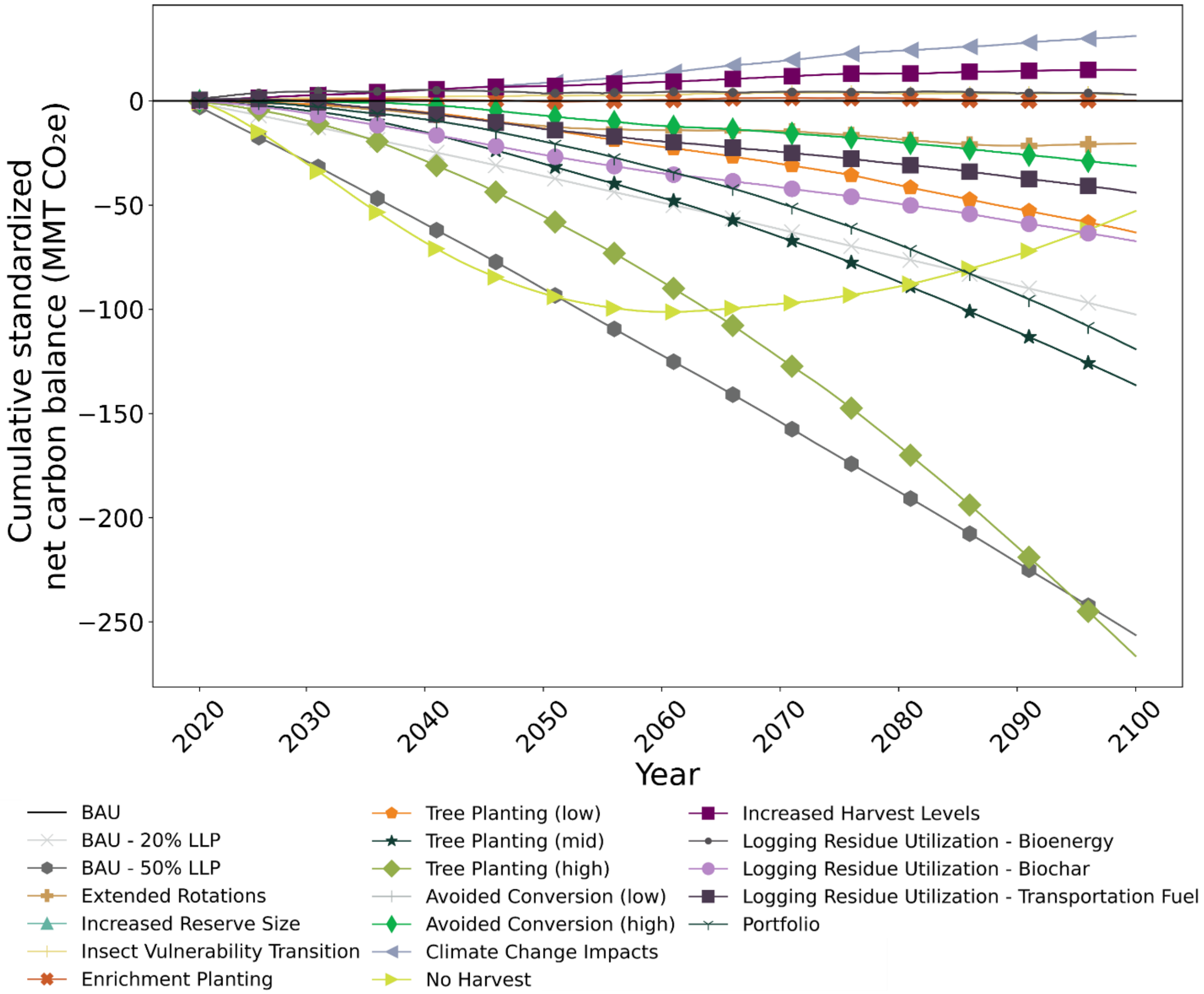

Figure 10. Cumulative net carbon balance for selected scenarios (2021-2100) standardized to BAU. Net carbon balance includes net ecosystem flux in the forest, transfers to HWP, emissions from wood products in use and in landfills, substitution benefits in years where harvest is different than BAU, and 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).

By 2100, the cumulative net carbon balance of the *Climate Change Impacts* scenario is +30 MMT CO_2e weaker than *BAU* (meaning less climate mitigation), while in the *Tree Planting (high)* scenario it is −266.4 MMT CO_2e stronger than *BAU* (meaning a higher level of climate mitigation; **Figure 10, Table 5**). This range illustrates the potential spread of climate mitigation potential for Minnesota's forests, depending on which future management decisions are implemented or if BAU practices and climate conditions are continued. By 2100, the *Portfolio* scenario results in a lower level of climate mitigation than the *Tree Planting (high)* scenario (-119.1 MMT CO_2e for the *Portfolio* vs −266.4 MMT CO_2e for the *Tree Planting (high)* scenario), but the *Portfolio* still represents an improvement in cumulative climate mitigation potential over a continuation of BAU practices. Critically, the *Portfolio* scenario also compensates for the increased relative emissions associated with the *Climate Change Impacts* scenario, which is included within the *Portfolio*. In addition to the *Climate Change Impacts* scenario, the *Portfolio* scenario also includes a wide range of concurrent climate-smart forest management practices, which are each represented separately in the single-effect scenarios. The majority of remaining scenarios modeled fall within +/-70 MMT CO_2e of cumulative net carbon balance relative to *BAU* (+/- 0.9 MMT CO_2e yr^{-1} on average), indicating more modest impacts of these scenarios when implemented alone.

We can further examine the components of cumulative net carbon balance for each scenario to illustrate the effect of different drivers—including changes in forest ecosystem carbon flux, HWP transfers, HWP emissions, leakage, and product substitution (**Figure 11**). For example, the *No Harvest* scenario accumulates the largest amount of additional carbon in the forest ecosystem relative to BAU by 2100, but also has the highest cumulative leakage, and the largest cumulative negative substitution effects (**Figure 11**). Initially, the cumulative net carbon balance of the *No Harvest* scenario strengthens relative to *BAU* (**Figure 10**), due to higher levels of forest ecosystem carbon sequestration and storage and lower levels of harvest transfers (**Figure 11**). However, as forest ecosystem productivity wanes with age, and HWP emissions, leakage, and negative substitution effects accumulate over time relative to *BAU*, the cumulative net carbon balance declines significantly between 2062 and 2100 (**Figure 10**). This difference amounts to a cumulative net carbon balance of -92.4 MMT CO_2e, -94.1 MMT CO_2e, and -52.9 MMT CO_2e more than *BAU* in 2050, 2075, and 2100, respectively (**Table 5**). This shift in cumulative net carbon balance for the *No Harvest* scenario illustrates that a large amount of the potential climate mitigation benefits accrued from 2021-2060 will be lost by 2100 due to decreasing growth rates and increasing HWP emissions. This scenario also highlights the important interplay between carbon storage in the forests and the forest products sector when considering total climate mitigation potential. Because the initial increase in cumulative sequestration and storage is driven mainly by increased forest productivity, harvest cessation could be seen as a short-term management strategy in the context of climate mitigation. However, adopting such a shift in management comes with longer-term downsides, such as increased emissions from decomposition of wood which could have otherwise been transferred to durable HWPs, and a shift in the forest age class distribution which limits the potential for future productivity and thus climate mitigation.

The other three forest management scenarios—*Increased Harvest, Extended Rotations,* and *Increased Reserve Size*—exhibit similar tradeoffs between ecosystem and HWP carbon, though to a smaller degree (**Figure 10**). The *Increased Harvest* scenario results in less carbon stored in the forest ecosystem and more carbon transferred to HWP relative to *BAU*, accompanied by a small amount of displaced emissions from positive product substitution (**Figure 11**). However, this additional transfer of carbon to the HWP sector leads to slightly greater HWP emissions each year relative to *BAU*. Collectively, these effects lead to a cumulative net carbon balance of +2.6 MMT

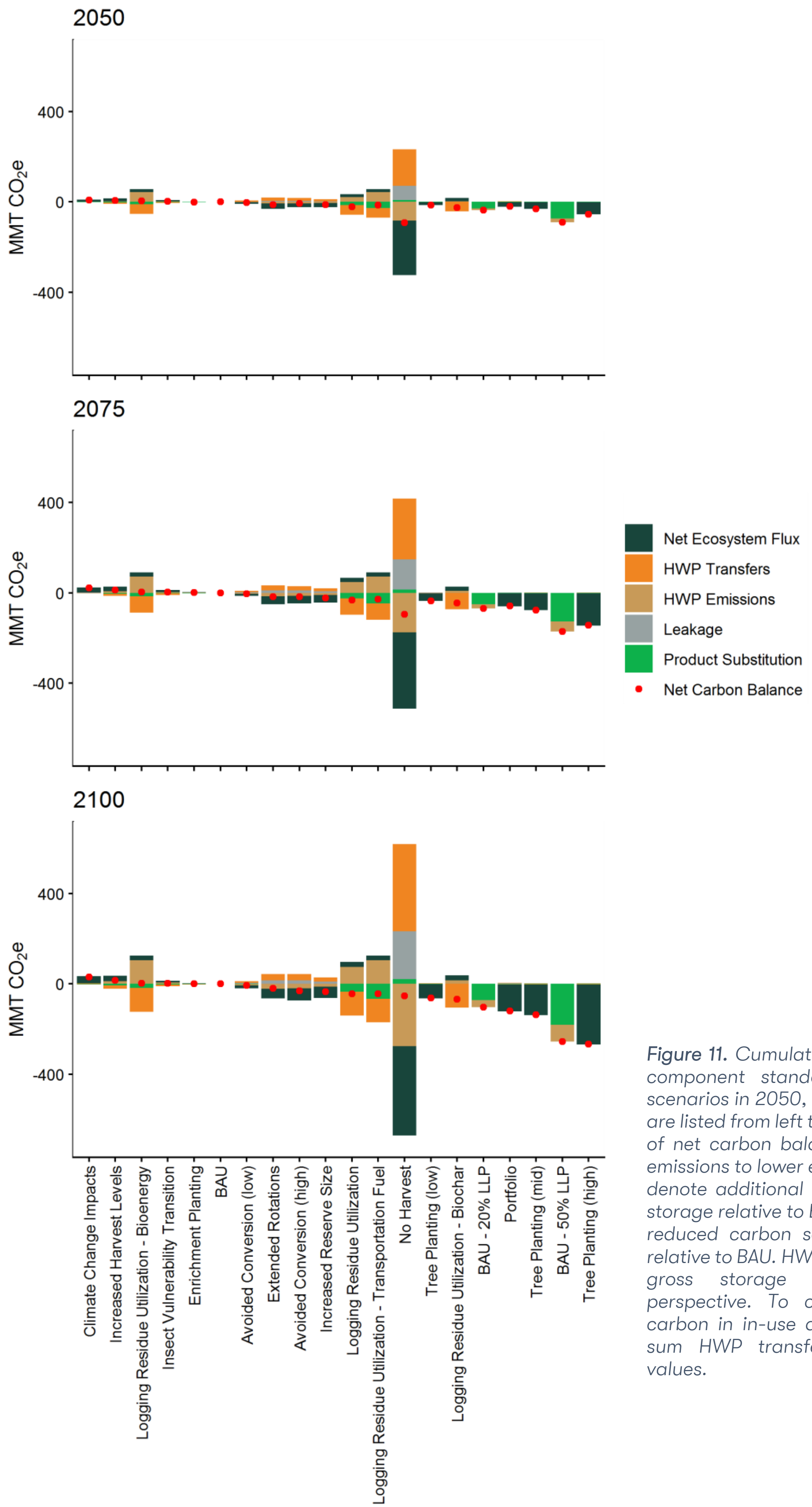

Figure 11. Cumulative mitigation potential by component standardized to BAUs for all scenarios in 2050, 2075, and 2100. Scenarios are listed from left to right in descending order of net carbon balance in 2100 (from higher emissions to lower emissions). Negative values denote additional carbon sequestration and storage relative to BAU. Positive values denote reduced carbon sequestration and storage relative to BAU. HWP transfers are depicted as gross storage from the system-level perspective. To calculate net storage of carbon in in-use and in-landfill HWP pools, sum HWP transfers and HWP emissions values.

CO_2e (meaning less climate mitigation) relative to *BAU* by 2050, +3.9 MMT CO_2e relative to *BAU* by 2075, and +2.9 MMT CO_2e relative to *BAU* by 2100 (**Table 5**). The *Extended Rotations* scenario, which simulates an increase in harvest rotation lengths for specific cover types, results in

a cumulative net carbon balance of -12.0 MMT CO_2e (meaning additional sequestration and storage) by 2050, -16.1 MMT CO_2e by 2075, and -20.5 MMT CO_2e by 2100 relative to the *BAU* scenario (**Table 5**). The *Increased Reserve Size* scenario, which doubles the merchantable volume left standing post-harvest for clearcut and other even-aged treatments, leads to a cumulative net carbon balance of -12.3 MMT CO_2e relative to *BAU* by 2050, -21.8 MMT CO_2e by 2075, and –34.7 MMT CO_2e by 2100 (**Table 5**). Of the four forest management scenarios, the *Increased Reserve Size* scenario results in a significant amount of cumulative climate mitigation relative to *BAU* despite a relatively small (-0.4 MMT CO_2e yr^{-1}) average annual net carbon balance (**Table 5**). In addition, unlike the *No Harvest* scenario, this mitigation benefit is expected to remain consistent over the simulated timeframe (**Figure 10**) and not have an effect on forest age class distribution (**Figure 12**), as the *Increased Reserve Size* scenario still allows for harvest, and thus similar post-harvest regeneration and productivity dynamics as under *BAU*.

The three Tree Planting scenarios—especially the medium and high versions of this management action—generate significant improvements in annual net ecosystem carbon flux (meaning additional carbon sequestration and storage) relative to the *BAU* scenario, which is expected given the net increase in forest area prescribed for each scenario (**Figure 11**). The total increase in forest area ranges from 0.45 million acres by 2100 for the *Tree Planting (low)* scenario, 0.9 million acres by 2100 for the *Tree Planting (mid)* scenario, and 1.79 million acres by 2100 for the *Tree Planting (high)* scenario (**Table 3**). Each of these three scenarios also results in a slight increase in HWP transfers, and thus a reciprocal increase in HWP emissions and positive substitution benefits relative to *BAU*. The cumulative net carbon balance of these scenarios (listed as low, mid, and high) range from –13.3, -30.1, and –55.2 MMT CO_2e by 2050, -34.7, -75.4, and -143.2 MMT CO_2e by 2075, and –63.2, -136.4, and -266.4 MMT CO_2e by 2100 relative to *BAU* (**Table 5**). Across all three tree planting scenarios, the annual mitigation benefit is proportional to the level of tree planting, suggesting even a small amount of tree planting across the state could be a leading climate-smart forestry management action.

The two Avoided Conversion scenarios, *Avoided Conversion (low)* and *Avoided Conversion (high)*, each reduce the rate of permanent conversion of forests to other land use types. This subsequently reduces the transfer of wood to the HWP sector, as it is assumed that a portion of forestland converted to other land uses each year results in a substantial fraction (~21% on average for the *BAU*) of the carbon transferred from the forest ecosystem to the HWP sector (**Figure 11**). These reduced transfers lead to lower HWP emissions, but also a small amount of leakage and negative product substitution. At the same time, both scenarios store more carbon in the ecosystem in the form of live trees and soil carbon stocks. The *Avoided Conversion (low)* and *Avoided Conversion (high)* scenarios generate respective cumulative net carbon balances of -2.87 and -7.04 MMT CO_2e by 2050, -4.5 and -17.3 MMT CO_2e by 2075, and -7.3 and –31.2 MMT CO_2e by 2100, each relative to *BAU* (**Table 5**). While annual differences in climate mitigation from *BAU* are relatively minimal for both Avoided Conversion scenarios (on average –0.1 MMT CO_2e yr^{-1} more than *BAU*; **Table 5, Figure 9**), when summed over the 81 years of simulation, both scenarios resulted in modest long-term climate mitigation benefits as compared to the *BAU* scenario. This suggests that both levels of *Avoided Conversion* would be beneficial as a climate-smart forest management action; however, as with the *Tree Planting* scenarios, the larger scenario footprint leads to higher levels of cumulative mitigation.

Overall, the three Climate Change Impacts and Adaptive Silviculture scenarios reflect minimal differences in cumulative net carbon balance relative to *BAU* (**Figure 10**). The *Climate Change Impacts* scenario was intended to illustrate the potential negative effects of climate change on the ability of forests to generate climate mitigation benefits, via a simulated increase in the area and severity of future insect mortality events. Results from this scenario suggest that the increase in insect disturbances over time drives a slight reduction in cumulative net primary productivity, and thus carbon sequestration, relative to *BAU*. This leads to less carbon in the forest ecosystem, lower cumulative transfers of carbon to the HWP sector, lower cumulative HWP emissions, leakage, and negative substitution effects (**Figure 11**). Of all scenarios assessed, the *Climate Change Impacts* scenario emits the most additional carbon relative to *BAU*, +8.6 MMT CO_2e by 2050, +22.1 MMT CO_2e by 2075, and +31.1 MMT CO_2e by 2100 (**Table 5**), though it should be noted that even with climate change impacts, the forest and forest products sector still remain a net carbon sink through 2100.

The *Enrichment Planting* scenario, which aims to supplement understocked stands by planting 360,000 acres of climate-adapted species by 2100, does not result in any meaningful change in cumulative ecosystem carbon storage, as ecosystem emissions and HWP transfers offset any additional carbon sequestration (**Figure 11**). Cumulative net carbon balance for the *Enrichment Planting* scenario was -0.1 MMT CO_2e (meaning slight additional carbon sequestration and storage) by 2050, falling to +1.2 MMT CO_2e by 2075, and recovering to +0.2 MMT CO_2e by 2100, relative to *BAU* (**Figure 11, Table 5**). Critically, these results are applicable only if current climate conditions continue through end of century, though research indicates that Minnesota's forests may experience changing habitat suitability and declining productivity under a range of future climate conditions (Handler et al. 2014). This suggests that underplanting 4,500 acres annually could have negligible effects on future mitigation potential under current climate conditions but could still potentially achieve other management objectives, including species diversity and resilience to future changes in climate.

The *Insect Vulnerability Transition* scenario reflects the concept of increasing forest resiliency by transitioning forest types susceptible to insect outbreaks to other forest types projected to be more resilient to future climate conditions. This is achieved by regenerating these stands post-harvest into different cover types predicted to be more resilient under future climate conditions. This scenario leads to a slight reduction in cumulative net primary productivity in these new forest types, but a concurrent and reciprocal decrease in cumulative forest disturbance and decomposition emissions (**Figure 11**) as insect mortality events decrease. At the same time, cumulative transfers of carbon to the HWP sector and cumulative HWP emissions are increased, with a small amount of displaced emissions from positive product substitution (**Figure 11**). The *Insect Vulnerability Transition* scenario cumulatively emits an additional +2.6 MMT CO_2e of carbon dioxide equivalent relative to *BAU* by 2050, +3.9 MMT CO_2e by 2075, falling to +2.9 MMT CO_2e by 2100 (**Table 5**). However, these additional emissions are smaller in scale than the projected emissions from insect outbreaks in the *Climate Change Impacts* scenario, illustrating how silvicultural strategies that enhance climate adaptive capacity can also align with climate mitigation objectives. Despite a reduction in climate mitigation relative to *BAU* under current climate conditions and insect outbreak levels, these management strategies are still climate smart as they help set the forest up to be more resilient to future climate impacts.

In addition to the scenarios above, we also tested six scenarios reflecting an array of different HWP utilization concepts. Two of these scenarios are based on the *BAU* ecosystem model, meaning that the forest ecosystem disturbance and harvest levels in these scenarios are identical to the *BAU* scenario. As such, these scenarios only differ from *BAU* in terms of wood utilization strategies, which in turn affect HWP emissions and product substitution. Both scenarios reflect the concept of re-allocating a fraction (20% and 50%) of HWP carbon away from shorter-lived wood products (pulp/paper) toward longer-lived products (LLPs), specifically composite panels. When HWP carbon is allocated to LLPs, this carbon is emitted more slowly over time as composite panels have a longer in-use half-life (59.4 vs 2.6 years; **Table 2**) and a longer landfill half-life (30 vs 2 years; **Table 2**) than pulp/paper. In addition, less of the overall carbon is emitted once the product is landfilled, as LLPs have a smaller degradable fraction (10%) than pulp/paper (50%). Finally, LLPs will substitute for more emissions-intensive alternatives, displacing emissions, and leading to overall emissions reductions relative to *BAU*. The respective cumulative net carbon balance of the *BAU – 20% LLP* and *BAU - 50% LLP* scenarios are -36.1 and –90.2 MMT CO_2e (meaning lower carbon emissions) by 2050, -68.4 and –170.9 MMT CO_2e by 2075, and –102.5 and –256.4 MMT CO_2e by 2100, each relative to the *BAU* scenario (**Table 5**). Both LLP scenarios reflect the potential for a significant decrease in cumulative net carbon balance relative to *BAU*, coming about solely from changes in the forest products sector. At the same time, these scenarios lead to an increase in the production of composite panels (73% increase for 20% *LLP* and 183% increase for *50% LLP*), which translates into a cumulative 1.85 million and 4.64 million MCF of additional composite panels produced over the amount produced when assuming BAU wood utilization. Of the scenarios tested, the *BAU – 50% LLP* scenario resulted in the second highest level of cumulative climate mitigation after the *Tree Planting (high)* scenario (**Figure 10**) and consistently provided annual climate mitigation exceeding *BAU* (**Figure 9**). While we did not test the concept of LLP allocation with alternative forest management, such a combination would likely yield synergistic effects, further boosting the climate mitigation potential of forests and the forest products sector.

The other four HWP scenarios are based on the *Logging Residue Utilization* ecosystem scenario. These scenarios model the removal and use of wood residue, which would otherwise be left in the forest as coarse woody debris. All other aspects of these scenarios, including harvest intensity (acres per year), are identical to *BAU*. As with the *Increased Harvest* scenario, these extra removals lead to cumulatively less carbon in the forest ecosystem relative to *BAU* and cumulatively more carbon allocated to HWP, accompanied by positive substitution benefits (**Figure 11**). However, this additional transfer of carbon to the HWP sector leads to cumulative HWP emissions which are higher than *BAU* (**Figure 11**). When the *Logging Residue Utilization* scenario is run with default (BAU) HWP assumptions (i.e., logging residue is treated as additional harvest and not allocated to a unique product), the cumulative net carbon balance is –21.8 MMT CO_2e more (meaning lower emissions) than *BAU* by 2050, -31.2 MMT CO_2e more than *BAU* by 2075, and –43.2 MMT CO_2e more than *BAU* by 2100 (**Table 5**).

We also evaluated three alternative HWP scenarios reflecting different uses of logging residues in the *Logging Residue Utilization* scenario, including bioenergy, transportation fuel, and soil amendment (biochar). For each scenario, modeled wood residue removals are allocated 100% to one of these three products, which are not currently produced at scale in Minnesota and thus not modeled in our BAU wood utilization assumptions. For both the *Wood Utilization - Bioenergy* and *Wood Utilization – Transportation Fuel* scenarios, we assume that these energy sources emit 100% of their carbon in the same year that they are produced, and as such, cumulative HWP emissions for both scenarios are substantially increased relative to the *BAU* scenario (**Figure 11**). At the same time, we assume that energy produced from these fuel sources displaces fossil energy sources (see **Appendix** for details on calculation of displacement factors), thus reducing overall emissions. The net effect is that the cumulative net carbon balance of the *Wood Utilization – Bioenergy* scenario, which has a smaller displacement factor, is +3.6 MMT CO_2e (meaning additional emissions) by 2050, +4.3 MMT CO_2e by 2075, and +2.9 MMT CO_2e by 2100 relative to the *BAU* scenario (**Table 5**). The cumulative net carbon balance of the *Wood Utilization – Transportation Fuel* scenario, which has a larger displacement factor, is -13.5 MMT CO_2e (meaning lower emissions) by 2050, -27.0 MMT CO_2e by 2075, and -44.1 MMT CO_2e by 2100 relative to the *BAU* scenario (**Table 5**).

Unlike the other two scenarios, the additional harvest transfer in the *Wood Utilization – Biochar* scenario does not lead to any product substitution, since biochar does not displace a more emissions-intensive alternative product. However, biochar has a very long in-use half-life (100 years), and very little of the carbon allocated to biochar will reach end of life during the 80-year simulation period. Accordingly, this scenario has similar cumulative HWP emissions to *BAU*, but substantially lower cumulative ecosystem emissions from lower levels of decomposition in the forest (**Figure 11**). This results in a cumulative net carbon balance of -25.9 MMT CO_2e (meaning lower emissions) by 2050, -45.1 MMT CO_2e by 2075, and -67.3 MMT CO_2e by 2100 relative to *BAU* (**Table 5**).

Of the six *Wood Utilization* scenarios, five provide additional climate mitigation relative to *BAU* (**Figure 10**), suggesting that the removal and use of wood in long-lived products, transportation fuels, and biochar could be climate-smart management options for Minnesota. However, as demonstrated by the increase in net carbon balance relative to *BAU* for the *Wood Utilization – Bioenergy* scenario, decisions about how these residues are used, how many additional emissions they generate, and what non-wood products they displace are critical to ensuring that they provide lasting climate mitigation over BAU wood use and management.

Representing a concurrent suite of climate-smart forest management actions (**Table 3**), the *Portfolio* scenario (which includes the effects of the *Increased Harvest Levels*, *Avoided Conversion (low)*, *Tree Planting (mid)*, *Enrichment Planting*, and *Climate Change Impacts* scenarios) illustrates an upper limit of climate mitigation potential when these actions are taken together. The *Portfolio* results in a cumulative net carbon balance of –19.4 MMT CO_2e (meaning lower emissions) by 2050, -58.6 MMT CO_2e by 2075, and –119.1 MMT CO_2e by 2100 relative to *BAU* (**Table 5**). While this scenario does not result in the largest amount of potential climate mitigation benefits (with a cumulative net carbon balance +147.3 MMT CO_2e relative to the *Tree Planting (high)* scenario; **Figure 11**), it none the less presents an opportunity for maintaining a strong forest carbon sink in Minnesota while accomplishing multiple climate-smart forestry and management goals, such as supporting a sustainable timber supply and overcoming some projected climate change impacts. This *Portfolio* also helps to highlight significant opportunities for additional climate benefits from ambitious state action on a wide range of forest management practices.

The Influence of Age Class on Climate Mitigation Potential

Age class distribution plays an important role in determining the mitigation potential of each scenario modeled in this analysis. As discussed in the **Impact of Business-as-Usual on Forest Age and Carbon** section, the modeled age class distribution under *BAU* shifts significantly over time, with the average age of Minnesota's forests increasing from 56 years old in 2020, to 70 years old in 2100 (**Figure 12**). In 2020, Minnesota forests are predominantly (44.8%) middle aged (60-120 years old); however, by 2100 under the *BAU* scenario, a larger proportion has shifted into mature (120+ years; 22.2%) and young (<60 years; 52.5%) age classes (**Figure 8**). The average forest age subsequently increases from 56 years old in 2020 to 70 years old in 2100 (**Figure 12**).

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 general, we can see that carbon stock density is the lowest in the oldest and very youngest stands, while the middle-aged stands hold the most carbon per area (**Figure 12**). The reduction in carbon density in older forests in our model is driven by increased emissions from dead organic matter (DOM) and soil carbon pools which outpace the annual rate of carbon sequestration from tree growth.

In the *BAU* scenario, average carbon stock densities increase from 275.93 $tCO_2e\ ac^{-1}$ in 2030 to 284.52 $tCO_2e\ ac^{-1}$ in 2100, while average carbon flux densities increase (meaning more sequestration occurs) from -0.705 $tCO_2e\ ac^{-1}yr^{-1}$ in 2030 to -0.722 $tCO_2e\ ac^{-1}yr^{-1}$ in 2100, with a maximum carbon flux density of −0.792 $tCO_2e\ ac^{-1}yr^{-1}$ in 2063 (**Figure 12**). Aggregated across the state, this trend of successive years of negative carbon flux (**Figure 4**) leads to an increase in net carbon stocks over the time as shown in **Figure 5.**

A few scenarios deviate from this *BAU* trend. In the *No Harvest* scenario, average age increases from 62 to 102 from 2030-2100, with 40.2% of forestland in the mature (120+ years old) age class in 2100, compared with just 15% mature in the *BAU* scenario (**Figure 12**). Though this scenario has allowed more forests to age into the mature forest category, it comes at the cost of dwindling young forest (<60 years old) representation on the landscape (24.6% vs 52.5% under *BAU*), a dynamic at odds with the balancing act needed to improve forest age diversity (Shifley and Thompson 2011). The *No Harvest* scenario prioritizes carbon storage over carbon sequestration, indicated by average carbon stock densities 2.25%-8.55% higher than *BAU* and carbon flux densities initially (in 2030) -34% stronger (meaning greater sequestration) before declining to +25% weaker (meaning less sequestration) than *BAU* by 2100 (**Figure 12**).

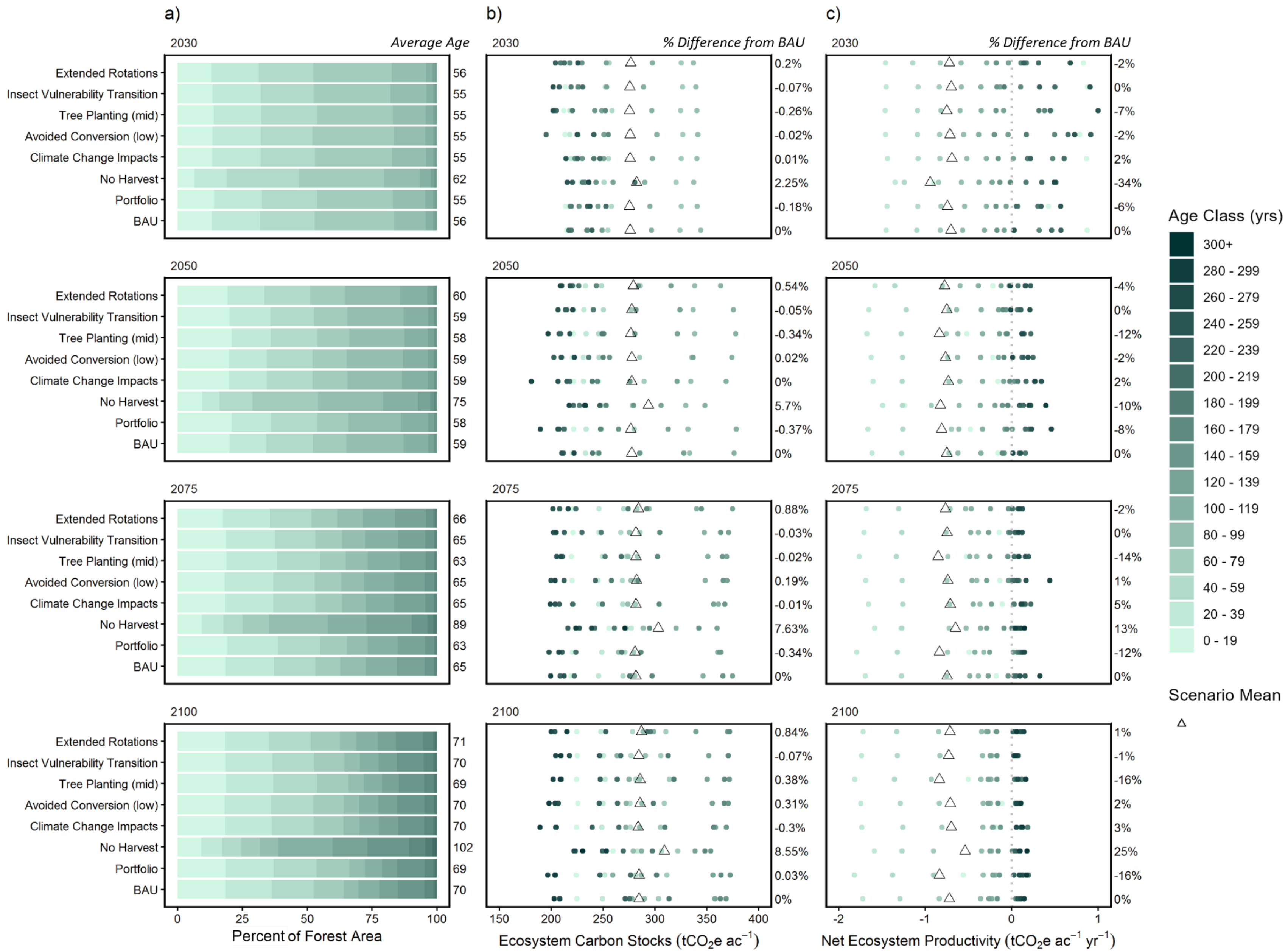

Figure 12. a) Age class distribution, b) ecosystem carbon stock density (tCO$_2$e ac^{-1}), and c) per-acre net ecosystem productivity (tCO$_2$e ac^{-1} yr^{-1}) for undisturbed forest in selected scenarios in 2030, 2050, 2075, and 2100. Net ecosystem carbon flux refers to the net yearly sequestration of carbon per acre of forest across all 14 ecosystem carbon pools, after accounting for decomposition, natural disturbance emissions, and wood product transfers. In panel b), positive values denote accruing carbon stocks. In Panel c), negative values denote carbon sequestration and positive values denote carbon emissions.

In the *Portfolio* scenario, carbon stock densities range from −0.18% lower to 0.03% higher than *BAU* from 2030-2100. Over the same period, carbon flux densities improve, ranging from -6% stronger than *BAU* in 2030 to -16% stronger than *BAU* in 2100 (**Figure 12**). This change in carbon stock densities is driven by a reduction in the rate of forest loss to deforestation (*Avoided Conversion*), combined with an increase in tree planting (*Tree Planting (mid)* and *Enrichment Planting*), with these newly planted stands only achieving a higher than average carbon stock density toward the end of the simulation. The age class distribution of the *Portfolio* scenario is largely similar to *BAU*, biased slightly toward the younger age classes by the tree planting component of the *Portfolio,* which decreases average forest age. These younger forests have higher carbon flux densities as they grow more vigorously than older trees (**Figure 12**), which helps strengthen carbon flux density averages for this scenario relative to *BAU.*

Other scenarios like *Extended Rotations, Insect Vulnerability Transition*, *Tree Planting*, *Climate Change Impacts*, and *Avoided Conversion* (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 through time. Of this group, the *Tree Planting (mid)* scenario generates the largest carbon sequestration gains relative to *BAU* by adding new young forests with a larger growth rate than *BAU.* As such, carbon flux densities are −13% and -16% stronger (meaning greater sequestration) than *BAU* in 2030 and 2100, respectively (**Figure 12**). The *Extended Rotations* scenario results in higher carbon stock densities than *BAU* (0.2% in 2030 and 0.84% in 2100). This comes from the fact that the age of minimum harvest eligibility is increased in this scenario, meaning harvests are deferred, allowing for a larger accumulation of carbon per acre in biomass and DOM carbon pools. These differences demonstrate the additional potential of specific management concepts to increase forest carbon sequestration and storage in Minnesota even without radically 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 Minnesota. 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 promotes resilience to future disturbances. Forest age diversity, in turn, supports the resilience and stability of Minnesota's forest climate mitigation potential.

Limitations

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

1. Uncertainties exist in the assumptions and simplifications needed to model various management and disturbance regimes. While some of the underlying data used in model parameterization could be used to estimate variation in the input data, the process-based nature of the CBM-CFS3 does not inherently provide metrics for uncertainty. Estimation of growth-yield curves, forest inventories, and the frequency and severity of disturbance

events add additional uncertainties to the trajectories of future net carbon balance in Minnesota. All modeling parameters are deterministic and should be interpreted as prescriptions rather than predictions. Additionally, we make no attempt to estimate changes in future growing conditions, climate-induced mortality, or changes in albedo which can have significant influences on forest growth and carbon.

2. We do not make assumptions based on the feasibility of implementing each modeled scenario; rather, we focus on our state partners' objectives for forest management and land-use and offer our assessment of the climate benefits of implementation. Each scenario modeled in this study should be further examined for the biophysical, political, and economic feasibility by land managers to incorporate localized knowledge in the planning and decision-making process.
3. The CBM-CFS3 is spatially referenced and not spatially explicit in modeling forest carbon dynamics. We do try to account for this by providing a spatial classifier to denote biogeographic units defined by physiographic, macroclimatic, and vegetation conditions, allowing for the filtering of results to certain areas. However, the results in these spatial units are based on historical trends and do not make predictions of future management activities or disturbances that might vary across ecological conditions.
4. Significant uncertainties remain in the future of wood markets and the climate mitigation benefits of substitution for both bioenergy and material substitution. The forest product markets are dynamic and constantly changing, which can shift product types and their respective half-lives, in turn affecting future carbon storage. Additionally, changes in mill efficiencies, supply chains, and the usage of forest and mill residues remain another point of uncertainty. Our analysis made no attempt to estimate changes in wood demand or shifts in the estimation of HWP emissions from changes to technology, which could result in an overestimation or underestimation of the climate mitigation potential of HWP.
5. It is critical to note that the components of net carbon balance shift with changing assumptions about leakage, particularly for the proportions of substitution benefits realized by each scenario. Leakage remains difficult to quantify and requires cooperation across state boundaries, and as such results presented in this analysis use our 84.4% leakage assumption for years when harvest is lower than *BAU*, as discussed in the **Harvested Wood Products Model** section. However, for different leakage assumptions we cannot simply subtract from or add to the leakage calculation– leakage and substitution benefits interact with each other in a more complicated way. This occurs because a higher leakage rate assumes that a higher proportion of wood product demand in the state will be met by imported HWPs, 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.

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 while supporting wildlife habitat, water quality, recreation, and the forest bioeconomy through the provision of wood products (Skog 2008; Smyth et al., 2014; Lempriere et al., 2013). This study evaluated the climate mitigation effects of several important themes including management of working forests, climate change and adaptive silviculture, wood product utilization, and changes in forest land use. We estimated the mitigation potential of 19 scenarios using a systems-level approach that quantifies the exchange of GHGs between forests, forest products, and the atmosphere over time. Results for this analysis indicate that under current conditions, Minnesota's forests are expected to continue to provide climate mitigation benefits from 2021-2100. Our results suggest there is a suite of strategies that can potentially provide additional climate mitigation benefits beyond business-as-usual practices, which can help achieve additional management objectives by balancing forest health goals, climate adaptation, and mitigation while providing a sustainable supply of timber and other ecosystem services. Based on these criteria, these climate-smart forest management practices for Minnesota include:

- ✓ **Continued sustainable management of working forestlands** to support the balance between harvest removals and forest growth into the future as represented in the *Business-as-usual* scenario

- ✓ **Maintain and increase forest area** by accelerating the rate of *tree plantings* and *avoiding conversion* of forests to other land uses such as development and agriculture

- ✓ **Bolster climate mitigation potential of the forest products sector** through wood utilization strategies including *increasing use of longer-lived wood products* and *innovative uses of logging residues*

- ✓ **Prepare for the impacts of climate change and related stressors** by maintaining a diversity of forest ages and species across the landscape while considering targeted efforts to maintain biological legacies through *increasing reserve size* retention following harvest and *transition insect-threatened forest types* and *plant understocked forests* with potentially climate-adapted species

Our results also suggest that implementing concurrent climate-smart forest management (CSF) practices included in the *Portfolio* scenario, which accounts for multiple CSF strategies and the impacts of increasingly intensified disturbance regimes concurrently, **could increase Minnesota's forest carbon sink by 16% in 2030 and 47% in 2100**, relative to *BAU.* Balancing multiple management goals such as wildlife habitat, clean water supply, timber, recreation, and climate benefits is predicated on the sustainable management of forestlands today and in the future.

Assuming demand for timber products remain at current levels, Minnesota's forests will remain a net carbon sink until the end of the century, suggesting that current bussies-as-usual management sustainably balances forest growth with the demand for forest products (Schulze et al., 2022). The results also suggest that *Tree Plantings* provide the largest climate mitigation potential compared to all other individual scenarios. This action presents additional opportunities to balance climate goals with other traditional management objectives such as enhancing opportunities for wildlife habitat, water quality and flow regulation, and while also increasing future timber supplies to meet any potential increase in demand. Further, *avoiding conversion* of forestland to other land-uses can provide carbon storage benefits while helping maintain forest diversity across the landscape (Nevins et al., 2021).

Reducing forest vulnerability to climate change is another promising CSF strategy for maintaining climate mitigation benefits—along with other traditional forest benefits—through 2100. Our results suggest that management actions such as *transitioning vulnerable forest types* such as ash and tamarack forests, *increasing reserve size* following harvest, and *underplanting understocked forests* with climate-adapted species provides potential climate mitigation benefits while balancing other climate adaptation goals.

Bolstering the climate mitigation potential of the forest products sector provides additional pathways to storing carbon. Increasing the use of wood fiber harvested in Minnesota for *longer lived wood products* (in place of shorter-lived products) is estimated to generate significant climate mitigation benefits. This is due to the longer residence time of carbon in long-lived products such as composite panels compared to pulp and paper products. *Innovative uses of logging residues* also result in climate mitigation benefits—especially for use in transportation fuels and soil amendment (biochar). Further, supporting the novel use of wood can provide additional economic benefits to communities that rely on forests.

The practices listed above are considered climate-smart because they balance both carbon storage and sequestration rates with forest health and resilience. Forest managers, decision-makers, and policymakers can support the adoption of these CSF concepts within the context of sustainable forestry. The continued stewardship of Minnesota's forestlands is predicated upon the consistent application of sustainable management practices that achieve a suite of management goals and disincentivizing actions that may lead to increased vulnerabilities and risk to forests. The state may work to achieve these outcomes by adjusting management priorities and interventions on public lands, and through education, incentives, tax programs, stewardship and management plans, cost-share programs, and engagement with forestry professionals and private landowners. There is no one-size-fits all approach to climate-smart forest management. Decision-making processes guided by site-specific information, data, and expertise, combined with broad-scale information such as this analysis, will continue to support the stewardship of forests and inform future mitigation and adaptation pathways going forward, ultimately leading to healthier and more resilient forests and communities that rely on them.

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Appendix

A. Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3)

Past and future carbon (C) stocks and stock changes were modeled using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) (Kull et al., 2019; Kurz et al., 2016). The CBM-CFS3 model was selected to analyze the forest ecosystem, management practices, and land-use change components within our systems-based approach. The CBM-CFS is fully consistent with IPCC guidelines for estimation and reporting utilizing tier III methodologies. Other empirically based models such as the USFS Forest Vegetation Simulator (FVS) (Anderson et al., 2020), Carbon Calculation Tool (CCT) (Smith et al., 2007; Woodall et al., 2011), or LANDIS-II (Scheller et al., 2007), offer some potential strengths for analyzing landscape to stand-level scales but generally lack sufficient quantification of ecosystem components such as soil carbon dynamics or the ability to assess diverse drivers of carbon stock changes. Further, the scale at which our analysis was conducted lends itself to utilizing an operational scale model that has the additional benefit of fully or readily integrating with harvested wood product process-based models. Importantly, the CBM-CFS3 allows seamless transition from past to future carbon stocks and stock changes whereas notable issues have been observed among other approaches (Kurz et al., 2016). CBM-CFS3 is flexible enough as a framework to allow for the incorporation of a variety of inventory, remote sensing, and qualitative survey datasets to characterize and quantify relevant factors driving the forest C cycle.

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 transfers between these pools and the atmosphere on annual timesteps, representing typical flows of carbon throughout the entire system. Carbon enters the system via photosynthesis. Carbon leaves the forest through ecosystem-based emissions such as decomposition, harvested wood, pyrogenic emissions, or other disturbance emissions associated with management or natural disturbances. Carbon that leaves the ecosystem via harvest is further assessed and tracked through its usage (in wood products and energy) and end of life (e.g., landfill storage and wood energy).

CBM-CFS3 is an empirically driven growth-yield ecosystem C model where forest growth is determined by mean annual increment (MAI) of biomass defined by forest type group, stocking class, and stand age. As simulations progress, disturbances and aging processes transfer carbon from biomass pools to dead organic matter (DOM) pools representing annual forest processes such as litter fall. Carbon is then partitioned among a variety of DOM pools based on the rate of DOM turnover and may be released back to the atmosphere through decay, decomposition, or disturbance processes where decay is both soil and temperature dependent. Transition matrices are utilized to reset the stand age to zero (as in the case of stand-replacing disturbance) or continue growing the stand dependent upon the curve's trajectory.

In addition to empirically-derived growth and yield curves to estimate forest growth, the CBM-CFS3 utilizes a detailed forest inventory comprised of the same data collected by operational scale foresters. Forest inventory data are categorized by a series of classifiers (**Table S1**) that define relevant characteristics of the forest landscape such as spatially referenced units (i.e., ecoregions, counties, management units, etc.), forest type, ownership, or stocking class. The CBM-CFS3 model combines this inventory data with growth-yield relationships and user defined management activities, natural disturbances, and land-use change to simulate past or present carbon dynamics utilizing a single starting forest inventory as opposed to estimating stock change across multiple inventory windows.

Table S1. List of Classifiers and descriptions

Code	Name	Description	ID	Value
UNIT_CD	Unit Code	Biogeographic unit that contains minor variation in physiographic, macroclimatic, and vegetation conditions	AP_PA	Aspen Parklands
			MNIAM_PA	Hardwood Hills
			NMDLP_PA	MN Drift and Lake Plains
			NMNOP_PA	Northern MN Ontario Peatlands
			NSU_PA	Northern Superior Uplands
			PALEPLAT_PA	Blufflands Roch Plateau
			PRAIRPK_PA	Praire Parkland
			WSU_PA	Western Superior Uplands
OWNGRPCD	Ownership Group	Code indicating the ownership group of forestland (See: FIADB User Guide for Phase 2 (version 9.0.1) for more information)	10	Forest Service
			20	Other Federal
			30a	State
			30b	County / Municipal
			40	Private and Native American
MNDNR_FT	Forest Type		101	Jack pine
			102	Red pine
			102PLT	Red pine plantation
			103	Eastern white pine
			103PLT	Eastern white pine plantation
			121	Balsam fir
			122	White spruce
			122PLT	White spruce plantation
			125	Black spruce
			126	Tamarack
			127	Northern white-cedar
			171	Eastern redcedar
			381	Other softwood
			503	Central Hardwoods
			504	Oak
			512	Walnut
			516	Ash
			701	Lowland hardwoods
			709	Cottonwood / Willow
			801	Northern hardwoods
			901	Aspen
			902	Birch
			903	Balsam poplar
			999	Nonstocked
			0	Nonforest
RESERVCD	Trust status		Trust	Land in a trust
			NonTrust	Land not in a trsut
SI_CD	Site Class Code		0	SI 0-15
			20	SI 20-30
			40	SI 35-50
			60	SI 55-70
			80	SI 75-90

Framework Selection & Business-as-Usual Parameterization

To understand the role forests can play in climate change mitigation, accurate assessment of forest carbon dynamics and interactions with other sectors is necessary. A systems-based approach provides a critical comprehensive look at the forest ecosystem and its interactions with land-use change, wood products, substitution effects of using wood products, and leakage. We selected the CBM-CFS3 in part for its direct applicability of being incorporated into a larger systems-based approach assessing not just the forest ecosystem but interacting factors with LUC and forest products. Secondly, the CBM-CFS3 utilizes the same data collected by operational foresters to estimate both forest inventory and forest productivity modeled using volume-age relationships. This framework is flexible enough to integrate disparate types of data such as operational scale inventory data, remote sensing data, and qualitative metrics to further describe human interventions within forests. Further, the use of operational forestry data makes both the modeling process and the modeling results more approachable to a wider range of audiences than other dynamic vegetation models or atmospheric inversion models that are driven by eddy-flux covariance systems or other atmospheric measurements.

To develop the Business-as-usual (BAU) scenario, we first consulted with state agency staff and forestry experts to understand forest management, priorities, concerns, and goals in Minnesota. The purpose of the BAU is to not forecast future climate states or economic trends in forest products, but to develop a plausible simulation of just one potential future outcome by projecting longer-term averages of activity data into the future. This does not account for changes in policies, climate, or economics, but nonetheless, remains a useful exercise to explore how the continuation of current behaviors and disturbances may affect future ecosystem and carbon cycling dynamics to inform current understanding of management practices and forest dynamics. Additionally, projecting current practices and disturbances into the future allows for a counterfactual comparison of alternative forest management, climate, and wood utilization scenarios in contrast to the BAU. Allowing for a quantification of the carbon mitigation potential of specific management practices or actions. Modeling each practice individually allows for the assessment and analysis of each practice in isolation.

To properly account for forest carbon dynamics, information regarding forest growth, forest management, natural disturbances, and land-use change is necessary to capture relevant factors that impact net carbon balances within the forest ecosystem. Harvest practices were identified and validated heuristically with direct input and participation from our state partners including definitions of common harvest regimes (**Table S3**). Utilizing a participatory approach with our state-partners, we were able to incorporate direct feedback from both model assumptions and preliminary results to ensure accuracy within both the forest ecosystem and forest products sector. Further, the active participation of partners allows us to prioritize and model both concerns and opportunities of forest management currently ongoing within the BAU. The BAU scenario projects onwards starting in 2021 until 2100. **Table 1** provides the BAU ecosystem disturbance parameters for Minnesota. The purpose of projecting until 2100 is to try and capture longer time horizons and longer rotation lengths.

Forest Inventory & Growth-Yield Data

The core of the CBM-CFS3 modeling framework utilizes a detailed forest inventory and empirically derived growth and yield data. The framework is flexible enough to allow for and incorporate multiple types of forest inventory data. Forest inventory for federal, county / municipal, and private forest lands were estimated using data from the Forest Inventory and Analysis (FIA) database (USDA Forest Service, 2020a). The FIA program was established as a national program to monitor and project forest attributes through space and time by utilizing a systematic grid of permanent plots allowing for spatially unbiased estimation on annual time steps (Smith, 2002; Tinkham et al., 2018). To estimate the inventory for our project period, we estimated the forest inventory from the 2014-2019 inventory window. Pooling estimates across an entire inventory window reduces estimate variation in the estimates by the pooling of panels across the entire survey cycle (Bechtold & Patterson, 2005) for private, federal, and municipal / county forestland ownership. Forest inventory data for state forestlands were provided by the Minnesota DNR. To merge the two inventory datasets, a new forest type classification scheme that incorporates information from both datasets was constructed using expert input with state partners. **Table S1** provides a detailed list of forest types utilized.

In the CBM-CFS3 model, forest productivity and regeneration are empirically driven by growth and yield curves (**Figure S1**) which represent the rate of biomass accumulation as a function of stand age and site productivity (quantified as MAI). Growth-yield curves were derived from previous modeling exercises using Remsoft forestry software to parameterize the CBM-CFS3 framework. Remsoft is a commonly used specialized software that helps in planning of natural resource asset management by organizing forest management planning, schedules, and optimization of forest supply chains. Growth-yield curves representing each unit code, ownership category, forest type, and site index were provided. Since Remsoft growth-yield curves are represented as cubic ft per acre, these values were converted into cubic meters per hectare. Additionally, the Remsoft curves represent merchantable volume of specific trees, the assumption was made with direct input from state partners to not represent mortality inherently in the curves and have them asymptote at their respective maximums acknowledging that the CBM-CFS3 framework makes no assumption about species mixes, but only merchantable carbon within a forest stand. Since the CBM-CFS3 is entirely prescriptive, we decided to only input successional shifts as disturbance events and not incorporate them directly into growth-yield curves.

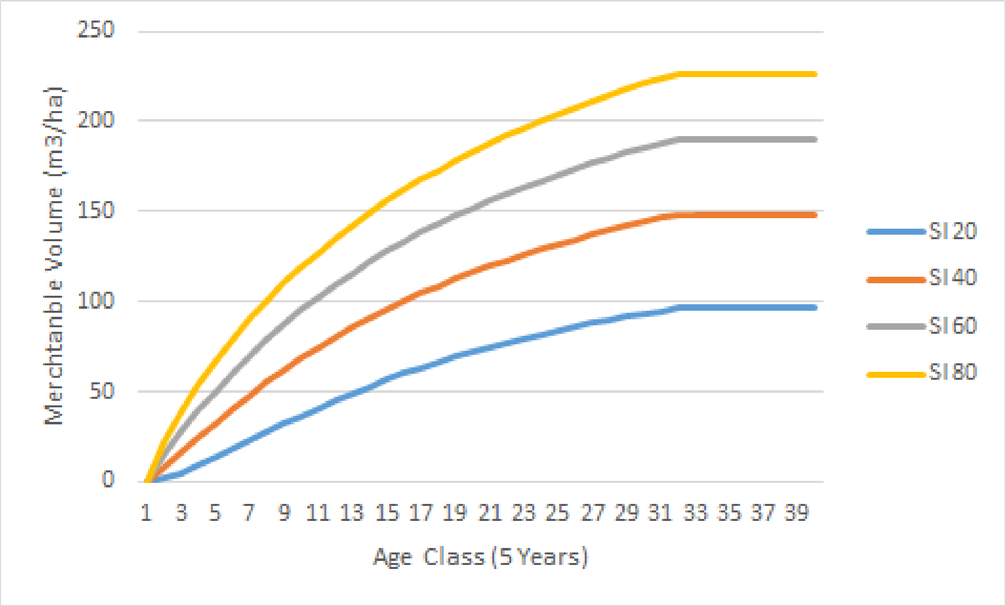

Figure S1. Growth-yield curve examples for MNDNR_FT == 801, & UNIT_CD == MNIAM_PA. Each age class represents 5-years.

Activity Data

Harvest Removals

Harvest removals were provided by state partners in terms of area targets and intensities from previous state planning exercises. Nonstate managed forestlands harvest acres were informed from previous harvest scheduling and harvesting data provided by MN DNR partners and USDA Forest Service Forest Inventory and Analysis data. Current and future harvest levels on state-managed forest lands were calculated based on state harvest planning data (Stand Exam List or SEL, MN DNR 2020). The SEL represents annual targets for timber harvest on state timberlands. These annual targets are generally higher than actual harvest rates due to logistical and operational factors (e.g. weather, inventory discrepancies, markets). To compensate for that difference, Division of Forestry staff developed a reduction factor based on a comparison of planned harvest acres to observed data on timber appraisal rates. This reduction factor was applied to current and future planned harvest acres from the SEL to generate rough estimates of actual harvest activity on state timberlands between 2017 and 2030. Average timber harvest rates between 2017 and 2030 were used to estimate harvest removals from 2031 through 2100.

Table S2. *Average stand age at time of harvest by forest type and harvest type from 2021-2100 (rounded to nearest 5-year age class). Values in the parentheses represent minimum and maximum values.*

Forest Type	Average stand age at harvest (range)	Harvest Type
101: Jack pine	80 (45-145)	Thinning
	45 (40-50)	Clearcut
102: Red pine	45 (20-90)	Thinning
	165 (120-260)	Clearcut
	130 (50-160)	Uneven-Aged
102PLT: Red pine plantation	60 (20-100)	Thinning
	85 (65-105)	Clearcut
	90 (30-115)	Uneven-Aged
103: Eastern white pine	45 (30-90)	Thinning
	170 (145-230)	Clearcut
	170 (50-240)	Uneven-Aged
103PLT: Easter white pine plantation	80 (50-90)	Thinning
	85 (60-110)	Clearcut
	75 (30-110)	Uneven-Aged
121: Balsam fir	45 (40-50)	Thinning
	85 (50-140)	Clearcut
122: White spruce	45 (20-50)	Thinning
	95 (50-135)	Clearcut
	100 (55-150)	Uneven-Aged
122PLT: White spruce plantation	50 (45-65)	Thinning
	70 (45-100)	Clearcut
	80 (55-110)	Uneven-Aged
125: Black spruce	130 (105-225)	Clearcut
126: Tamarack	80 (75-85)	Thinning
	125 (80-220)	Clearcut
127: Northern white-cedar	90 (85-95)	Thinning
	130 (65-290)	Clearcut
	260 (240-290)	Uneven-Aged
171: Eastern redcedar	100 (95-105)	Clearcut
381: Other softwood	75 (70-80)	Clearcut
503: Central Hardwoods	45 (40-50)	Thinning
	100 (75-170)	Clearcut
504: Oak	50 (40-80)	Thinning
	150 (115-170)	Clearcut
	140 (65-185)	Uneven-Aged
512: Walnut	105 (40-160)	Uneven-aged
516: Ash	75 (60-80)	Thinning
	150 (80-220)	Clearcut
	100 (60-280)	Uneven-Aged

Table S2, cont. Average stand age at time of harvest by forest type and harvest type from 2021-2100 (rounded to nearest 5-year age class). Values in the parentheses represent minimum and maximum values.

Forest Type	Average stand age at harvest (range)	Harvest Type
701: Lowland hardwoods	60 (25-70)	Thinning
	80 (50-150)	Clearcut
	120 (50-260)	Uneven-Aged
709: Cottonwood / willow	115 (75-140)	Clearcut
801: Northern hardwoods	70 (65-75)	Thinning
	155 (130-190)	Clearcut
	130 (40-190)	Uneven-Aged
901: Aspen	45 (40-50)	Thinning
	65 (45-145)	Clearcut
	50 (35-155)	Uneven-Aged
902: Birch	45 (40-50)	Thinning
	110 (55-170)	Clearcut
903: Balsam poplar	80 (40-125)	Clearcut
999: Nonstocked	135 (105-225)	Clearcut

Table S3. Descriptions and intensity of silvicultural treatments by harvest type

Harvest Type	Description	Intensity
Clearcut	A silvicultural method used to regenerate a stand by the removal of most or all woody vegetation during harvest creating a completely open area leading to the establishment of an even-aged stand. Regeneration can be from natural seeding from adjacent stands or from trees cut in the harvest operation. Regeneration is established during or following stand removal.	~95% removals
Uneven-aged	A silvicultural method used to regenerate a stand by manipulating the overstory and understory to create conditions favorable for the establishment and survival of desirable tree species. Harvest regimes can utilize a variety of methods including shelterwoods, overstory removals, or single-tree-selection systems. An uneven-aged stand is maintained by periodically regenerating new age classes while manipulating the overstory structure to facilitate continual development of quality growing stock. Stand regeneration is achieved by periodically manipulating the overstory and understory to create conditions favorable for the establishment and survival of desirable tree species. Generally, most regeneration is seed origin (high forest method), although a component can be vegetative.	~33% removals
Thinning	Thinning is a cultural treatment conducted in stands past the sapling stage to reduce stand density, primarily to improve tree growth, enhance tree health, or recover potential mortality. It entails the removal of trees to temporarily reduce stocking to concentrate growth on the more desirable trees. Normal thinning does not significantly alter the gross production of wood volume. Thinning does impact stand growth, development, and structure. It provides the main method, implemented between regeneration and final harvest, to increase the economic productivity of stands. Individual thinnings can be commercial or non-commercial (TSI), depending on landowner objectives and local markets for materials cut in the thinning operation. Regeneration is not an objective of thinning; overstory gaps are small and should close rapidly	~25% removals

Three harvest types were implemented (i) thinnings, (ii) uneven-aged management, (iii) clearcuts. Harvest intensities for clearcuts (95% merchantable removal) and thinnings (25% merchantable removal) were the same across all management units. Uneven-aged management (~33% removal for each reentry interval) varied by management unit specifically on state-managed lands that were managed by different units including the forestry division or the fish and wildlife division. Rotational ages prescribed varied widely by ownership and management unit as well as if the forest was enrolled in a trust. **Table S2** provides model estimated average age of harvest or cutting by harvest regime regardless of management unit or ownership. Additionally, the minimum year and maximum year of harvest throughout the model simulation are provided as well. Harvest regimes and harvesting rules were developed utilizing a variety of resources including USFS management handbooks on forest types, Schwalm (2009), MN DNR (2020), and correspondence with MN

DNR biometricians. **Table S3** outlines the major harvest regimes developed represented by the percentage of merchantable carbon removed. Following discussion with state partners to ensure residuals left on site were being accurately represented within the simulation results, we opted to keep CBM-CFS3 default values for logging residues left on site post-harvest.

Land-use Change

We assessed land-use change trends using FIADB where annual rates of both afforestation and deforestation were estimated across three inventory windows by ownership and forest type. Annual shifts between forests and wetlands were dropped from the estimations following consultation with MN DNR employees as gradual shifts in wetland areas led to an over estimation of afforestation in the northern management units in Minnesota. Annual estimates of LUC were in general agreement with other estimates such as the National Land Cover Database (NLCD) dataset.

Natural and Fire Disturbances

To estimate defoliating and mortality events caused by insect and disease outbreaks, annual estimates were derived from the FIADB by forest type. As the FIADB does not attribute any level of severity or intensity, the USDA National Insect and Disease Detection Surveys (IDS; USDA Forest Service 2020) were used to attribute severity and intensity to individual defoliating or mortality events. Both the IDS and FIADB estimated annual area of defoliating and mortality events were generally in agreement with each other.

Similarly, FIADB was used to estimate annual wildfire areas, but the Monitoring Trends in Burn Severity (MTBS, Eidenshink et al., 2007) was utilized to assign severity, intensity, and average extent to fire disturbances. Wildfire disturbances were input as spatially random but constrained by regional classifiers to not make assumptions about the likelihood of fire affecting specific areas or forest types. Prescribed fire estimates were derived from MN DNR workbooks used to describe annual areas of prescribed fires. Severity, intensity, and average extent of natural and fire disturbances were informed by both data and a literature review of regionally relevant articles when possible (Busby and Canham, 2011; Cleland et al., 2004; Flower et al., 2013; Gough et al., 2007; Hicke et al., 2012; Wilson et al., 2019; White and Host, 2008).

Table S4. Impacts of prescribed fire on carbon pools in the CBM-CFS3 in Minnesota, 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

We created a new disturbance matrix for prescribed fire, as CBM-CFS3 does not contain default assumptions for prescribed fires. This new disturbance matrix aims to better represent lower fire intensity and lack of stand mortality associated with prescribed fire in the Lake States region. Based on literature review, we determined that prescribed fires in the Lake States region typically consume 40% of understory material with no significant impact on the overstory, though impacts differ by carbon pool (see **Table S4** Clark et al., 2015; Elliott & Vose, 2010; Hartman, 2004; Hubbard et al., 2004; Hutchinson et al., 2005; Waldrop et al., 2010). Proportions of greenhouse gas emissions from prescribed fire follow CBM-CFS3 defaults (burned material emissions are 90% CO2, 9% CO, and 1% CH4). Natural disturbances were grouped into 3 levels of severity for wildfire, defoliator events, mortality events, and 2 levels of severity for abiotic events.

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 Minnesota, we also collected data on the historical occurrence (in terms acres per year) of these events from 2002-2020. We used these historical values to calibrate our model during spin up and applied annual averages based on the historical period for each disturbance type in our BAU scenario from 2021-2100 across ownership types and forest types when applicable.

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. For disturbances that are not stand replacing such as prescribed fires, thinnings, or light severity events, stands do not transition to other yield curves. Natural disturbance events of higher severity would transition all or parts of the record back to age zero to simulate regeneration determined by region specific literature reviews (Cleland et al., 2004; Wilson et al., 2019).

B. Harvested Wood Products Model

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-MN 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 is accounted for (either emitted or stored); 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 in hard and softwood products 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 2020 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 2020, representing *inherited carbon* (i.e., carbon entering the HWP stream before the start of our BAU scenario), was calculated using roundwood volumes from TPO surveys (USDA Forest Service 2019b; 2023a) and MN DNR's Forest Resources reports (De Pellegrin Llorente et al. 2024). We converted these volumes from chords to a carbon mass using conversion factors from Smith et al. (2006), using wood-type (i.e., hardwood or softwood) specific gravities based on species typically harvested in Minnesota, which we calculated from FIA data (USDA Forest Service 2021a).

Exports

We calculated HWP exports at two stages: raw roundwood exports before commodity production, and commodity exports after production. Based on data from the 2020 MN Forest Resources Report (De Pellegrin Llorente et al. 2024), we estimated that in 2019 1.243% of all harvested hardwood pulpwood was exported. After conversations with state partners, it was determined that this export was all to a single sawmill in Canada, and that this export volume was typical, and thus representative of recent export trends. Because the CBM-HWP-MN model does not distinguish between roundwood types (e.g., sawtimber vs pulpwood) we used TPO data from 1997, 2002, 2007, 2017, and 2018 (USDA Forest Service 2019b; 2023a) to determine the percent of hardwood roundwood which was pulpwood, before assuming that 1.243% of this was exported (0.534% of hardwood roundwood harvest on average). We assumed that all exported roundwood was going toward the production of composite panels, and applied corresponding product half-lives.

We used data from Howard and Liang (2019) for US-level commodity exports and found that an average of 12.4% of softwood commodities and 15.7% of hardwood commodities were exported annually from 1965-2018. 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 were aggregated into a single commodity export region and were subject to international HWP half-lives (**Report Table 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-MN. We used mill efficiency data from RPA and TPO reports (USDA Forest Service 2019b; 2023a; 2023b) for 2010-2018 to estimate mill residues as a proportion of total harvest volume after export for domestic HWP. We found that Minnesota mills have an average mill efficiency of 65.6% for softwoods and 81.8% for hardwoods, meaning that the remaining material – 34.4% and 18.2% 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 TPO data in 2018: pulpwood, composite panels, bioenergy, and unused residues (see **Table 3** for proportions for softwoods and hardwoods).

Primary Product Ratios

As noted above, the CBM-HWP-MN model works by tracking proportions of carbon as they move through the HWP streams. 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-MN 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 Minnesota from RPA data, 1997-2017 (**Table 3**, **Figure S2**; USDA Forest Service 2023a). Again, we differentiated between softwood and hardwood inputs.

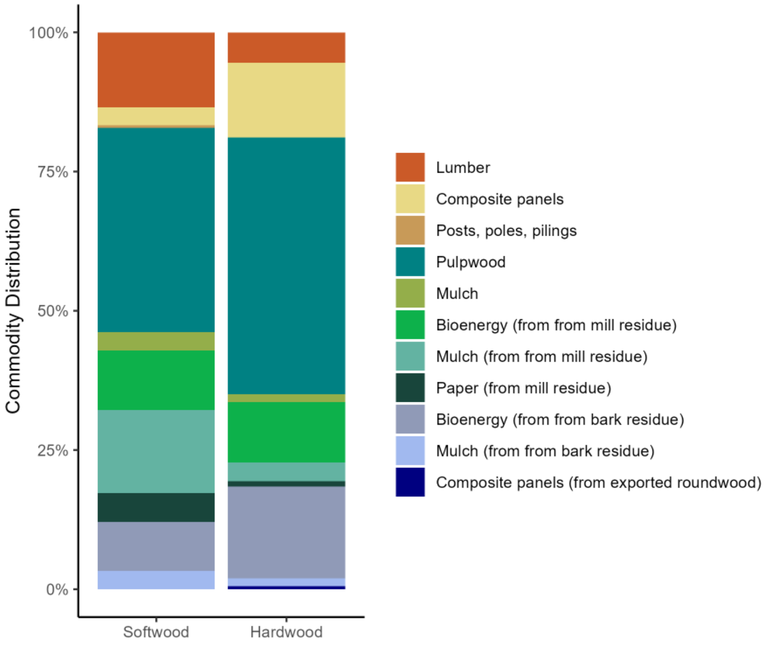

Figure S2. Primary product ratios for commodities produced in Minnesota, differentiated by softwood and hardwood inputs.

To account for carbon losses during the manufacture of these primary products, we incorporated end-loss and manufacture efficiency data from Row & Phelps (1996), Franklin Associates (1998), and Skog & Nicholson (2000). We modeled efficiencies of 92.5% for lumber, 93% for composite panels, 98% for poles, and 95% for pulp products. We allocated any end-loss carbon that occurs when products are placed into their end-use (7.5% for lumber, 7% for composite panels, 2% for poles, 5% for pulp) directly to landfills.

Domestic End-Use Consumption and Half-Lives

Once we had calculated exports, mill residues, and primary products from annual harvest volumes, we determined 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 Minnesota 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 3** for half-life assumptions for both domestic and international product use.

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 2017a; 2017b22b; 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 anaerobic landfilled wood and 10% of carbon in anaerobic landfilled paper could eventually be emitted. We then applied IPCC default landfilled material half-lives for wet, temperate climates (IPCC 2019); 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 Minnesota from 1981-2010 (Midwestern Regional Climate Center). International landfilled product half-lives, from IPCC (Towprayoon et al. 2019), were modeled at 26.5 years for wood and 13.5 years for paper. 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 m^3/yr from wood and 0.06 m^3/yr from paper. Finally, we assumed that 67.4% of generated methane was flared or recovered for energy (creating emissions of CO_2 rather than methane) and 32.6% was unrecovered based on data reported in the 2015 US National Inventory Report Annex I (EPA 2015).

Product Substitution 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, bioenergy, and transport fuel 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 timber product substitution, we coupled Minnesota-specific production data (USDA Forest Service 2019b; 2023a; 2023b) , 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: 2.058; hardwood: 2.355) and composite panels (softwood: 2.342; hardwood: 1.739), 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 first assumed that 50% of biomass would go toward electrical production and 50% would go toward combined heat and power (CHP) production. Then, using data from the U.S. Energy Information Administration (2024), we calculated the proportion of electrical and CHP production coming from fossil sources (coal, oil, and natural gas), and used these proportions and the LCAs from Smyth et al. (2017) to estimate a weighted composite LCA. Then, based on the assumption that wood used in bioenergy has an energy density of 2 MWh tC^{-1} (Federal Energy Management Program 2004), we calculated displacement factors for electric (0.502 tC tC^{-1}) and CHP (0.194 tC tC^{-1}) for bioenergy. Because Minnesota has a 100% clean energy goal by 2040 (Frentz et al. 2023), we assumed that from 2041 onward electrical bioenergy would no longer displace any fossil carbon fuel sources. The rationale here is that 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. As such, we applied a decreasing displacement factor to the electrical proportion of the bioenergy such that it decreases linearly until reaching zero in 2040.

To account for substitution benefits associated with transport fuel, we first assumed that 100% of biomass would go toward production of sustainable aviation fuel (SAF). We used an LCA from the CORCIA standard (Prussi et al. 2021) which was developed for the International Civil Aviation Organization's carbon lifecycle accounting when using alternative (SAF) fuel sources. There are a number of different SAF pathways for woody biomass, however after consultation with state partners we chose to model the Iso-butanol alcohol-to-jet (Iso-BuOH ATJ) pathway. We used data from Akter et al. (2024) to estimate the mass of wood/carbon which goes into making a unit of SAF at 0.15 kg of wood/MJ. Based on this, we calculated a displacement factor for SAF of 0.238 tC tC^{-1}.

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 84.4%, meaning that 84.4% of reduced harvest relative to the BAU was assumed to leak out-of-state and the remaining 15.6% 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.

C. Scenario Description / Development

Extended Rotations

Altering rotation lengths, specifically extending rotations, serves as one strategy to boost the climate mitigation potential of forests. In this scenario all red pine plantations at 80 years (an ~20-30-year change depending on management unit). Additionally, this scenario increases all aspen rotations by +20 years, and +30 years on spruce and tamarack rotations. Lastly, all thinning and uneven-aged entries are extended by +10 years.

Increase Reserve Size

One possible pathway of increasing carbons storage is to leave more carbon on site after harvest by increasing the number of living residual trees left behind. Removing a substantial portion of trees except for reserve trees, produces a fully exposed microclimate for the development of new age classes where regeneration can be driven by natural seeding, direct seeding, planted seedlings, or advance reproduction. The scenario serves to represent an increase in the average reserve size of clearcuts to 10% as opposed to the current 5% in the BAU scenario.

Insect Vulnerability Transition

Climate change is poised to impact specific forest types through introducing new and novel pests/diseases as well as exacerbating both the intensity and severity of mortality events. Proactive management of forest types predicted to be impacted the most provides a clear pathway to ensure carbon is not lost. Through either natural regeneration or replantings and enrichment plantings, certain forest types can be guided along with this transition. For this scenario, ash and tamarack stands are clearcut and through some level of management will regenerate as different cover types that are predicted to be more resilient under climate change. In this scenario, ash regenerates as 100% lowland hardwood whereas tamarack will regenerate as 50% black spruce and 50% northern white cedar following clearcut harvests.

Enrichment Planting

Artificially increasing the stocking level of underperforming stands that have failed to regenerate serves as another viable option to increase both carbon storage and carbon sequestration (Aide et al., 2000; Dalle et al., 2006). This scenario as 4,500 acres per year targeted for enrichment plantings for the entirety of the simulation targeting (ecoregion represented in paratheses): Aspen (MDL); Balsom Fir (NSU); Birch (NSU); Lowland hardwoods (MDL); Northern hardwoods (NSU); and Oak (MDL). The acreage targets are apportioned evenly across all six cover types identified representing 750 acres targeted per cover type per year.

Tree Planting

Increasing forest extents is one of the most cost-effective methods for climate change mitigation. We implemented three afforestation scenarios (low, medium, and high) that reforested an additional 5,600 acres annually (4x BAU estimates), 11,200 acres annually (8x BAU estimates), and 22,400 acres annually (16x BAU estimates). New forests were established at a rate of 25% red pine, 20% white pine, 20% white spruce, 25% oak, and 10% walnut.

Avoided Conversion

Maintaining forest extent is another highly cost-effective method for climate change mitigation. Avoiding the conversion of forests to non-forests ensures a stronger carbon sink and a more sustainable supply of timber while meeting additional conservation goals. We modeled two (low and high) avoided conversion scenarios that saw a respective 10% decrease and 30% decrease in permanent forest loss to other land-uses such as settlements or agriculture.

Climate Change Impacts

Understanding the future dynamics of disturbance regimes on carbon helps elucidate potential pathways to mitigate and adapt to those impacts. This scenario realized a 10% increase in mortality caused by insect and disease pathogens in terms of annual disturbance rate (i.e., area) and intensity. This scenario represents a very coarse way to evaluate the potential carbon flux implication of increased mortality due to climate change.

No Harvest

This scenario illustrates a passive management approach in which no harvesting or thinning activities occur at all. Modeling a passive management approach provides a useful counterpoint to other modeling scenarios that illustrate active management approaches. These modeling results provide a scientific and quantitative basis for an on-going discussion about the role of timber harvest and harvested wood products in meeting climate mitigation goals. The scenario does include a small annual transfer of some carbon to HWPs resulting from permanent forest conversion.

Increased Management

Harvests, cuttings, and other intermediate treatments are some of the primary tools foresters and forestry practitioners have in managing forests. If done properly, these tools can be used to sustainably manage timber resources and provide sufficient timber crops. Currently, gross tree growth in Minnesota outpaces removals and mortality suggesting that increases in timber removals would not severely impact future growth and regeneration (USDA Forest Service, 2020). This scenario increases mature timber harvests percent increase on all mature harvesting (not thinnings or other intermediate treatments) by 10% on privately-managed lands. Additionally, partners were interested in the effects of additional wood utilization of the increased removals using BAU product splits.

Logging Residues

This scenario saw increased residues removed from harvest sites which were then sent to HWP. This scenario realized ~350,000 tC of residuals were removed and transferred to HWP per year. Residues are allocated 100% to one of three products (bioenergy, biochar, or transport fuels) depending on which alternate HWP model is used. If the BAU HWP model is used, residues are treated like any other input of HWP (e.g., subject to the normal bark/merchantable/fuelwood split).

Long-Lived Wood Products

These two alternative HWP models see a fraction (20% or 50%) of carbon allocated away from shorter-lived wood products (pulp/paper) toward longer-lived products (LLPs) to which we assign the HWP parameters for composite panels. These use BAU ecosystem inputs, so only differ from BAU in their HWP emissions and product substitution. The ecosystem dynamics, and thus HWP transfer and leakage, are identical to BAU.