



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

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August 17, 2026

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Acknowledgements

The research team is grateful to Werner Kurz, Eric Neilson, Scott Morken, and other staff of the Carbon Accounting Team of the Canadian Forest Service of Natural Resources Canada for invaluable advice and support on this project and for providing the training, models, and code templates necessary for this work; to Greg Edge, Ram Dahal, Brian Anderson, and Ryan Heiderman for support and input from the Wisconsin Department of Natural Resources, and to the United States Climate Alliance for funding and support.

Suggested Citation

Papa, C. P., Davidson, K. J., DeLyser Roney, K., Magnan, M., Gadoth-Goodman, D., Clay, K., Diedrich, G., Ontl, T., & Cooper, L. (2026) Modeling climate-smart forestry and wood utilization for climate mitigation potential in Wisconsin. American Forests.
https://doi.org/10.5281/zenodo.21981805

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Summary and Implications for Decision Makers

Forests as Natural Climate Solutions

Climate change presents an unprecedented global challenge to society and the forest 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. There is also increasing consensus of forests' importance as a nature-based solution to climate change, or natural climate solution (NCS) (Drever et al. 2021; Griscom et al. 2017; Fargione et al. 2018).

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. In 2023, US forests captured and stored nearly 890 million metric tons of carbon dioxide equivalency (MMT CO_2e), enough to offset 14.4% of gross greenhouse gas emissions in the same year (EPA 2025). Almost 90% of this climate benefit was provided by existing forests and forest products, and assessments of NCS 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 in magnitude throughout the 21st century due to forest loss and forest health declines, in part driven by a changing climate (Wear and Coulston 2015; Oswalt et al. 2019).

Future management and policy decisions that integrate mitigation goals with adaptation to future climate conditions can maintain and strengthen the NCS capacity of forests. This dynamic is central to the concept of *climate-smart forestry (CSF)*, a sustainable forest management approach that seeks to balance the ability of forests to adapt to and mitigate climate change while continuing to provide fundamental wood products and ecosystem services (Nabuurs et al. 2018; Bowditch et al. 2020; Verkerk et al. 2020). This approach acknowledges the importance of maintaining or increasing carbon storage in forests and forest products as a climate solution but also emphasizes the need for robust carbon sequestration rates to continue to draw carbon out of the atmosphere as part of a global effort to mitigate climate change, seeking to balance carbon sequestration and storage rates throughout the forest. CSF techniques focus on long-term forest health and resilience in the face of climate change as part of sustainability in forest management, and they aim to accomplish all these goals while supporting a strong wood products sector. According to the IPCC, meeting our global climate goals is not possible without forests (Calvin et al. 2023), and forests need the health and resilience benefits provided by CSF to play their part. Therefore, the most promising NCS practices for forests follow a CSF approach.

State and local 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. Increasingly, states such as Minnesota, Wisconsin, and Michigan plan to use information about the current influence that forests, forest management, and forest policies have on emissions levels, as well as the interaction with predicted decline in forest health and climate benefits, to better inform decision making and policy regarding forests and climate action. This report is designed to inform Wisconsin's future decision making towards

carbon stewardship, forest management and policy, and wood utilization in state-level climate action planning. Here, we present results for a broad range of forward-looking forest management and wood utilization scenarios and assess the mitigative potential of forests and carbon stored in HWP, along with an analysis of the substitution benefits from using wood in place of other emissions-intensive materials.

Modeling Forest Management and Wood Utilization in Wisconsin

Following similar assessments in Papa et al., 2023; DeLyser et al. (2022a; 2022b; 2025); Davidson et al. (2026) and Dugan et al. (2018; 2019; 2021), we assess carbon trends and management scenarios in the forest ecosystem and forest products sector for Wisconsin utilizing a systems-based approach. This systems approach accounts for the influence of forest management activities beyond the forest itself and allows us to examine potential trade-offs or synergies between management strategies that maximize forest ecosystem carbon stocks, HWP volumes, or other important forest ecosystem services (Dugan et al. 2018). Our modeling process includes:

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

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 Wisconsin, ii) a state-specific model of harvested wood products dynamics (CBM-HWP-WI) utilizing the Abstract Network Simulation Engine (ANSE) framework, and iii) displacement factors to evaluate substitution benefits from using wood products and bioenergy in place of more emissions-intensive materials; and

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

Through a series of meetings with the Wisconsin Department of Natural Resources, we identified several management priorities and concerns for forests in Wisconsin: **harvesting practices**, **forest health and regeneration**, **land-use change and forest conservation**, **climate change impacts**, and **wood utilization and markets**. Many of these priorities are not exclusive to Wisconsin and have been recognized as concerns regionally and nationally. From these state priorities, we developed 12 modeling scenarios to cover a broad range of forest management, climate change impacts, and wood utilization scenarios, grouped into 5 categories representing similar objectives: 1) altered rotation lengths and management; 2) forest health and

Box 1. MODELED SCENARIOS

- Extended Rotations*
- Increased Harvest Retention Size
- Increasing Harvest Levels
- Increased Regeneration*
- Coarse Woody Debris Enhancement
- Afforestation*
- Forest-Type Conversion*
- Increased Harvest Residue Utilization
- Increased Softwood Utilization
- Increased Hardwood Utilization
- Composite Panels from Pulpwood
- Portfolio (concurrent implementation of scenarios marked with *)

regeneration 3) tree planting; 4) climate adaptive management; and 5) wood utilization and markets (**Box 1**). For full scenario descriptions and parameters, see **Report Table 3**.

Climate-Smart Forestry in Wisconsin

Forests and the forest products sector already contribute strong climate mitigation benefits in Wisconsin as a net carbon sink, and undertaking changes in land use and forest management could increase these benefits substantially. Key factors for successfully implementing CSF include establishing and maintaining a diverse and multi-age forest landscape that balances the two critical mechanisms through which forests benefit the climate – carbon sequestration (removing carbon from the atmosphere and converting it into wood through photosynthesis) and carbon storage (holding that carbon in forests and wood products rather than emitting it to the atmosphere).

Some forestry practices have nearly universal climate mitigation benefits no matter where they are applied such as planting trees. Yet, Wisconsin's forests and wood products sector offer their own unique case, and certain practices are particularly promising for the state from a carbon perspective as Wisconsin has a diversity of forest communities, both structurally and compositionally, that are managed for a variety of forest products and other ecosystem services. This analysis demonstrates that a diverse set of climate-smart strategies exists for Wisconsin (**Box 2**).

BOX 2. CLIMATE-SMART FORESTRY PRACTICES IN WISCONSIN

- ✓ **Continued sustainable management of working forestlands** to support climate mitigation potential and the forest bioeconomy through current practices represented in the *Business-as-Usual* scenario and through increasing forest extent by *Afforestation.*
- ✓ **Increase carbon sequestration and the carbon retention potential** of the forest through *Extending Rotations* and increasing the *Harvest Retention Size* following harvesting and other forestry operations.
- ✓ **Support climate mitigation and adaptation** by incorporating climate change considerations into forest management, such as proactively promoting more adaptive *Forest-Type Conversions* or by implementing the suite of practices represented by the *Portfolio* scenario.
- ✓ **Bolster climate mitigation potential of the forest products sector** through wood utilization strategies including increased utilization of *Harvest Residues*, increased production of *Longer-Lived Wood Products* or by altering current commodity production ratios such as producing additional *Composite Panels from Pulpwood.*

The benefits of expanding climate-smart forestry in Wisconsin

Our results suggest that by continuing *Business-As-Usual* (BAU) practices, Wisconsin's forests will be a consistent net carbon sink, (**Box 3**) with an average annual *Net Ecosystem Carbon Flux* (NECF) of -5.56 MMT CO_2e yr^{-1}. When this NECF value is combined with an average annual transfer of 8.79 MMT CO_2e yr^{-1} to harvested wood products, Wisconsin is projected to have a

Box 3. CARBON METRICS

Net Ecosystem Carbon Flux refers to the net annual sequestration of carbon by forests across all ecosystem carbon pools after accounting for decomposition, natural disturbance emissions, land-use change, and wood product transfers.

Net Carbon Balance includes net ecosystem carbon fluxes, net emissions from HWP in use and in landfills, substitution benefits from the use of wood in place of more emission intensive materials, and leakage in years where harvest is less than BAU to account for some level of emissions leaking outside of the study area due to a reduction in harvests.

Net Ecosystem Carbon Flux and ***Net Carbon Balance*** are presented from the atmospheric perspective where negative numbers represent a net carbon sink (more carbon removed from the atmosphere), and positive numbers represent a net carbon source (more carbon emitted to the atmosphere).

cumulative *Net Carbon Balance* (**Box 3**), of -487.08 MMT CO_2e between 2021-2100, provided that current trends in land-use change, natural disturbances, and timber harvesting continue. These results suggest that continuing current management practices and harvest rates will allow Wisconsin's forests to act as a net carbon sink throughout the end of the century, while still providing a steady supply of HWP. Further, we also found that by implementing concurrent CSF management practices as represented by the *Portfolio* scenario, which includes *Extended Rotations*, *Increased Regeneration*, *Afforestation*, and adaptive *Forest-Type Conversion*, could increase Wisconsin's forest carbon sink by 29.4% in 2030 and 28.5% in 2050, relative to BAU. This equates to an additional -31.32 MMT CO_2e sequestered by 2050. While our results suggest that BAU management would provide a reliable carbon sink and a sustainable timber supply through the end of the century, implementing additional CSF management actions could increase the mitigation potential of forests, further contributing to net-zero GHG emission goals without disrupting timber supplies or other management objectives.

Forests in all scenarios modeled in this analysis remained net carbon sinks until the end of the century, indicating that Wisconsin's forests will be a reliable natural climate solution into the future. However, by examining the future trends of individual scenarios we can ascertain additional details about the magnitude and mechanism underpinning each scenario's climate mitigation potential (whether increased or decreased) relative to BAU. For example, the *Extended Rotation* scenario, which increases the minimum harvest age by 20-95 years, accumulates a large amount of additional carbon in the forest ecosystem, while at the same time experiencing decreased transfer to, and storage of, carbon in the wood products sector. As a result of this decreased transfer to HWP this scenario is subject to leakage and negative substitution effects. The net of these opposing factors results in a 5.6% increase in carbon sequestration and storage (an additional -27.56 MMT CO_2e) by 2100 as compared to BAU. The *Increased Harvest Retention Size* scenario, in which a larger reserved area is set aside following harvest, also results in significant carbon being accumulated in the forest ecosystem and less carbon transferred to the wood products sector, resulting in leakage and negative substitution benefits. Consequently, the *Increased Harvest Retention Size* scenario experiences a 14.1% increase in carbon sequestration and storage (an additional -68.73 MMT CO_2e) by 2100 as compared to BAU.

The *Afforestation* scenario results in a small increase in forest area across the simulation which reverses the net forest area loss trend (-3,934 ac yr^{-1}) in the BAU simulation. This alteration of land-use change trends via planting an additional 277,944 ac by 2100 corresponds with an increase in climate mitigation of 7.5% (an additional -36.67 MMT CO_2e sequestered) by 2100 as compared to BAU. The *Forest-Type Conversion* scenario, which assumes secondary succession of older aspen stands to mixed stands of longer-lived hardwood and softwood species by allowing other longer-lived species to be established, leads to a 2.4% increase in climate mitigation (an additional -11.92 MMT CO_2e) by 2100 as compared to BAU, largely due to the fact that the more mature successional forest types can sequester and store additional carbon, particularly in the older age-classes, relative to the aspen stands they replace.

Although forests in all scenarios remained net carbon sinks until the end of the century, not every scenario led to an increase in climate mitigation relative to BAU. For example, three scenarios, *Increased Regeneration*, *Increased Harvest Levels*, and *Coarse Woody Debris Enhancement*, remain net carbon sinks, yet sequester less carbon by 2100 as compared to BAU. The *Increased Regeneration* scenario, which increases supplemental planting on understocked stands and increases the rate of regeneration harvests on sites with failed regeneration, experiences 3.9% less climate mitigation (18.9 MMT CO_2e less carbon sequestration) by 2100 as compared to BAU. This mainly occurs as the increased productivity from restocking treatments does not offset the loss of carbon and carbon sequestration capacity from additional regenerative harvests and cuttings. The *Increased Harvest Levels* scenario, which increases annual harvest volume targets by ~10%, experiences 4.5% less climate mitigation (26.11 MMT CO_2e less carbon sequestration) by 2100 as compared to BAU. Like in the *Increased Regeneration* scenario, this effect comes from increased harvest levels which, all else being equal, lower the sequestration capacity of the forest, despite an increase in storage of carbon in the wood products sector. Finally, the *Coarse Woody Debris Enhancement* scenario led to 6.2% less climate mitigation (30.00 MMT CO_2e less sequestration and storage) than BAU by 2100. This outcome, the worst of any of the scenarios tested, is driven in part by decreases in forest productivity from additional material being cut and left on site, as well as slight decreases in HWP transfers and storage relative to BAU.

All four wood utilization and markets scenarios represented opportunities for increased climate mitigation potential as compared to BAU. The *Increased Harvest Residue Utilization* scenario, in which harvest residues normally left in the forest are instead used in biochar production, led to a 16.5% increase in climate mitigation (an additional -80.21 MMT CO_2e) as compared to BAU by 2100. This is because biochar has a long product half-life, and thus relatively low HWP emissions over the modeled timeframe. As such, the small increase in HWP emissions from biochar decomposition is more than offset by a large reduction in ecosystem emissions due to less decomposition of harvest residues. The *Increased Softwood Utilization* scenario increased softwood harvest volume targets by 8.5%, with all of this additionally harvested material allocated to mass timber. This increase in harvest and HWP production led to a 9.1% increase in climate mitigation (an additional -44.40 MMT CO_2e) by 2100 as compared to BAU. Similarly, increasing the harvest targets for hardwood species by 5% with the intent to increase the production of longer-lived (e.g., lumber) products, as represented by the *Increased Hardwood Utilization* scenario, increased climate mitigation by 4.9% (an additional -24.10 MMT CO_2e) by 2100 as compared to BAU. Finally, the *Increased Pulpwood Utilization* scenario, which diverts pulpwood away from shorter-lived wood products such as paper to the production of composite panels, increased climate mitigation by 3.9% (an additional -19.06 MMT CO_2e) as compared to BAU by 2100. These four scenarios all increased the carbon storage capacity of the forest products sector either by decreasing HWP emissions or increasing input into commodity streams with longer half-lives (or both), while

simultaneously providing additional positive substitution benefits when certain commodity production levels are increased.

Other Considerations

It is important to note that the scenarios tested in this analysis are constructed based on prescriptive projections rather than true predictions for future model parameters. That is, our model projections take long-term averages of contemporary management and apply them to the future, rather than dynamically altering future management in response to potential future conditions. Further, our BAU assumptions make no attempt to predict future climate conditions and their subsequent impact on carbon dynamics (e.g., growth rates and/or natural disturbance regimes). Results are reported entirely in terms of carbon and do not draw explicit conclusions about the impacts of our scenarios on other forestry goals such as biodiversity, water cycling, recreation, economic impacts, and other vital ecosystem services forests provide. However, in conjunction with our state partners, our scenarios were designed with co-benefits in mind. Other studies suggest that practices such as *Afforestation* (Niu and Duiker, 2006, Stai et al, 2010, Doelman et al, 2020), *Increased Harvest Retention Size* (Nunery and Keeton, 2010, Zugic et al, 2021), *Extending Rotations* (Roberge et al., 2016, Roberge et al., 2018), and *Forest-Type Conversion* (Nave et al, 2017, Gough et al, 2021, Nave et al, 2024) can potentially increase the mitigation potential of forests in addition to meeting a suite of other management goals including slowing deforestation rates, promoting forest conservation, and increasing the adaptive capacity of forests to cope with climate change.

Conclusion

Forests are managed for a myriad of goals and objectives. Identifying strategies and policies that can optimize and balance forest benefits remains crucial to the future health and stewardship of natural and working forestlands. Our results suggest that current BAU practices could lead to both a stable carbon sink and a sustainable timber supply throughout the end of the century. This analysis further demonstrates that various climate-smart forest management actions – including increasing the area of forestland, maintaining forest health and regeneration, sustainable use of timber products, and managing for future impacts of climate change – provide relatively low-cost solutions to increase the mitigation of Wisconsin's forests. While this report only assesses outcomes in terms of climate mitigation and carbon balance dynamics, many of these CSF tactics provide other forest co-benefits in support of forest stewardship. Our results do not suggest that Wisconsin is currently at a critical point of a future weakened net carbon sink. However, our results do suggest that specific and concerted actions can be taken now to increase both the resilience and climate mitigation potential of Wisconsin's forests and forest products sector.

Introduction

Forests as a Natural Climate Solution

Climate change presents an unprecedented global challenge to society, and the forest ecosystems society relies on. Forests have become increasingly important in 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. In 2023, US forests captured and stored nearly 890 million metric tons of carbon dioxide equivalency (MMT CO_2e), enough to offset 14.4% of gross greenhouse gas emissions in the same year (EPA 2025). 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 and forest health declines fueled by climate change (Wear and Coulston 2015; Oswalt et al. 2019).

To maintain and strengthen the NCS capacity of forests, future management and policy decisions will need to mesh mitigation goals with adaptation to future climate conditions. This dynamic is central to the concept of climate-smart forestry (CSF), a sustainable forest management approach that seeks to balance the ability of forests to adapt to and mitigate climate change while continuing to provide fundamental wood products and ecosystem services (Nabuurs et al. 2018; Bowditch et al. 2020; Verkerk et al. 2020). This approach acknowledges the importance of maintaining or increasing carbon storage in forests and forest products as a climate solution but also emphasizes the need for robust carbon sequestration rates to continue to draw carbon out of the atmosphere as part of a global effort to mitigate climate change, seeking to balance carbon sequestration and storage rates throughout the forest. CSF techniques focus on long-term forest health and resilience in the face of climate change as part of sustainability in forest management, and they aim to accomplish all these goals while supporting a strong wood products sector. According to the IPCC, meeting our global climate goals is not possible without forests (Calvin et al. 2023), and forests

need the health and resilience benefits provided by CSF to play their part. Therefore, the most promising future NCS practices for forests will need to follow a CSF approach.

Assessing Forest Climate Benefits in Wisconsin

State and municipal governments can leverage climate benefits from forests, and mediate 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 policies and programs that lower greenhouse gas emissions, maintain current carbon storage, increase stored carbon pools, and enhance sequestration rates. As part of this push, more states are supporting lateral efforts (e.g., participating in the US Climate Alliance) and undertaking assessment, planning, and monitoring within their jurisdictions. Given the NCS potential of forests, states are exploring measures to demonstrate, promote, and support an active sustainable forest industry and are considering options for increasing the role of forests and HWP in state climate mitigation plans.

To achieve such ambitious climate targets, states need additional information about the impact that forests and forest management currently have on emissions levels, as well as an understanding of their future implications on forest health and climate mitigation potential. State governments within the Lake States region (Minnesota, Wisconsin, and Michigan) desire to use this information to improve decision making and inform policy regarding forests and climate action. Minnesota, Michigan, and Wisconsin collectively contain 54.66 million acres of forestland, and all states are seeking information about climate mitigation and adaptation opportunities in their forests to incorporate in revisions to state-level Forest Action Plans and Climate Action Plans. By working together in this regional study, the Lake States region can learn about shared forest management challenges and goals and collaborate to develop effective management and policy strategies, with the understanding that issues, barriers, and opportunities will be similar across the region.

This report is designed to inform Wisconsin's future decision making towards carbon stewardship, forest management and policy, and wood utilization in state-level climate action planning. Here, we present results for a broad range of forward-looking forest management scenarios and assess the mitigative potential of forests and carbon stored in HWP, along with an analysis of the substitution benefits from using wood in place of other emissions-intensive materials.

The Context of Wisconsin Forests

Wisconsin has 16.94 million acres of forest land (~47% of the state). Over the past decade, annual gross forest productivity has outpaced both annual removals and mortality to provide a reliable carbon sink (USDA Forest Service, 2021). Wisconsin's forests provide numerous ecosystem services such as wildlife habitat, clean air and water, erosion control, and improving the quality of life in urban and rural areas. Wisconsin's forests are primarily composed of hardwood species including oak-hickory forests (26% of total forested area), maple-beech-birch (22% of total forested area), and aspen-birch (17% of total forested area). Lowland forests dominated by elm and ash trees account for approximately 10% of forested areas. Conifers, while less dominant, remain an important aspect of Wisconsin forests with pine and spruce-fir forests representing about 18% of forested area (WI DNR, 2021). Approximately 70% of forests are privately owned, with about 10% managed by federal agencies and the rest owned by state, local, and Tribal entities.

Forestry and the forest product sector contribute significantly to Wisconsin's economy, in large part due to the crucial role that timber harvest plays in sustaining a vibrant forest-based economy. The forestry sector also plays a large role in promoting and managing the health of forests actively managing forests and creating economic incentives for forest stewardship and conservation. Over 64,000 people are employed in the forest products sector; however, since 2006, both the number of people employed and wages have decreased (WI DNR, 2017). Additionally, paper mills have continued to decline statewide primarily driven by the stumpage price for pulpwood (WI DNR, 2017). Similar to the other Lake States, concerns have arisen about Wisconsin's aging forest sector workforce and a lack of continued investment in forestry related businesses (Gc et al., 2020).

Wisconsin's forests have been profoundly impacted by native peoples, specifically using fire to maintain and establish favored plant and animal communities. The forests of Wisconsin provided native peoples for centuries with foraging, food, other tree crops, and habitat for hunting and trapping. The arrival of European settlers removed or confined native populations throughout the 1800s, which began a process of cutting forests and burning the land for agriculture. The latter half of the 19th century saw logging increasingly becoming an important part of the Wisconsin economy. However, by the 1930s, most of the valuable timber in the state had been removed or destroyed by fire. This depletion of forest resources led to the implementation of fire control strategies and a blossoming conservation movement to revert abandoned land back to forests (WI DNR 2021; WI DNR 2020b). Today, Wisconsin's forests support a wide range of forest ecosystems; however, climate change and other non-native health threats persist (WI DNR 2021; WI DNR 2020b). Wisconsin's forests provide a unique case study of assessing future climate mitigation potential in support of net zero GHG emission targets without hampering forest ecosystems and other environmental services.

Research and Modeling Process

Following methodologies derived in Papa et al., 2023; DeLyser et al. (2022a; 2022b; 2025); and Dugan et al. (2018; 2019; 2021), we assessed carbon trends and management scenarios in the forest ecosystem and forest products sector for Wisconsin utilizing a systems-based approach. This systems approach accounts for the influence of forest management activities beyond the forest itself and allows us to examine potential trade-offs or synergies between management strategies that maximize forest ecosystem carbon stocks, HWP volumes, or other important forest ecosystem services (Papa et al., 2023; Dugan et al., 2018). Our modeling process included:

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

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 Wisconsin, ii) a state-specific analysis of harvested wood products model (CBM-HWP-WI) dynamics utilizing the Abstract Network Simulation Engine (ANSE) framework, and iii) displacement factors to evaluate substitution benefits from using wood products and bioenergy in place of more emissions-intensive materials; and

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

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 Accounting

Trees uptake carbon as they grow, which then cycles through various components of the forest. Accrual of carbon in the forest ecosystem also depends on accumulation of other carbon pools including dead wood, leaf litter, and soil (Smith et al. 2006), as well as the rate of decomposition and respiration (Gower 2003). 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 stored in wood products (**Figure 1**). *Carbon sequestration* refers to the annual uptake rate of carbon from the atmosphere by forests, primarily driven by rates of tree growth, mortality, decomposition, respiration, and loss of carbon from disturbance. These elements combine to represent the forest's climate mitigation potential. Forests that sequester and store more carbon than they release from decomposition and respiration each year represent a *net carbon sink*; conversely, forests that release more carbon than they sequester and store become a *net carbon source.*

To understand the role forests can play in mitigating climate change, we need more accurate assessments of these forest carbon dynamics and interactions. The systems approach used in this analysis provides a comprehensive look at not only the forest ecosystem dynamics at play, but also forests' interactions with land-use change, the forest products sector in terms of emissions from harvested wood products (HWP) while in use and during disposal, potential leakage from changing harvest rates, and substitution of wood products in place of more emissions-intensive materials (**Figure 1**). Excluding any one of these components would lead to an incomplete accounting of forest carbon, misrepresenting net forest emissions and climate mitigation potential – therefore, a systems approach is necessary (Smith et al. 2006; Papa et al. 2023; Dugan et al. 2018; Kurz et al. 2009; Nabuurs et al. 2007). Our approach follows IPCC Tier 3 Good Practice Guidance for systems-level accounting of forest carbon, which allocates emissions from harvest, transportation, and manufacturing of HWP to other sectors rather than the forestry sector (Kurz et al. 2009), so these elements are not included in this analysis. We also follow IPCC's production approach, meaning we report carbon in forests and trees grown in Wisconsin and their ultimate destination as HWP (including exports) but do not consider carbon from out-of-state trees that are later imported and used in-state.

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 (though changing the land-use classification from forest to non-forest, for example, does not necessarily mean that all carbon is immediately emitted – instead, it has moved into the carbon budget for a different sector). Carbon can also leave the forest through harvested wood, which is further assessed and tracked through its usage (in wood products and energy), decay, and end of life (e.g., landfill storage and wood energy) via the CBM-HWP-WI model described below. Wood products

from sustainable forest management that are used in place of more emissions-intensive products like concrete and steel are also counted as a climate solution by providing renewable and lower-emissions materials alternatives (McKinley et al. 2011). If harvest levels decrease within the system boundary, there is a chance that harvest activities and associated emissions will increase, or "leak" outside the system to make up for any unmet HWP demand (Nabuurs et al. 2007). Our methodology, and common practice in carbon offset protocols (Haya et al. 2023), requires we also account for this possibility of leakage.

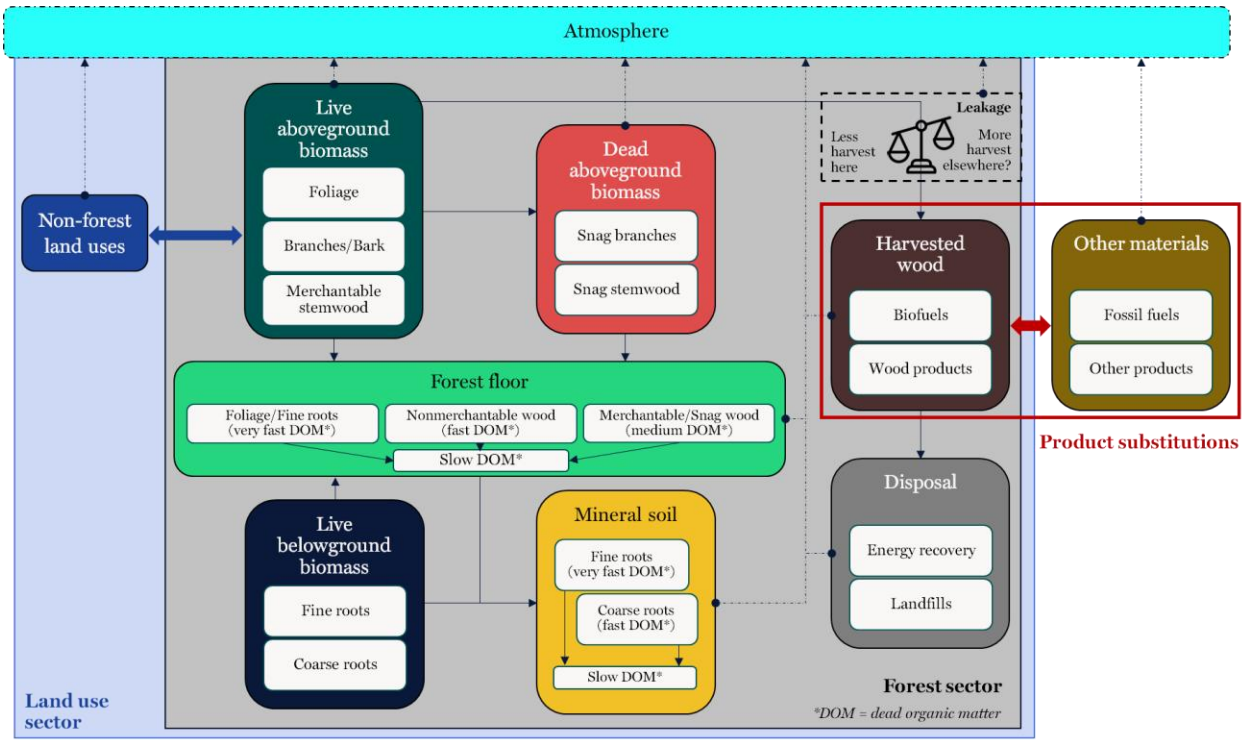


Figure 1. Simplified systems view of land uses and sectors influencing forest carbon stocks and sequestration. The Forest sector (gray box) provides a graphical representation of forest carbon pools and transfers in the CBM-CFS3 model and ANSE carbon accounting tool. For DOM pools, "very fast", "fast", "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).

In this analysis, we calculate various metrics to represent these dynamics and determine the carbon sink or carbon source status of forests and the forest sector. *Net ecosystem carbon flux* refers to the net yearly sequestration of carbon by forests across all 14 ecosystem carbon pools, after accounting for decomposition, natural disturbance emissions, and wood product transfers from the ecosystem to the forest products sector. Net ecosystem carbon flux is presented from the atmospheric perspective, where negative numbers represent a net carbon sink (less carbon in the atmosphere) and positive numbers represent a net carbon source (more carbon in the atmosphere). We combine net ecosystem carbon flux with carbon storage and emissions from HWP, potential leakage, and substitution benefits to calculate the *net carbon balance* of the forest sector. Net carbon balance presents the system-wide view of carbon dynamics and is therefore the final metric used to assess the climate mitigation potential for each of our modeled scenarios.

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; DeLyser et al. (2022a; 2022b; 2025); Davidson et al. (2026); Pilli et al. 2013; 2014; 2017; 2022; Cienciala and Melichar 2024) 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 (USDA Forest Service, 2019) to ensure accuracy for Wisconsin forests. We use the CBM-CFS3 for this study at the request of Wisconsin DNR staff, to expand on previous modeling efforts for state forests in both the Mid-Atlantic region and across the Lake States region.

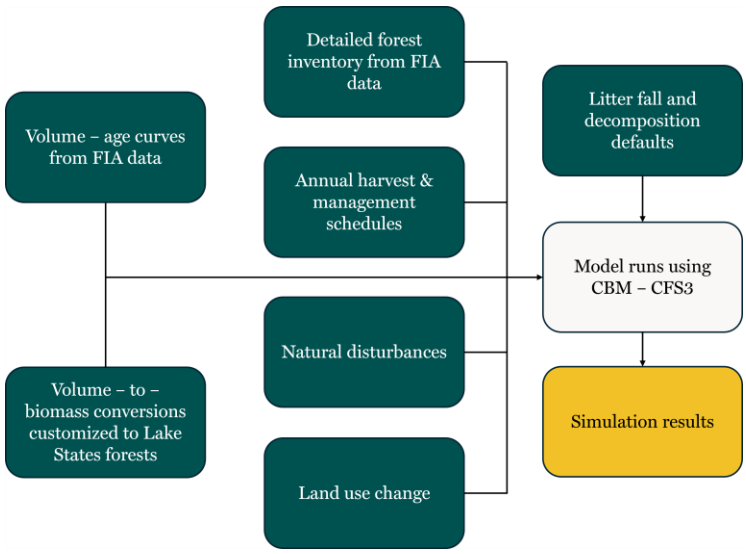


Figure 2. Modeling inputs and processes for CBM-CFS3. Adapted from Kull et al. 2019.

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

Management and natural disturbance data are also necessary inputs – CBM-CFS3 does not independently predict future events but instead follows a user-determined schedule of annual management, disturbance, and land-use change (LUC) events (collectively termed *disturbances*) for the simulation period. Disturbances can be targeted to certain classifiers and stand ages using a rule-based approach as appropriate. In addition to event schedules, 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).

For this analysis, we used the FIA database (USDA Forest Service 2022) to estimate a statewide forest inventory, generate growth-yield curves to estimate forest productivity, calibrate volume-to-biomass equations, and determine harvest allotments. Harvest and land-use change (LUC) activity data were estimated across a 12-year periods (2007-2019). FIA derived estimates of LUC were validated and had broad agreement with the National Land Cover Database (NLCD; Wickham et al. 2021). Insect and disease data including defoliation and mortality events were derived from the USDA National Insect and Disease Detection Surveys (USDA Forest Service 2020). Similarly, total area burned by wildfire was derived from the FIA database (USDA Forest Service 2022). Acreages were assigned one of three levels of burn severity determined by percent mortality following proportions determined by the Monitoring Trends in Burn Severity database (MTBS; Eidenshink et al. 2007). Data for prescribed fire was estimated using the Wisconsin DNR Fire Management Dashboard (WI DNR 2023). The disturbance matrices used for this study have been parameterized to represent Lake States forest conditions and practices. See **Table 1** in the **Developing Modeling Scenarios** section for BAU ecosystem disturbance parameters and 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-WI 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 historical 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-WI 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 Wisconsin products and markets.

Some *disturbance events* (particularly, though not exclusively, harvest or cutting 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-WI model. These carbon inputs are partitioned into various HWP streams based on current practices in the forest products sector in Wisconsin (**Figure 3;** data sources provided below). Of that which enters the industrial roundwood stream, a portion is first allocated to roundwood exports. We assume that 100% of exported roundwood is sent for processing into lumber products (including building materials, veneers, and other aggregated wood products). 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 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 in an anaerobic landfill (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).

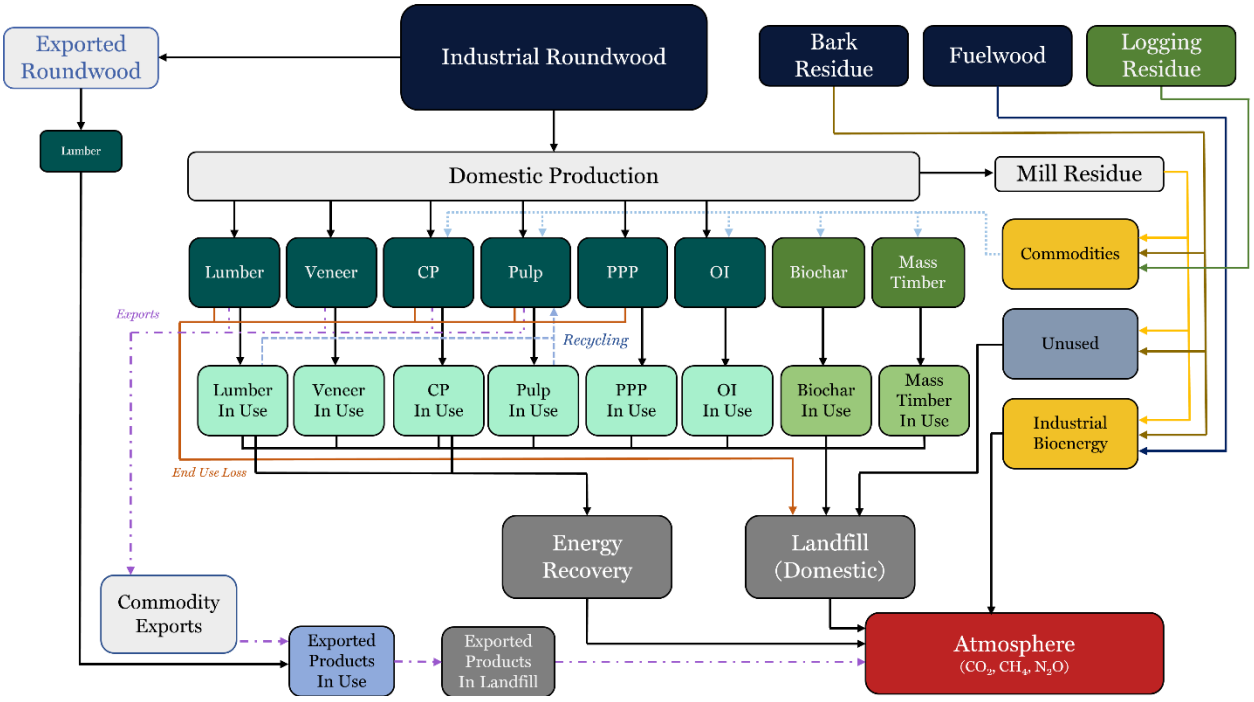


Figure 3. Pathways for carbon in harvested wood products in the CBM-HWP-WI model used for analysis of the fate of harvested carbon in Wisconsin. CP stands for composite panels; PPP stands for poles posts and pilings, and OI stands for other industrial products. Logging residue inputs, biochar, and mass timber product categories are included for alternative wood utilization scenarios and do not represent current active industries in Wisconsin.

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, and mass timber 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-WI model, we use state-specific harvest, commodity, and trade data from USDA Forest Service (USDA Forest Service 2001; 2004; 2009; 2014; 2023), 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 Wisconsin, 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 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 (Towprayoon et al. 2019). See **Table 2** 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 Wisconsin DNR Division of Forestry staff, we identified several management priorities and concerns for forests in Wisconsin. Discussions were focused on how these priorities and concerns would relate to influences on forest carbon stocks and therefore did not cover an exhaustive list of forest management issues within the state. Likewise, not all priorities discussed were possible to model using CBM-CFS3. We used this information to construct various scenarios for our model, both for a forward-looking BAU scenario and alternative management scenarios representing a departure from BAU practices. Priorities indicated for Wisconsin include:

- **Keep forests as forests** to maintain the long-term value and benefit they provide by integrating the best available science into management decision making and sustaining a vibrant forest-based economy.

- **Maintain healthy and resilient forests** to support forest-based industries and the local communities that rely on them. Balance overarching forest management goals of social, ecological, and economic benefits across all ownerships using forest management activities and applied silviculture to address emerging forestry issues and development of new forest markets.

- **Maintain or enhance climate mitigation potential** of Wisconsin's forests and forest products through advancing carbon storage opportunities, innovative wood products, addressing

climate change impacts such as invasive species and diseases, and supporting forest regeneration and conservation.

- **Prioritizing climate adaptation** through addressing forest health threats with adaptive and responsive actions and conserving the diverse structure, composition, function, and complexity of forested landscapes.

These priorities align well with the core principles of CSF: balancing adaptation, mitigation, and ecosystem services like water and wood products while focusing on long-term forest health and resilience in the face of climate change. In the case of Wisconsin's forests, CSF may in part require proactive management that anticipates and addresses future ecosystem and climate conditions, rather than prioritizing and maximizing carbon stocks. The close alignment between our state partners' priorities and CSF goals makes CSF a useful framework for evaluating performance of the scenarios modeled in this analysis.

Developing Modeling Scenarios

Starting from the priorities and concerns listed above, we developed modeling scenarios based on available data and expected relevance for landscape-scale carbon dynamics. Some of the identified concerns, though important for forest resilience or individual tree health, are not expected to have a demonstrable impact on carbon at the landscape scale of the CBM-CFS3. Other identified priorities may have reasonably been expected to influence carbon on a landscape scale but were novel or unstudied enough that available data quantifying those carbon influences were limited. Given the input data and pre-determined disturbance schedule requirements of the CBM-CFS3, these priorities could not be included in our analysis. After narrowing the above list to practices with sufficient data and expected carbon impacts to incorporate as a scenario, we parameterized each scenario as described below. In total, we developed 13 scenarios to forecast and assess potential CSF pathways.

Business-as-Usual Scenario

A core objective of this project is to estimate the differential carbon impacts of various forest management and wood utilization strategies in Wisconsin. This requires the development of a business-as-usual (BAU) scenario to provide the basis for comparison to alternative scenarios. The BAU represents a continuation of current management practices (i.e., harvests, thinnings, prescribed fire, reforestation, wood utilization), land-use changes (afforestation and deforestation), and natural disturbances (i.e., wildfires, windthrow, and insect and disease outbreaks) at historical average levels, which allows for the estimation and projection of current practices and their collective effects on net carbon balance into the future. Though this scenario construction does not account for changes in policies, climate, or economics, it is a useful exercise to explore how the continuation of current behaviors and disturbances may affect future forest dynamics and carbon cycling. This also allows for comparison to scenarios with different assumptions from BAU by estimating the difference in mitigation potential between scenarios.

The analysis covers the period from 2021-2100, based on projections of historical averages from 2007-2019 (**Tables 1** and **2**). This longer-term simulation period encompasses multiple rotations of management through Wisconsin forests, allowing for assessment of management impacts 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 2021.

Table 1. BAU ecosystem disturbance parameters. Values based on historical average rates from 2007-2019. Values represent area or carbon targets held constant throughout simulation runs from 2020-2100. All carbon values are in metric tons (tC). See **Appendix** *for assumptions and data sources.*

Land-use change			
Forest loss	-51,712 ac yr^{-1}	Forest Gain	47,778 ac yr^{-1}
Natural disturbances			
Wildfire	3,161 ac yr^{-1}	Abiotic (wind, animal)	34,560 ac yr^{-1}
Insect / disease defoliation	57,451 ac yr^{-1}		
Insect mortality	81,378 ac yr^{-1}		
Forest management practices			
Prescribed fire (~40% understory consumption)	6,934 ac yr^{-1}		
Federal forests			
Clearcut (90% merchantable biomass removal)	26,789 tC yr^{-1} (4,605,891 ft^3 yr^{-1})	Thinning (30% merchantable biomass removal)	11,281.7 tC yr^{-1} (1,943,571 ft^3 yr^{-1})
Shelterwood cut (50% merchantable biomass removal)	8,347.3 tC yr^{-1} (1,185,517 ft^3 yr^{-1})	Single-tree selection (25% merchantable biomass removal)	3,516 tC yr^{-1} (519,183 ft^3 yr^{-1})
Coppice cut (90% merchantable biomass removal)	5,869.9 tC yr^{-1} (1,065,790 ft^3 yr^{-1})		
State / county forests			
Clearcut (90% merchantable biomass removal)	78,737.5 tC yr^{-1} (13,240,959 ft^3 yr^{-1})	Overstory removal (90% merchantable biomass removal)	20,341.5 tC yr^{-1} (2,815,391 ft^3 yr^{-1})
Shelterwood cut (50% merchantable biomass removal)	128,385.4 tC yr^{-1} (18,178,698 ft^3 yr^{-1})	Thinning (30% merchantable biomass removal)	75,957.1 tC yr^{-1} (12,294,543 ft^3 yr^{-1})
Coppice cut (90% merchantable biomass removal)	118,086.7 tC yr^{-1} (21,440,791 ft^3 yr^{-1})	Single-tree selection (25% merchantable biomass removal)	31,068.8 tC yr^{-1} (4,587,671 ft^3 yr^{-1})
Private forests			
Clearcut (90% merchantable biomass removal)	166,313.2 tC yr^{-1} (28,549,750 ft^3 yr^{-1})	Overstory removal (90% merchantable biomass removal)	142,578.9 tC yr^{-1} (19,848,615 ft^3 yr^{-1})
Shelterwood cut (50% merchantable biomass removal)	352,862.6 tC yr^{-1} (50,130,850 ft^3 yr^{-1})	Thinning (30% merchantable biomass removal)	238,229 tC yr^{-1} (36,434,396 ft^3 yr^{-1})
Coppice cut (90% merchantable biomass removal)	121,314.1 tC yr^{-1} (2,026,775 ft^3 yr^{-1})	Single-tree selection (25% merchantable biomass removal)	122,554.7 tC yr^{-1} (1,809,664 ft^3 yr^{-1})

Table 2. Wisconsin BAU HWP parameters. Values are based on most recent available data from 1997-2020. Percentages may not sum to 100% due to rounding. See **Appendix** *for assumptions and data sources.*

Removals distribution (proportion of carbon inputs distributed to various modeling streams)			
Softwood removals		**Hardwood removals**	
Industrial Roundwood	83.10%	Industrial Roundwood	68.22%
Fuelwood	2.59%	Fuelwood	16.63%
Bark Residue	14.13%	Bark Residue	15.15%
Roundwood exports			
Softwood exports	0%	Hardwood exports	0.64%
Commodity distribution (proportion of carbon distributed to various commodities)			
Softwood commodities			
Lumber	28.41%	Composite Panels from mill residue	1.84%
Veneer	0.24%	Unused mill residue	0.26%
Composite Panels	1.10%	Industrial Bioenergy from bark residue	12.69%

Table 2, cont. *Wisconsin BAU HWP parameters. Values are based on most recent available data from 1997-2020. Percentages may not sum to 100% due to rounding. See* **Appendix** *for assumptions and data sources.*

Commodity distribution (proportion of carbon distributed to various commodities)			
Softwood commodities			
Pulp	40.35%	Other Industrial from bark residue	1.91%
Post, Poles, Pilings	0.31%	Pulp from bark residue	0.04%
Other Industrial	0.30%	Composite Panels bark residue	0.02%
Industrial Bioenergy from mill residue	4.31%	Unused bark residue	0.02%
Other Industrial from mill residue	3.92%	Lumber from exported roundwood	0.00%
Pulp from mill residue	4.28%		
Hardwood commodities			
Lumber	25.44%	Composite panels from mill residue	1.62%
Veneer	0.21%	Unused mill residue	0.44%
Composite panels	0.99%	Industrial bioenergy from bark residue	13.85%
Pulp	36.14%	Other industrial from bark residue	3.41%
Post, poles, pilings	0.28%	Pulp from bark residue	0.18%
Other industrial	0.27%	Composite panels bark mill residue	0.07%
Industrial bioenergy from mill residue	8.13%	Unused bark residue	0.54%
Other industrial from mill residue	3.92%	Lumber from exported roundwood	0.49%
Pulp from mill residue	3.78%		
Product half-lives			
Domestic use			
Softwood lumber	47.21 years	Post, poles, pilings	30 years
Hardwood lumber	22.87 years	Other industrial uses	2 years
Softwood veneer	51.94	Bioenergy	0 years
Hardwood veneer	38.52	Biochar	100 years
Composite panels	27 years	Softwood mass timber	73.3 years
Pulp	3 years	Hardwood mass timber	85.5 years
International use			
Wood	30 years	Fuel	0 years
Paper	2 years		
Product retirement (100% to landfill unless specified)			
Sawlogs	67.16% landfill 15.7% energy recovery 8.57% recycled to sawlogs 8.57% recycled to pulp	Pulp	25.56% landfill 6.23% energy recovery 68.21% recycled
Landfills			
Decomposable materials	Paper: 50% Wood: 10%	Methan generation rate *k*	Paper: 0.06 $m^3\,yr^{-1}$ Wood: 0.03 $m^3\,yr^{-1}$
Landfilled product half-lives	Domestic Paper and Wood: 30.52 years Exported Paper: 13.5 years Exported Wood: 26.5 Years	Methane release	72.7% flared/burned for energy 27.2% unrecovered

Alternative Management, Disturbance, and HWP Scenarios

For this analysis, we constructed alternative scenarios by changing BAU parameters beginning in 2021, representing potential changes in future decision making, disturbances, or market dynamics. Scenarios relate to one specific practice or objective, where only one BAU practice is changed while all other parameters remain the same. This allows for the examination of the specific influences of each altered management practice on forest carbon dynamics and evaluate its relative power as CSF and NCS actions. Our 12 alternative scenarios cover a broad range of forest management and wood utilization practices, grouped into *5* categories representing similar management objectives and priorities: 1) altered rotation lengths and management; 2) forest health and regeneration; 3) tree planting; 4) climate adaptive management; and 5) wood utilization and markets (**Table 3**; see the **Appendix** for additional scenario details).

We developed three scenarios to assess the impacts of **Altered Rotation Lengths and Management** practices on carbon dynamics. The *Extended Rotations* scenario increases the minimum harvest age for certain management practices and forest types, increasing (or extending) the average harvest rotation length. Extending rotation lengths is a popular tool aimed at increasing long-term carbon storage in aboveground biomass (Kaarakka et al. 2021). For this scenario, we extended the rotation lengths for key forest types including red pine, white pine, and oak by 30-95 years depending on the silvicultural regime and forest type (**Table S5**). Additionally, we increased the re-entry interval for single-tree-selection harvests for maple/beech/birch forests. The *Increased Harvest Retention Size* scenario modeled an increase in the retention size (i.e. the amount of forest left standing) following clearcuts, overstory removals, coppice cuts, shelterwood cuts, and single-tree-selection harvest regimes. Doing so represents a decrease in harvest intensity leaving more live trees on site, with the potential to increase future carbon storage potential (Peckham et al. 2013) and promote species, structural, and functional diversity (Nyamai et al. 2020). Finally, the *Increased Harvest Levels* scenario explored a 10% increase in all harvest levels statewide to provide further insights into tradeoffs between harvest levels, timber supply, and potential HWP carbon storage.

We constructed two scenarios to assess the carbon impacts of various **Forest Health and Regeneration** practices. The *Increased Regeneration* scenario increased the rate of supplemental planting to restock understocked forest stands and increased the rate of regenerative cuts. Underplanting and other supplemental planting techniques have shown significant potential to boost regeneration and the carbon storage potential of forests (Paquette et al. 2006a; Paquette et al. 2009b; Paquette et al 2009). Supplemental planting was modeled on red/white/jack pine, oak/pine, and oak/hickory forest types. Regeneration cuts such as overstory removal treatments, shelterwoods, and other regenerative cutting methods have long been common techniques to improve stand quality and regeneration of stands, especially for certain deciduous species (Granger et al. 2018; Johnson et al. 2019). Increased regenerative cuts were modeled on elm/ash/cottonwood and maple/beech/birch forest types. The *Coarse Woody Debris (CWD) Enhancement* scenario increased the amount of coarse woody debris of merchantable size left on site following harvest by 10% by cutting and leaving additional materials beyond merchantable harvest levels. CWD represents a small but important proportion of the overall ecosystem carbon flux (Gough et al. 2007). Increasing the amount of CWD on site following harvest has the potential to store additional carbon for years to decades especially as deadwood (Spetich et al. 1999; Idol et al. 2001). Additionally, varying deadwood volume has shown potential to increase regeneration (Bolton and D'Amato 2011) and provide essential wildlife habitat (Goodburn and Lorimer 1998). The *Afforestation* scenario modeled an increased rate of tree planting on farmland that previously supported natural tree cover, converting idle or abandoned agriculture land uses to forests. This

scenario included 3,474 acres of tree planting per year, which corresponds roughly with 1% of available idle or abandoned farmlands as determined by agency partners.

Designed to assess potential carbon implications of **Climate Adaptive Management**, the *Forest-type Conversion* scenario transitioned +9,783 acres of aspen stands to maple/beech/birch and white pine forest types by not coppicing stands and encouraging other species to regenerate along the southern extent of the aspen range. The scenario assumed that a specific proportion of eligible aspen stands (>80 years old) would transition into longer-lived softwood and hardwood species depending upon physiographic conditions (Bergen & Dronova 2007; Harniss, 1981; Nave et al., 2017; Smith et al., 2011) through natural processes where longer-lived softwood and hardwood species encroach, establish, and eventually out compete aspen trees causing a transition in stand structural and compositional characteristics. While each individual scenario above represents a potential CSF management tactic, 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 visualize the cumulative potential of Wisconsin's forests to provide climate mitigation benefits. These scenarios included the *Extended Rotations*, *Increased Regeneration*, *Afforestation*, and *Forest-Type Conversion* scenarios. Scenarios were chosen with consultation from project partners to determine plausible pathways that could reasonably be implemented given real-world contexts and constraints.

We developed four scenarios aimed at assessing the impact of **Wood Utilization and Markets** on carbon sequestration and storage, particularly in the HWP sector. The *Composite Panels from Pulpwood* scenario used BAU forest management assumptions paired with alternate HWP assumptions where a proportion (1% each year from 2028-2037, for a total of 10%) of roundwood that would normally be allocated toward pulp was instead allocated toward the production of composite panels (**Table 3**). In addition to altering product production, this scenario also has downstream effects on product retirement and landfill emissions, and leads to substitution benefits from using wood- derived composite panels in place of other emissions-intensive alterative commodities.

For the other three HWP-focused scenarios, forest management parameters were adjusted along with HWP model parameters. In the *Increased Harvest Residue Utilization* scenario, additional wood, which would otherwise be left in the forest as CWD, was removed during the harvest process and transferred to the HWP sector. On average, this volume constituted 23.3% of the BAU harvest removal volume (+ 657,032 tC yr^{-1}) with 100% of this additional harvest residue allocated to biochar production. In the *Increased Softwood Utilization* scenario, softwood removal volumes were increased by an average of 5.6% over BAU harvest levels (+22,631 tC yr^{-1}) with 100% of this additional softwood harvest allocated to mass timber production. Finally, in the *Increased Hardwood Utilization* scenario, hardwood removal volumes were increased by an average of 3.0% over BAU harvest levels (+75,413 tC yr^{-1}) with 100% of this additional hardwood harvest allocated to lumber production. For the *Increased Harvest Residue Utilization* scenario and the *Increased Softwood Utilization* scenario, novel product half-lives and substitution benefits were calculated and applied to biochar and softwood mass timber, respectively.

Table 3. Ecosystem and wood utilization scenario parameters for Wisconsin. Unless otherwise noted, scenario changes from BAU are immediate and last for the entire simulation period (2021-2100). Scenarios that are components of the Portfolio are marked with the † symbol. See **Appendix** *for assumptions and data sources.*

Altered rotation lengths and management

Scenario Name	Objective	Parameter to Change	Change from BAU	Scenario impact. 2021-2100
Extended Rotations†	Increase average harvest age of stands	Minimum harvest age	+30-95 years on clearcuts, shelterwoods, coppice cuts, and overstory removal cuttings for red pine, white pine, and oak-hickory forest types	Average age of harvest: 104 years → 132 years
			+20 years on single-tree-selection reentry intervals for northern hardwoods	Average age of harvest: 109 years → 116 years
Increased Harvest Retention Size	Increase reserve size following clearcuts, shelterwoods, seed tree cuts, overstory removals, and single-tree-selection.	Harvest intensity rate	5X increase in retention levels of clearcuts, overstory removals, and coppice cuts	Increase clearcut, coppice cut, and overstory removal retention size: 3% → 15%
			+10% increase in retention levels on shelterwood cuts	Increase shelterwood retention size: 50% → 55%
			+21% increase in retention levels on single-tree-selection systems	Increase STS retention size: 70% → 85%
Increased Harvest Levels	Increase annual harvest targets	Annual rate of harvest	+10% tC yr^{-1} harvested	+206,667 tC yr^{-1} transferred to HWP

Forest health and regeneration

Scenario Name	Objective	Parameter to Change	Change from BAU	Scenario impact, 2021-2100
Increased Regeneration†	Increase supplemental planting to restock understocked stands	Annual rate of supplemental planting	+988 ac yr^{-1} of red/white/jack pine stands	+ 217,452 ac supplemental planting
			+494 ac yr^{-1} of oak/pine stands	+ 296,526 ac regenerative cuts
	Increase rate of regenerative cuts	Annual rate of regenerative cuts	+1,236 ac yr^{-1} of oak/hickory stands	
			+741 ac yr^{-1} of elm/ash/cottonwood stands	
			+2,965 ac yr^{-1} of maple/beech/birch stands	
Coarse Woody Debris (CWD) Enhancement	Increase amount of coarse woody debris left on-site following harvest	Amount of merchantable volume left on-site following harvest	+10% of merchantable volume left on site following all harvest regimes	-11,131 tC yr^{-1} transferred to HWP

Table 3, cont. *Ecosystem and wood utilization scenario parameters for Wisconsin. Unless otherwise noted, scenario changes from BAU are immediate and last for the entire simulation period (2021-2100). Scenarios that are components of the Portfolio are marked with the † symbol. See* **Appendix** *for assumptions and data sources.*

Tree plantings

Scenario Name	Objective	Parameter to Change	Change from BAU	Scenario impact, 2021-2100
Afforestation†	Increase rate of tree plantings per year on idle farmland	Annual rate of afforestation	+3774 ac yr^{-1} (1% of available farmland)	+277,944 ac afforested

Climate adaptive management

Scenario Name	Objective	Parameter to Change	Change from BAU	Scenario impact, 2021-2100
Forest-Type Conversion†	Increase rate of aspen succession to other HW/SW forest types	Annual rate of aspen forest type transitioning through site selection and natural processes	+9,783 ac yr^{-1} of aspen forests transitioning to northern hardwoods (6,958 ac yr^{-1}) and white pine (2825 ac yr^{-1}) forests	+547,842 ac transitioned to northern hardwoods +222,434 ac transitioned to white pine

Wood utilization and markets

Scenario Name	Objective	Parameter to Change	Change from BAU	Scenario impact, 2021-2100
Increased Harvest Residue Utilization	Increase rate of harvest residues sent to HWP	Annual target rate of harvest residues sent to HWP	+23.3% increase of total C sent to HWP	+ 657,032 tC yr^{-1} of harvest residues utilized for biochar
	Increase annual biochar wood utilization	Annual rate of C transferred to biochar	100% of additional harvest utilized for biochar	
Increased Softwood Utilization	Increase annual harvest targets of SW stands	Annual harvest rate of softwood forest types	+8.5% tC yr^{-1} of softwood harvest targets	+5.6% increase in softwood harvest yr^{-1}
	Increase annual mass timber wood utilization	Annual rate of C transferred to mass timber	100% of additional harvest utilized for mass timber	+22,631 tC yr^{-1} utilized for mass timber
Increased Hardwood Utilization	Increase annual harvest targets of hardwood stands	Annual harvest rate of hardwood forest types	+5% tC yr^{-1} of hardwood harvest targets	+3.0% increase in hardwood harvest yr^{-1}
	Increase annual LLP wood utilization	Annual rate of C transferred to lumber	100% of additional harvest utilized for lumber	+75,413 tC yr^{-1} utilized for lumber
Composite Panels from Pulpwood	Incrementally decrease the percentage of softwood going into pulp products each year for 10 years.	Reduce the rate of C transferred to pulp products	Softwood pulp production from 57.07% of total in 2027 to 47.07% of total in 2037	-17,265 tC yr^{-1} utilized for pulp products
	Put additional wood into an increase in composite panel production.	Increased the rate of C transferred to composite panels	Softwood composite panel production from 1.56% of total in 2027 to 11.56% of total in 2037	+18,202 tC yr^{-1} utilized for composite panels

Table 3, cont. *Ecosystem and wood utilization scenario parameters for Wisconsin. Unless otherwise noted, scenario changes from BAU are immediate and last for the entire simulation period (2021-2100). Scenarios that are components of the Portfolio are marked with the † symbol. See* **Appendix** *for assumptions and data sources.*

Portfolio

Scenario Name	Objective	Parameter to Change	Change from BAU	Scenario impact, 2021-2100
Portfolio	Ensemble of concurrent scenarios (marked with † above) to illustrate potential for Wisconsin to fully leverage its forests as natural climate solutions	*This portfolio combines the Extended Rotations, Increased Regeneration, Afforestation, and Forest-Type Conversion scenarios with BAU management and natural disturbance not affected by other component scenarios*	+30-95 years on clearcuts, shelterwoods, coppice cuts, and overstory removal cuttings for red pine, white pine, and oak-hickory forest types	Average age of harvest: 104 years → 132 years
			+20 years on single-tree-selection reentry intervals for northern hardwoods	Average age of harvest: 109 years → 116 years
			+988 ac yr^{-1} of red/white/jack pine stands	+ 217,452 ac supplemental planting
			+494 ac yr^{-1} of oak/pine stands	+ 296,526 ac regenerative cuts
			+1,236 ac yr^{-1} of oak/hickory stands	
			+741 ac yr^{-1} of elm/ash/cottonwood stands	
			+2,965 ac yr^{-1} of maple/beech/birch stands	
			+3774 ac yr^{-1} (1% of available farmland)	+277,944 ac afforested
			+9,783 ac yr^{-1} of aspen forests transitioning to northern hardwoods (6,958 ac yr^{-1}) and white pine (2825 ac yr^{-1}) forests	+547,842 ac transitioned to northern hardwoods +222,434 ac transitioned to white pine

Results and Discussion

Results of our analysis show that both the forest ecosystem and the forest products sector already contribute strong climate mitigation benefits in Wisconsin and will continue to do so until the end of the century. Several alternative management and wood utilization strategies could further enhance the future climate mitigation potential of Wisconsin's forests without perturbing timber supplies. Our results indicate that there are important trade-offs between climate goals and other traditional management objectives to consider that can significantly impact future forest health, resilience, and climate mitigation potential.

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

In the BAU scenario, Wisconsin's forests remain a net carbon sink from 2021-2100 (**Figure 4a**) with a gradual increase in the strength of the carbon sink throughout the end of the century, represented by a net ecosystem carbon flux below zero. *Net ecosystem carbon flux (NECF)* refers to the net annual sequestration of carbon in forest ecosystems after accounting for decomposition, natural disturbance emissions, and wood product transfers. NECF is presented from the atmospheric perspective, where negative numbers represent a net carbon sink (less carbon in the

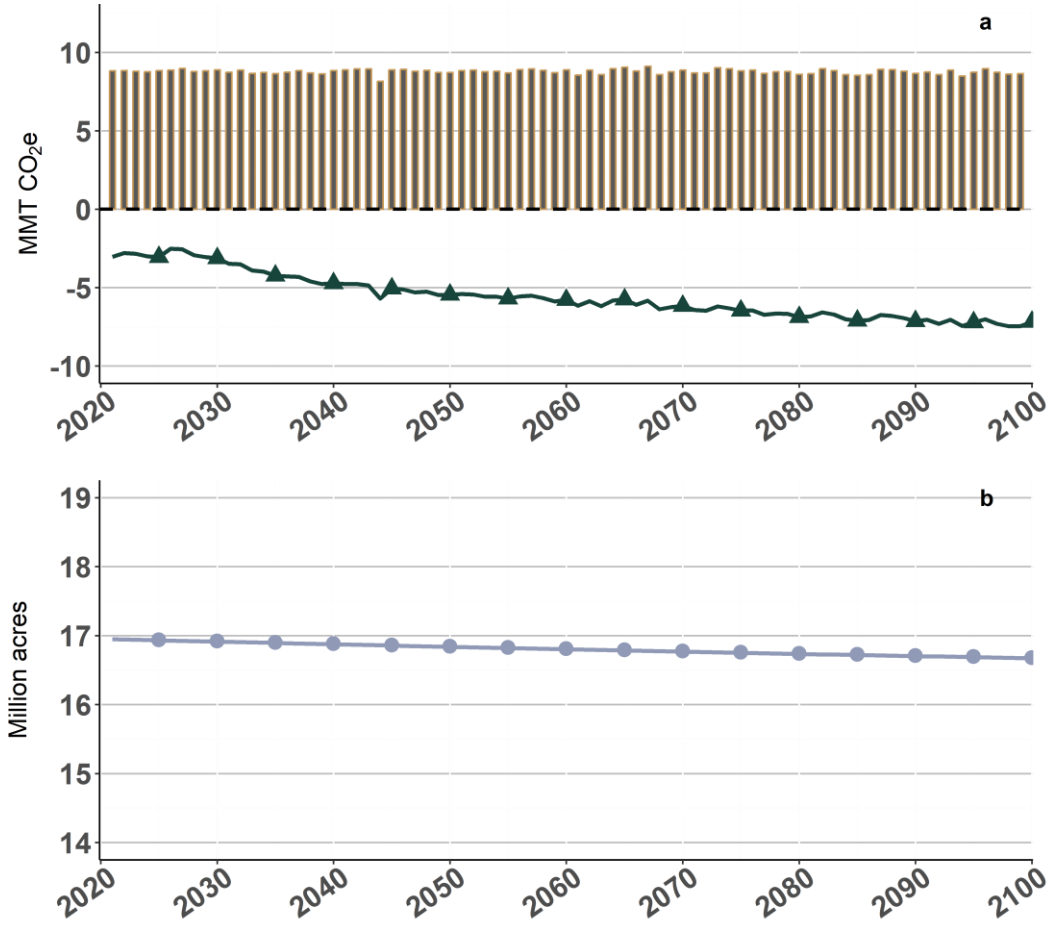


Figure 4. a) BAU scenario forest ecosystem results showing net ecosystem carbon flux (green line) and harvest removals (dark brown bars). Net ecosystem carbon flux represents all growth minus respiration, decomposition, and disturbance emissions (including carbon transfers to HWP). b) represents forest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

atmosphere and a carbon gain to the ecosystem) and positive numbers represent a net carbon source (more carbon in the atmosphere and a carbon loss or emission from the ecosystem).

Across the 80-year BAU simulation, net ecosystem carbon flux was on average -5.56 MMT CO_2e yr^{-1} with an additional 8.79 MMT CO_2e yr^{-1} being transferred to HWP (**Figure 4a**). Forest area decreased by 3,425 ac yr^{-1} on average (**Figure 4b**), following a continuation of recent (2000-2020) land-use change trends. Further, ecosystem carbon stocks per acre increased through the duration of the simulation (**Figure 5**), indicating the total amount of carbon in forests can still increase (i.e., as growth outpaces mortality, removals, and LUC) despite decreases in total forest area (**Figure 4b**).

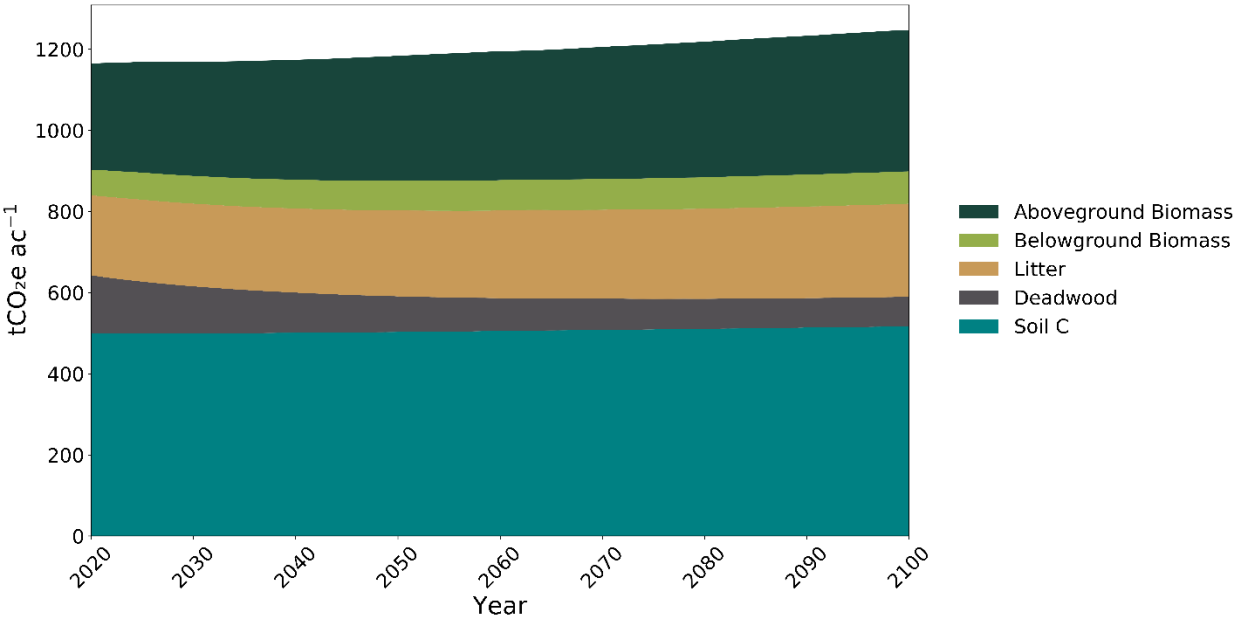


Figure 5. BAU scenario results for per acre carbon stocks (tCO_2e ac^{-1}) in IPCC reporting pools from 2007-2100. Positive numbers represent accruing carbon stocks. Litter layer includes carbon in the L horizon, fine and small woody debris including dead coarse roots in the forest floor, and carbon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

Our results suggest that Wisconsin's forests will increase in carbon density as forests continue maturing and shifting into older age-classes. Aboveground biomass saw the greatest increase in carbon density under the BAU scenario, however, despite this increase in aboveground biomass, the deadwood pool density decreases, suggesting an important interaction between carbon storage across a shift in forest age-demographics.

The amount of carbon transferred to HWP remained stable for the BAU scenario, despite small annual fluctuations in the forest area eligible for harvest, due to restrictions placed on the age range for harvest eligibility across multiple harvest types (**Table S3, Figure 4a**). Assuming static future HWP demand, Wisconsin'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 similar proportions (+75.5% for hardwood and +57.7% for softwood, **Figure 6**), though hardwood stocks are on average 3.8 times larger than softwood stocks. By 2100, HWP carbon storage is dominated by the landfill categories, comprising 70.6% and 61.8% of hardwood and

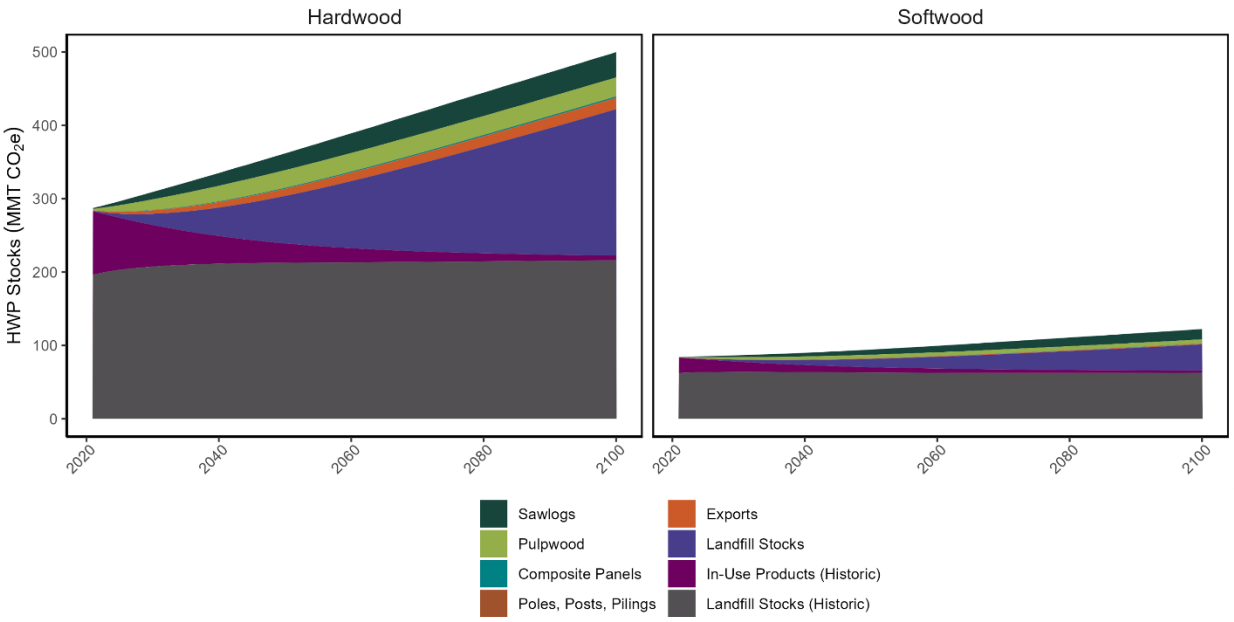


Figure 6. HWP carbon stocks (MMT CO_2e) by primary product for hardwood and softwood from 2021-2100. Positive numbers denote accruing carbon stocks. Historic in-use stocks and landfill stocks represent materials cut prior to the beginning of the simulation. Historic in-use stocks transfer to historic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

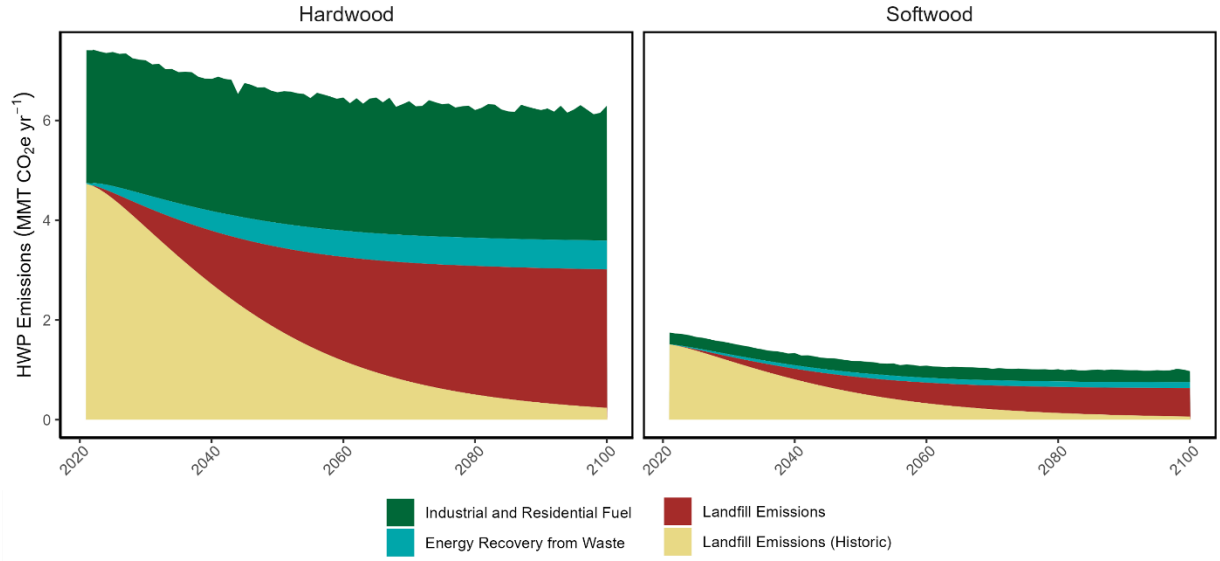


Figure 7. Annual HWP emissions distribution (MMT CO2e yr-1) for hardwood and softwood from 2021-2100 for the BAU scenario. Emissions are the result of woody material that is cut and removed from the forest and do not include any residues or other materials left on site. Historic landfill emissions come 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.

softwood stocks, respectively (**Figure 6**). Of the in-use categories, the largest components are lumber (53.5% of total in-use hardwood, and 58.5% of total in-use softwood stocks in 2100), and pulpwood (30.4% of total in-use hardwood, and 22.7% of total in-use softwood stocks in 2100). HWP carbon emissions for both hardwood and softwood species decline over the simulation, dropping to 84.9% of 2020 levels for hardwoods in 2100, and 55.8% of 2020 levels for softwood in 2100. This shift occurs due to a change in the composition of products in the landfill, away from materials with a higher degradable fraction like paper products, and toward products with a

smaller degradable fraction like lumber (**Table 2**). Products produced and in landfills prior to 2020 shift from being the dominant source of emissions (63.8% and 86.4% of hardwood and softwood HWP emissions, respectively, in 2021) to being the smallest source of emissions (3.8% and 6.4% of hardwood and softwood HWP emissions, respectively, in 2100), replaced by contemporary landfill emissions (44.1% and 58.7% of hardwood and softwood HWP emissions, respectively, in 2100, **Figure 7**). Emissions from industrial and residential fuelwood (which are assumed to occur in the same year in which the harvest occurs) are also a large emission category (representing 40.3% and 20.5% of average annual hardwood and softwood emissions, respectively) and mirror overall trends of harvest inputs. Because transfers of carbon from the forest to the forest products sector outweigh HWP emissions (both from current wood products in use and inherited products and landfills), net HWP carbon balance accrues additional carbon (-0.52 MMT CO_2e yr^{-1} on average) meaning that HWPs represent a growing carbon storage pool for Wisconsin.

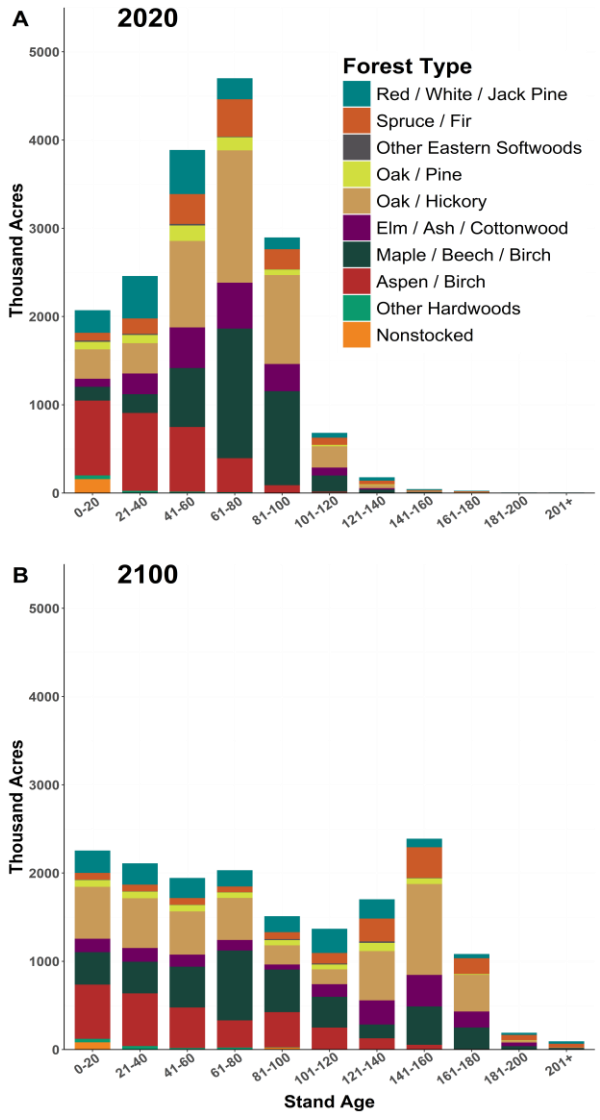


Figure 8. BAU scenario age-class distribution by forest type in A) 2020 and B) 2100

Forest age and other age-dependent successional dynamics play an important role in determining current and future net carbon balances. In 2020, approximately 77.3% of forest area was <80 years old (**Figure 8a**) which suggests that Wisconsin's forests should continue to provide strong mitigation potential in the nearer term as younger forests generally exhibit faster carbon accumulation. By year 2100, only approximately 51.7% of forestland is still <80 years old under BAU, with an additional 32.7% being >120 years old, signifying a notable shift in forest age demographics.

As forests age, productivity per area tends to decline (Coomes et al., 2012), meaning that if forests continue to age unabated, productivity declines could lead to a weaker carbon sink — noting that productivity is still predicted to outpace emissions from decomposition and removals in our BAU scenario. It is also important to note that the present observed age-class distribution at the state level is largely determined by legacies of previous management actions such as land clearing for agriculture and the abandonment of such lands. The age-class distribution by 2100 in the BAU scenario (**Figure 8b**) is beginning to shift into a more uniform distribution where our simulation shows more forest aging into mature classes (i.e., escaping both natural or anthropogenic disturbances) and a balancing of younger age classes.

Alternative Management and Wood Utilization Results

When accounting for just the forest ecosystem, all scenarios modeled in this analysis remain a net carbon sink from 2021-2100, indicated by a net ecosystem carbon flux (NECF) less than zero (**Figure 9**). Five scenarios sequester additional carbon (had a lower NECF) as compared to BAU: the *Portfolio*, *Extended Rotations*, *Increased Harvest Retention Size*, *Afforestation*, and *Forest-Type Conversion* scenarios. The remaining six scenarios - *Increased Regeneration*, *Increased Harvest Levels*, *CWD Enhancement*, *Increased Harvest Residue Utilization*, *Increased Softwood Utilization*, and *Increased Hardwood Utilization* - sequestered less carbon (had a higher NECF) relative to BAU. It is important to note that the reduction in carbon sequestration for scenarios with increased levels of harvesting including *Increased Regeneration* is primarily driven by the additional harvest removals and temporary reductions in forest productivity as forests begin to regenerate. Towards the end of the century. The *Increased Regeneration* scenario begins to sequester additional carbon each year; however, not at a rate to surpass BAU in total carbon sequestered. Other important trends to highlight include the *Forest-Type Conversion* scenario, initially performing worse, but eventually switching to increased mitigation potential as compared to BAU as forests continue to mature, sequestering additional carbon.

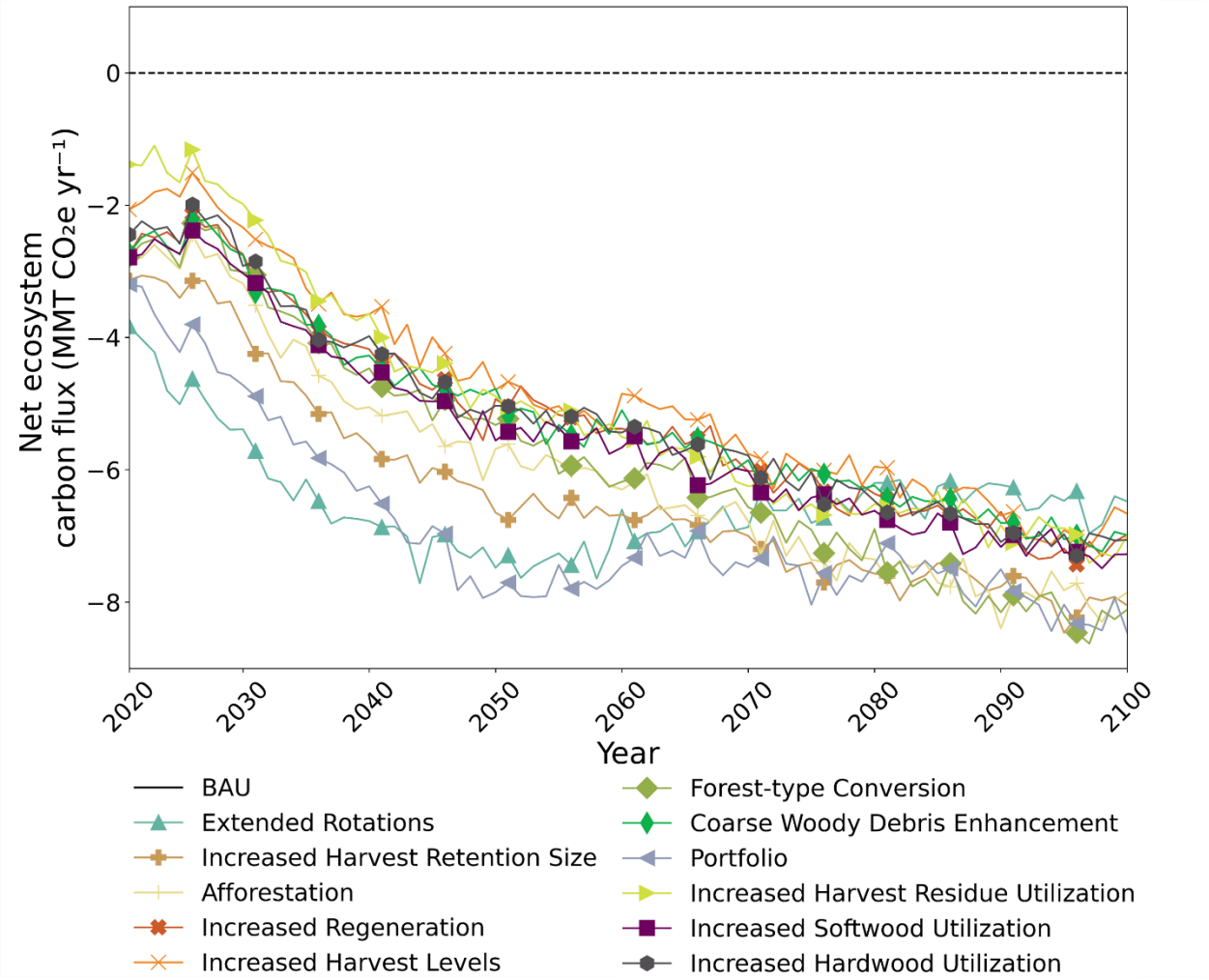


Figure 9. Annual net ecosystem carbon flux for selected scenarios, 2020-2100. Net ecosystem carbon flux includes total growth minus emissions from respiration and decomposition and all disturbance related emissions including C transferred to HWP. Negative values denote carbon sequestration (a net carbon sink). Positive values denote carbon emissions (a net carbon source).

Annual Mitigation Potential in Forests and the 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 (**Figure 10**). *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 a net carbon sink (less carbon in the atmosphere and more carbon stored in forests and wood products) and positive numbers represent a net carbon source (more carbon in the atmosphere and a carbon loss or emission from forests and wood products).

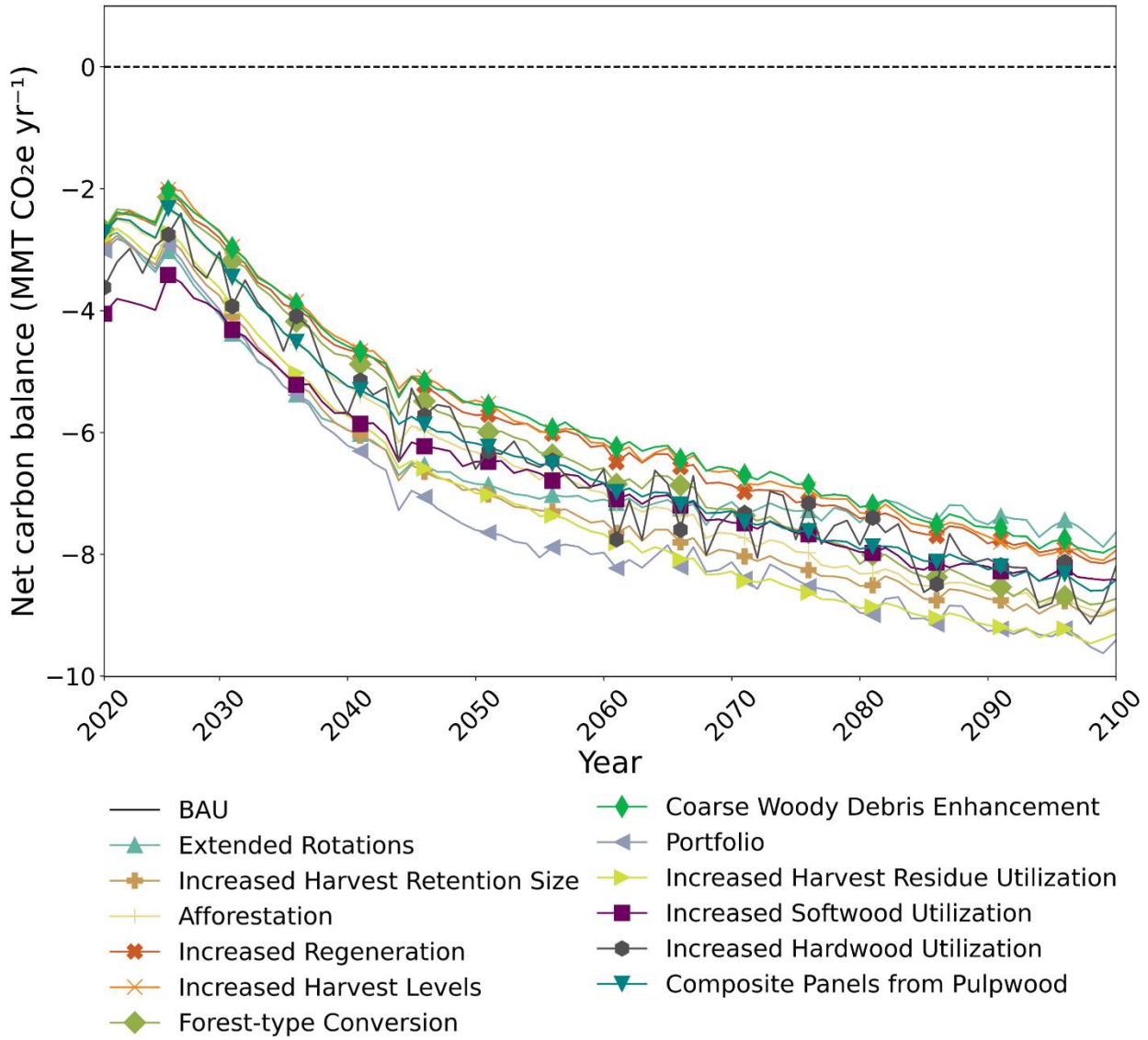


Figure 10. Annual net carbon balance for selected scenarios (2021-2100). Net carbon balance includes net ecosystem carbon flux in the forest, transfers to HWP, emissions from wood products in use and in landfills, substitution benefits in years where harvest is different than BAU, and leakage in years where harvest is less than BAU. Negative values denote carbon sequestration (a net carbon sink). Positive values denote carbon emissions (a net carbon source).

The *Portfolio* scenario, which includes *Extended Rotations*, *Increased Regeneration*, *Afforestation*, and adaptive *Forest-Type Conversion*, presents the best opportunity for increasing forest carbon sink strength, with an annual net carbon balance 29.4% stronger than BAU in 2030 and 28.5% stronger in 2050, falling to 15.8% stronger in 2100 (**Figure 10**). These values help boost the annual net carbon balance to +151.9% of its current (2021) level in 2050 and +211.9% of its current (2021) level in 2100. The I*ncreased Harvest Residue Utilization* scenario also provides opportunities for additional climate mitigation potential, matching or surpassing the *Portfolio* scenario in annual net carbon balance in some years towards the end of the century (**Figure 10**). This suggests that increasing the rate of harvest residue removal from the forest for use in biochar provides significant long-term mitigation potential, but that this mitigation potential, which arises from reducing decomposition emissions from coarse woody debris and instead diverting that carbon into durable wood products, can take years to decades to fully manifest. Other scenarios with an improved net carbon balance relative to BAU include all additional wood utilization and markets scenarios (*Increased Softwood Utilization*, *Increased Hardwood Utilization,* and *Composite Panels from Pulpwood*), as well as the *Afforestation* and *Increased Harvest Retention Size* scenarios.

Cumulative Mitigation Potential in Forests and the Forest Products Sector

To better illustrate the differential impact of each scenario when compared to BAU, further results will be discussed in *standardized* terms. This standardized mitigation potential is calculated by subtracting the annual net carbon balance of the BAU from the annual net carbon balance of each scenario. This allows for a more direct assessment of the relative mitigation potential of each alternative management practice. Furthermore, the cumulative standardized carbon balance (**Figure 11**) is calculated by summing all standardized net carbon balance values through time.

By 2100, the C*oarse Woody Debris (CWD) Enhancement* scenario sequesters and stores +30.00 MMT CO_2e (6.2%) less than BAU, while the *Portfolio* scenario sequesters and stores –97.80 MMT CO_2e (19.9%) more than BAU over the same timeframe (**Figure 11**). This range illustrates the potential spread of carbon outcomes for Wisconsin's forests and forest products sector, depending on future management decisions. The *Portfolio* scenario demonstrates future climate mitigation potential from implementing multiple concurrent climate-smart forest management practices in Wisconsin. The majority of the remaining scenarios modeled fall within +/-40 MMT CO_2e carbon sequestered and stored relative to BAU by 2100, indicating more modest impacts of these scenarios when implemented alone.

We can further examine the components of cumulative carbon sequestration and storage for each scenario to understand the relative impacts of each scenario on the forest ecosystem itself and on the forest products sector (**Figure 12**). For example, the *Extended Rotations* scenario accumulates the largest amount of additional carbon in the forest ecosystem relative to BAU each year but also has the largest amount of forgone HWP transfers, leakage, and negative substitution effects. The net effect of these factors leads the *Extended Rotations* scenario to sequester and store more carbon than BAU, but the net carbon balance of this scenario decreases (becomes less negative) from 2083 onwards once the majority of harvest deferrals have ended. This difference amounts to -25.85 MMT CO_2e, -37.63 MMT CO_2e, and –27.56 MMT CO_2e more carbon sequestered and stored than BAU in 2050, 2075, and 2100, respectively (**Figure 12**).

Other scenarios affecting harvest levels exhibit similar tradeoffs between ecosystem and HWP carbon, though to a smaller degree. The *Increased Harvest Retention Size* scenario, which enlarges the reserve size associated with clearcuts, seed tree cuts, and single-tree-selection, also results in more carbon stored in the forest ecosystem and less carbon transferred to HWP relative to BAU,

accompanied by a small amount of leakage and negative substitution benefits. However, because of the reduced transfer of carbon to the HWP sector, HWP emissions are slightly lower than BAU. Collectively, these effects lead to -23.68 MMT CO_2e more carbon sequestered and stored under this scenario relative to BAU by 2050, -47.62 MMT CO_2e more by 2075, and –68.73 MMT CO_2e more by 2100 (**Figure 12**). In contrast, the *Increased Harvest* scenario, which increased the annual harvest volume target by ~10%, does not improve net carbon balance relative to BAU, with increased harvests leading to less ecosystem carbon storage and higher HWP emissions. Even though this scenario stores more carbon in the in-use and in-landfill HWP pools than BAU, and benefits from positive substitution benefits from increased production of certain HWP, it still sequesters and stores +11.12 MMT CO_2e less carbon relative to BAU by 2050, +20.23 MMT CO_2e less by 2075, and +26.11 MMT CO_2e less by 2100 (**Figure 12**).

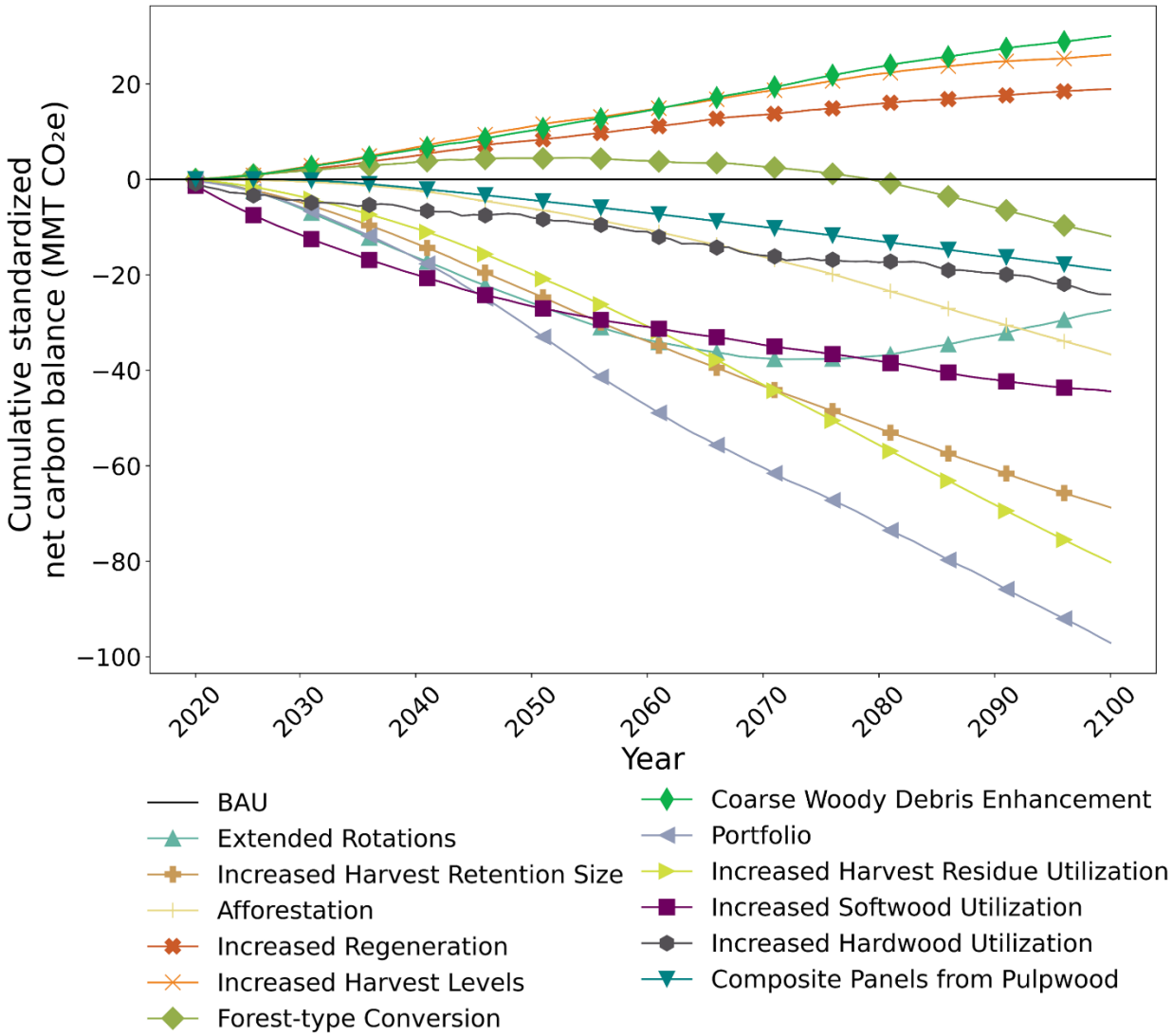


Figure 11. Cumulative net carbon balance for selected scenarios (2021-2100) standardized to BAU. Net carbon balance includes net ecosystem carbon flux in the forest, transfers to HWP, emissions from wood products in use and in landfills, substitution benefits in years where harvest is different than BAU, and leakage in years where harvest is less than BAU. Negative values denote carbon sequestration (a net carbon sink). Positive values denote carbon emissions (a net carbon source).

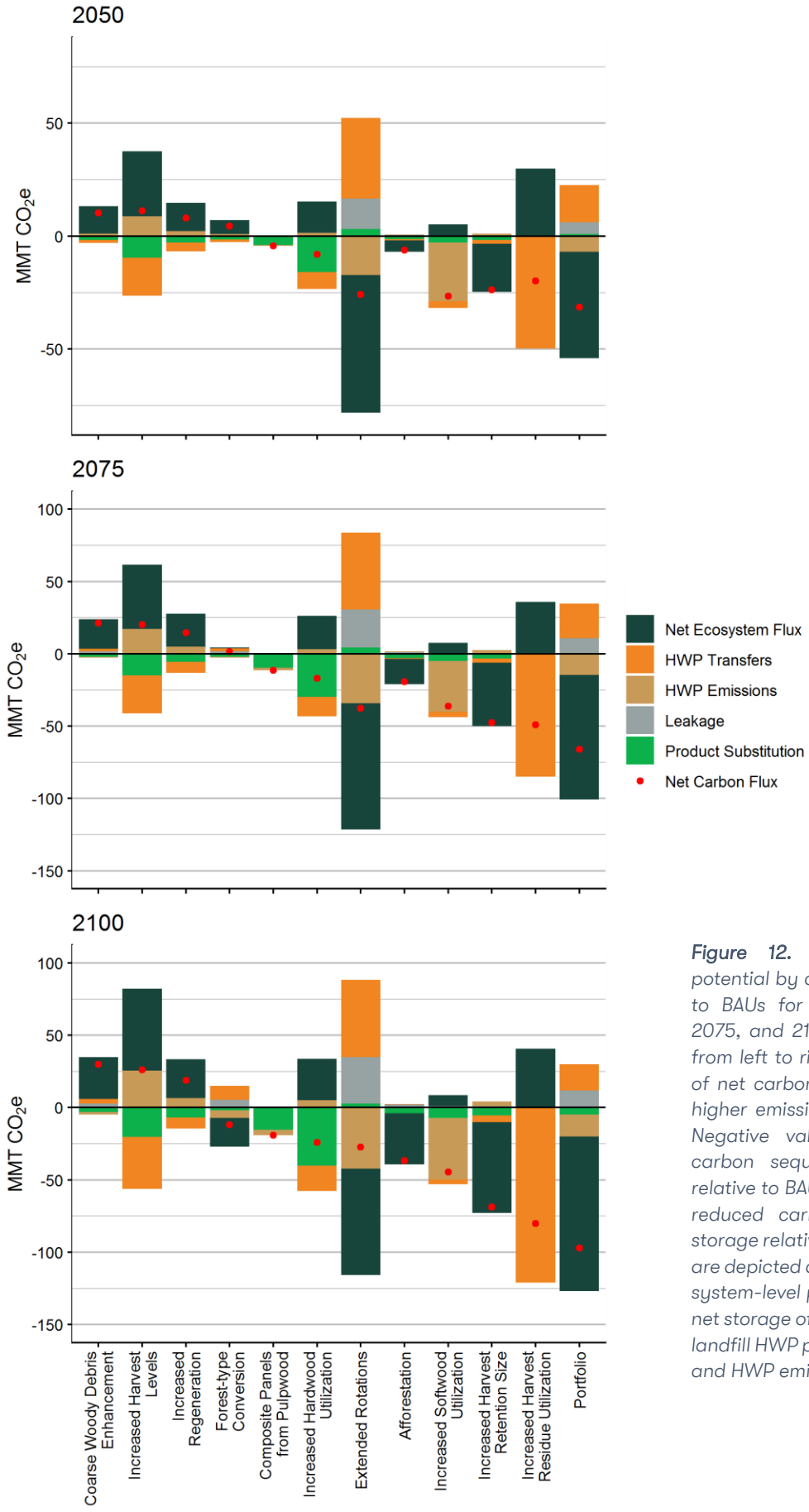


Figure 12. Cumulative mitigation potential by component standardized to BAUs for all scenarios in 2050, 2075, and 2100. Scenarios are listed from left to right in descending order of net carbon balance in 2100 (from higher emissions to lower emissions). Negative values denote additional carbon sequestration 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.

Both scenarios under the theme of improved forest health and regeneration lead to the highest (least negative) cumulative net carbon balance, meaning they sequester and store less carbon than BAU. The *Coarse Woody Debris Enhancement* scenario reduces the merchantable wood volume removed following all harvest types and instead leaves this wood in the forest as coarse woody debris. As a result, in order to maintain a similar harvest yield to BAU, the harvest intensity is increased slightly, meaning less residual growing stock is left undisturbed to maintain a higher level of merchantable timber left on site without disrupting harvest levels. This has the effect of increasing (making less negative) net ecosystem carbon flux due to a reduction in net primary productivity. Interestingly, the *Coarse Woody Debris Enhancement* scenario actually reduces overall decomposition emissions, as the changes in harvest pressure reduce the annual rate of litterfall, thus reducing a source of low residency time dead organic matter, though this reduction in emissions is smaller than the complementary change in primary productivity. This scenario also slightly lowers harvest transfers and HWP emissions, resulting in a small amount of leakage and negative substitution. These effects combined lead to +10.23 MMT CO_2e, +21.35 MMT CO_2e, and +30.00 MMT CO_2e less carbon sequestered and stored than BAU in 2050, 2075, and 2100, respectively (**Figure 12**). The *Increased Regeneration* scenario, which aims to supplement understocked stands by planting 217,453 ac by 2100 and increasing regeneration harvests by 276,758 ac, does not result in any meaningful increase in ecosystem carbon storage, instead having a higher (less negative) net ecosystem carbon flux than BAU. This is the result of a decline in productivity brought on by the regeneration harvests, which is larger than the increase in productivity from restocking. Because of these regeneration harvests, HWP transfers and emissions are higher than under BAU, and this scenario benefits from some positive product substitution. Taken together, these effects lead the *Increased Regeneration* scenario to have a net carbon balance +8.11 MMT CO_2e less than BAU by 2050, growing to +14.67 MMT CO_2e, and +18.9 MMT CO_2e less carbon sequestered and stored by 2075, and 2100, respectively (**Figure 12**).

Like the *Increased Harvest Retention Size* and *Extended Rotations* scenarios, the *Afforestation* scenario leads to a large increase in the forest ecosystem's mitigation potential, which is not unexpected given the net increase in forest area under this scenario. The *Afforestation* scenario adds 277,944 ac of forest area from 2021-2100 as compared to BAU. This scenario also experiences small annual deviations from BAU in HWP transfers from altered land-use change activities, and thus a small amount of leakage (when removals are reduced) and positive substitution benefits (when harvest is increased). The resultant carbon sequestration and storage impacts for this scenario are −6.10 MMT CO_2e more than BAU by 2050, -19.22 MMT CO_2e more than BAU by 2075, and −36.67 MMT CO_2e more than BAU by 2100 (**Figure 12**).

Under the theme of Climate Adaptive Management, the *Forest-type Conversion* scenario, which simulates secondary succession in some aspen stands, has the smallest difference in carbon sequestration and storage compared to BAU of any of the scenarios tested. Interestingly, this scenario switches from cumulatively sequestering and storing less carbon than BAU (up until 2079) to cumulatively sequestering and storing more carbon than BAU from 2080 onward (**Figure 11**). This scenario assumes that approximately 9,783 ac yr^{-1} of older aspen stands begin to transition into longer-lived mixed stands comprised of both hardwood and softwood species. This change in forest composition initially results in a decrease in net primary productivity; however, as these new stands age, net primary productivity increases and surpasses BAU. In addition, because aspen represents a forest type with high harvest rates, the reduction in area of aspen forest types in this scenario leads to lower HWP transfer, lower HWP emissions, and leakage. However, because of an increase in production of some softwood products like lumber and composite panels, this scenario leads to a small amount of positive product substitution despite the lower overall rate of harvesting.

Altogether, the *Forest-type Conversion* scenario initially leads to +4.41 MMT CO_2e less carbon storage and sequestration relative to BAU by 2050, before reversing this trend with +1.49 MMT CO_2e less sequestration and storage by 2075, and –11.92 MMT CO_2e more sequestration and storage by 2100 (**Figure 12**).

In addition to the scenarios above, we also tested four scenarios using alternate HWP model parameters. One of these, the *Composite Panels from Pulpwood* scenario, was based on the BAU ecosystem model, with the HWP model updated to allocate a fraction (1% per year for 10 years starting in 2027) of carbon away from shorter-lived wood products (pulp/paper) toward the production of composite panels. This scenario only differs from BAU in its HWP emissions and product substitution, as the ecosystem dynamics, and thus HWP transfer and leakage, are identical to BAU. When HWP is allocated to composite panels rather than pulp/paper, this carbon is emitted more slowly as composite panels have a longer in-use half-life than pulp/paper (27 vs 3 years). In addition, less of the overall carbon is emitted, as composite panels have a smaller degradable fraction (10%) than pulp/paper (50%) in landfills. Finally, composite panels will substitute for more emissions-intensive alternatives, displacing emissions, and leading to overall emissions reductions relative to BAU. Collectively, these factors lead the *Composite Panels from Pulpwood* scenario to store an additional –4.33 MMT CO_2e by 2050, -11.44 MMT CO_2e by 2075, and –19.06 MMT CO_2e by 2100 relative to BAU (**Figure 12**).

The other three alternate HWP scenarios each have alterations in both their ecosystem and HWP parameters. In the *Increased Harvest Residue Utilization* scenario, 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. 100% of this additional removal is allocated to biochar, a novel product with a very long (100 years) in-use half-life. Because harvest residue would otherwise be left on site to decompose, transferring this carbon out of the forest reduces decomposition emissions, though overall ecosystem carbon storage is reduced as this material is removed from the forest. At the same time, this carbon is allocated to the in-use and in-landfill pools of the wood products sector, and because of the long half-life for biochar, HWP emissions are only marginally increased over the 80-year simulation period. When the overall changes in storage as the result of *Increased Harvest Residue Utilization* are considered, this scenario stores an additional –19.79 MMT CO_2e more than BAU by 2050, -49.22 MMT CO_2e more than BAU by 2075, and –80.21 MMT CO_2e more than BAU by 2100 (**Figure 12**), making this the single scenario with the largest additional accumulation of carbon.

The *Increased Softwood Utilization* and *Increased Hardwood Utilization* scenarios each increase the harvest levels of their respective wood types and allocate 100% of this additional (above BAU levels) harvest toward mass timber (for softwood) or lumber (for hardwood). As with the I*ncreased Harvest* scenario, this leads to a decrease in ecosystem carbon sequestration and storage, though to a lesser extent as the harvest volume targets for these scenarios are lower (+8.5% for softwood and +5% for hardwood vs 10% across both wood types). As expected, both scenarios also transfer more carbon to the HWP sector and benefit from positive product substitution as the result of mass timber or lumber replacing more emissions-intensive alternatives. In addition, the *Increased Softwood Utilization* scenario also sees lower overall HWP emissions than BAU, which come as the result of increased softwood harvest relative to BAU (for mass timber production) early in the simulation, which limits softwood harvest (for all commodities) later in the simulation. Collectively, these factors lead the *Increased Softwood Utilization* and *Increased Hardwood Utilization* scenarios to store an additional (relative to BAU) -26.56 and –8.01 MMT CO_2e by 2050,

-36.27 and −19.97 MMT CO_2e by 2075, and −44.40 and −24.10 MMT CO_2e by 2100, respectively (**Figure 12**).

Representing a concurrent suite of climate-smart forest management actions (**Table 3**), the *Portfolio* scenario provides the best climate mitigation benefits of all scenarios modeled, sequestering and storing an additional −31.33 MMT CO_2e by 2050, -66.03 MMT CO_2e by 2075, and −97.08 MMT CO_2e by 2100 relative to BAU while supporting a sustainable timber supply (**Figure 12**). As noted in the **Alternative Management and Wood Utilization Results** section above, this scenario presents the best opportunity for maintaining a strong forest carbon sink in Wisconsin, highlighting significant opportunities for additional climate benefits from ambitious state action on a wide range of forest management practices.

The Influence of Age Class on Mitigation Potential

Like with the BAU scenario, age class distribution plays an important role in determining the mitigation potential of each scenario modeled in this analysis. As discussed in the **Impact of Business-as-Usual on Forest Age and Carbon** section, age class distribution under BAU shifts significantly over time, with 67.8% of Wisconsin's forests under 80 years old in 2020, dropping to 51.7% under 80 years in 2100. (**Figure 6**). The average forest age subsequently changes from 58 years old in 2020 to 85 years old in 2100 (**Figure 14**), reflecting a shift toward a more mature age-class distribution.

Per-acre carbon storage (*carbon stock density)* and per-acre net ecosystem productivity values 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 (Coomes et al., 2012, 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 very youngest stands, while the middle-aged and older stands hold more carbon per area (**Figure 14**). The very oldest stands sometimes have a carbon density closer to the statewide average, potentially driven by increased emissions from dead wood and/or soil carbon pools.

In the BAU scenario, average carbon stocks remain surprisingly stable, going from 353.57 tCO_2e ac^{-1} in 2030 to 353.27 tCO_2e ac^{-1} in 2100. Over the same time, average per-acre net ecosystem productivity increases from -0.725 tCO_2e ac^{-1} yr^{-1} in 2030 to -0.979 tCO_2e ac^{-1} yr^{-1} in 2100, in a near linear fashion over the course of the simulation (**Figure 14**). A few scenarios deviate notably from this BAU trend. In the *Increased Harvest Levels* scenario, average age still increases (from 61 to 83 years from 2030-2100) but is lower than BAU, as the result of a slightly higher harvest intensity each year, leading to a slightly fraction of the forest below the age of minimum harvest eligibility (**Table S3**). Because of this increased harvest intensity, carbon stock densities decline, going from 352.97 tCO_2e ac^{-1} in 2030 to 350.22 tCO_2e ac^{-1} in 2100, which are −0.17% and −0.86% below BAU levels in each year, respectively. At the same time, per-acre net ecosystem productivity increases from -0.700 tCO_2e ac^{-1} yr^{-1} in 2030 to -0.973 tCO_2e ac^{-1} yr^{-1} in 2100, but again remains less than BAU (+3% and +1% in 2030 and 2100, respectively). In contrast, the *Extended Rotations* scenario increases average stand age (87 vs 85 years for BAU in 2100) and carbon stock densities (357.41 tCO_2e ac^{-1} vs 353.27 tCO_2e ac^{-1} for BAU, or 1.17% higher in 2100) relative to BAU through time, but its difference in per-acre net ecosystem productivity is more dynamic. This scenario initially has greater (more negative) per-acre net ecosystem productivity than BAU (-8% in 2030 and −6% in

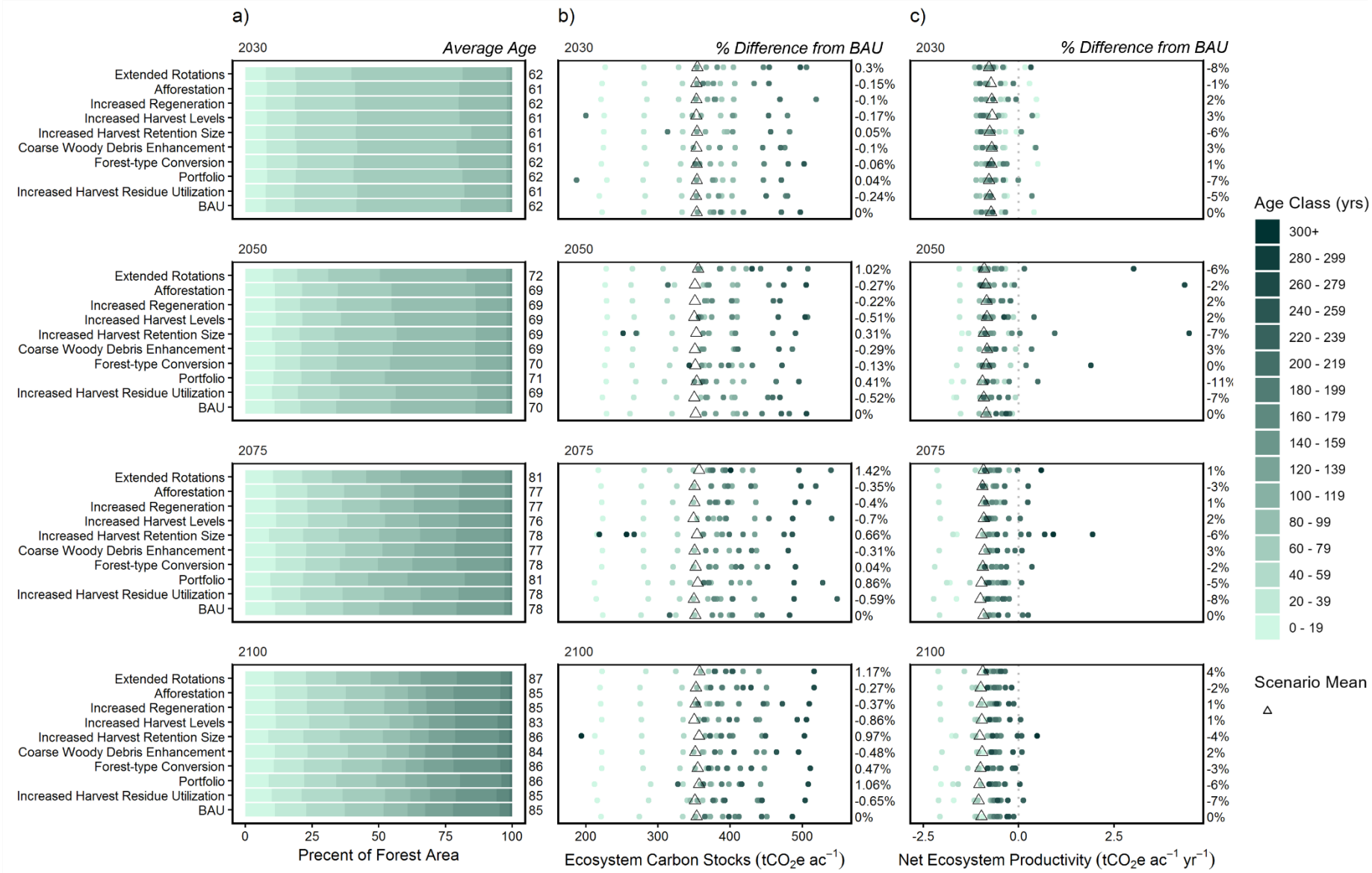


Figure 14. a) Age class distribution, b) ecosystem carbon stock density ($tCO_2e\ ac^{-1}$), and c) per-acre net ecosystem productivity ($tCO_2e\ ac^{-1}\ yr^{-1}$) for selected scenarios in 2030, 250, 2075, and 2100. Net ecosystem productivity refers to the net yearly sequestration of carbon per acre of forest across all 14 ecosystem carbon pools, after accounting for decomposition but not including carbon flux from natural disturbance emissions or 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.

2050), before seeing a lower per-acre net ecosystem productivity from 2071 onward (+1% in 2075 and +4% in 2100). These dynamics are driven by lower BAU harvest levels early in the simulation due to the extended rotation times, which allow the forest to accumulate more carbon per acre, and remain at a higher per-acre net ecosystem productivity. Later in the simulation when harvest levels increase, per-acre carbon density is still higher, but cutting more mature and productive forests means that higher per-acre net ecosystem productivity declines relative to BAU.

In the *Portfolio* scenario, carbon stock densities increase by 0.04% to 1.06% (meaning there is more carbon stored per acre) relative to BAU from 2030-2100, and per-acre net ecosystem productivity also increases, ranging from -5% to -11% (meaning more carbon sequestered per acre) over BAU for the same time period (**Figure 14**). This increase in carbon stock densities is driven by an increase in tree planting (*Afforestation* and *Increased Regeneration)*, as well as the transition of aspen stands to forest types with higher biomass density (*Forest-type Conversion*). The age distribution of the *Portfolio* scenario is largely similar to BAU, in line with management practices which attempt to improve forest age diversity (Shifley and Thompson 2011). Because the *Portfolio* scenario promotes younger forests and the new non-aspen forest types, both of which have higher per-acre net ecosystem productivity (**Figure 14**), this helps improve average per-acre net ecosystem productivity for this scenario.

Other scenarios like *Increased Harvest Retention Size, Coarse Woody Debris Enhancement*, and *Increased Harvest Residue Utilization* have similar age class trends to BAU, with comparable average ages and age class distributions over time. Of this group, the *Increased Harvest Retention Size* scenario generates the best carbon storage gains relative to BAU by increasing reserve sizes following harvest, thus ensuring more forest area and carbon is maintained long term. As such, carbon stock densities range from just 0.05% higher in 2030 to 0.97% higher in 2100 (**Figure 14**). The *Increased Harvest Residue Utilization* scenario also provides substantial improvements in per-acre net ecosystem productivity by reducing the amount of ecosystem decomposition emissions, with carbon flux densities –5% and -7% greater (meaning more carbon sequestration and storage) than BAU in 2030 and 2100, respectively (**Figure 14**). These differences demonstrate the additional potential of CSF management practices to increase forest carbon sequestration and storage in Wisconsin even without altering current age class trajectories.

A final consideration for age class impacts on mitigation potential is the link to forest resilience. *Forest resilience* here refers to the capacity of a forest to respond to disturbance by withstanding permanent damage or change and recovering quickly (Mina et al. 2022). 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 Wisconsin. Diversity of species composition and forest structure at a stand scale is key to facilitating ecosystem resilience (Mina et al. 2022; Seidl et al. 2016). Creating and maintaining a diversity of age classes at a landscape scale, already a priority for our state partners, can further support forest resilience to future disturbances. Forest age diversity, in turn, supports the resilience and stability of Wisconsin's forest climate mitigation potential.

Uncertainties and Limitations

The models and assumptions used in this analysis introduce a few key uncertainties and 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 adds additional uncertainties to the trajectories of future net carbon balance in Wisconsin. Underlying assumptions and simplification in the development of harvest regimes in our model, especially on privately managed lands, could significantly contribute to future uncertainty in the model results. Additionally, we make no attempt to estimate changes in future growing conditions, climate-induced mortality, or changes in albedo, which similarly can have significant influences on carbon balance. Furthermore, 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 practice should be further examined for biophysical, political, and economic feasibility by land managers to incorporate localized knowledge in the planning and decision-making process.
2. 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.
3. Significant uncertainties remain in future wood markets and the climate mitigation benefits of substitution for both bioenergy and material substitution. Furthermore, leakage remains difficult to quantify and requires cooperation across state boundaries. The forest product market is 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.
4. 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. Results presented in this analysis use our 84.4% leakage assumption for years when harvest is lower than BAU, discussed in the **Harvested Wood Products Model** section. However, for different leakage assumptions we cannot simply subtract from or add to the leakage 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 products, decreasing the need for other products to be used in place of wood. This dynamic assumes a static demand for wood products even with decreased in-state supply of HWP.

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 the forest bioeconomy through the provision of wood products (Skog 2008; Smyth et al., 2014; Lempriere et al., 2013). Results for this analysis indicate that Wisconsin's forests already provide strong climate mitigation benefits, and that key climate-smart forest management practices have

strong potential to provide additional benefits beyond business-as-usual practices in Wisconsin, strengthening the forest carbon sink until the end of the century. These practices can help achieve management objectives by balancing forest health goals, climate adaptation, and mitigation while providing a sustainable supply of timber and other ecosystem services. These climate-smart forest management practices are (in no particular order):

- **Continued sustainable management of working forestlands** to support climate mitigation potential and the forest bioeconomy through current practices represented in the *Business-as-Usual* scenario and through increasing forest extent by *Afforestation.*

- **Increase the carbon retention potential of the forest** through *Extending Rotations* and increasing the *Harvest Retention Size* following harvesting and other forestry operations.

- **Support climate mitigation and adaptation** by incorporating climate change considerations into forest management, such as proactively promoting more adaptive *Forest-Type Conversions* or by implementing the suite of practices represented by the *Portfolio* scenario.

- **Bolster climate mitigation potential of the forest products sector** through wood utilization strategies including increased utilization of *Harvest Residues*, increased production of *Longer-Lived Wood Products* or by altering current commodity production ratios such as producing additional *Composite Panels from Pulpwood.*

Our results also suggest that implementing concurrent climate-smart forest management practices included in the *Portfolio* scenario, which accounts for multiple CSF strategies described above, could increase Wisconsin's forest carbon sink by 29.4% in 2030, 28.5% in 2050, and 15.8% in 2100, relative to BAU. Balancing multiple management goals such as timber, recreation, and climate benefits is predicated on the sustainable management of forestlands today and in the future.

The continuation of current demands for forest products in Wisconsin suggests that Wisconsin's forest carbon sink will continue to strengthen until the end of the century. Despite a gradual projected decline in forest area, forest growth in our scenarios still outpaces all emissions from timber harvests, natural disturbances, and LUC. The *Afforestation, Increase Harvest Retention Size, Extended Rotations,* and all three *Increased Wood Utilization* scenarios all represent potential CSF opportunities to increase the climate mitigation potential of Wisconsin's forests without hindering other forest co-benefits such as timber, recreation, and clean air and water (Schulze et al. 2022). These actions present increasingly desirable opportunities to balance climate goals with other more traditional forest management objectives.

Other scenarios such as the *Forest-Type Conversion* scenario represent additional opportunities to increase the future mitigation potential of forests while promoting climate adaptive practices and potentially reducing the future risk to forests from a changing climate (Nevins et al. 2021). The *Increased Regeneration* scenario, while providing less climate mitigation potential as compared to BAU (though still remaining a net carbon sink through 2100), represents a potential tradeoff between near-term carbon storage and sequestration and longer-term future resilience through restoration of working forest lands. Further, our results suggest that investments in durable and longer-lived wood products may provide significant climate mitigation benefits by increasing the carbon storage potential of forest products while providing additional economic potential for rural communities

Forest managers, decision makers, and policymakers should identify and advance policy mechanisms and incentives that support and increase the adoption of climate-smart forest management practices in support of reducing GHG emissions. The continued stewardship of Wisconsin's forestlands is predicated upon incentivizing sustainable management practices that achieve a suite of management goals and disincentivizing actions that may lead to increased vulnerabilities and risk to forests. There is no one-size-fits-all approach to climate-smart forest management. Any climate-smart forest management approach will necessitate site-specific information and expertise combined with broad-scale information, such as what is provided in this analysis, to inform future mitigation and adaptation pathways.

Future CSF efforts in Wisconsin could focus on incentivizing maintaining or increasing forest area on privately managed lands through mechanisms such as tax programs, stewardship and management plans, voluntary offset projects, and other cost-share programs that can influence forest management behaviors. Technical assistance programs designed for small non-industrial landowners can also provide needed help in the sustainable management of forest resources. Further, the continued incorporation of new data and information iteratively affords decision makers greater opportunities to refine management objectives and other GHG emission targets and goals. The creation of flexible decision-making processes guided by data-driven information will continue to support the stewardship of Wisconsin's forests, ultimately leading to healthier and more resilient forests and communities that rely upon 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 for 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 United States Forest Service (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 model 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 for 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. 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 carbon 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 and project carbon dynamics across a specified time period.

Table S1. List of Classifiers and descriptions

Code	Name	Description	ID	Value
ECO_SEC	Ecosection	Biogeographic unit that contains minor variation in physiographic, macroclimatic, and vegetation conditions	1	Southwest Savanna
			2	Southeast Glacial Plains
			3	Southern Lake Michigan Coastal
			4	Western Coulees and Ridges
			5	Central Sand Plains
			6	Central Sand Hills
			7	Northern Lake Michigan Coastal
			9	Northeast Sands
			10	Forest Transition
			11	North Central Forest
			12	Northern Highlands
			13	Northwest Sands
			14	Northwest Lowlands
			15	Superior Coastal Plain
			16	Western Prairie
			17	Central Lake Michigan Coastal
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
			30	State / County
			40	Private and Native American
FORTYPCD	Forest Type	Code indicating the specific forest cover type defined by a leading species (See: FIADB User Guide for Phase 2 (version 9.0.1) for more information)	101	Jack pine
			102	Red pine
			103	Eastern white pine
			104	Eastern White pine / eastern hemlock
			105	Eastern hemlock
			121	Balsam fir
			122	White spruce
			125	Black spruce
			126	Tamarack
			127	Northern white-cedar
			171	Eastern redcedar
			381	Scotch pine
			384	Norway Spruce
			401	Eastern white pine / northern red oak / white ash
			402	Eastern redcedar / hardwood
			409	Other pine / hardwood
			503	White oak / red oak / hickory
			504	White oak
			505	Northern red oak
			509	Bur oak
			512	Black walnut
			513	Black locust
			515	Chestnut oak / black oak / scarlet oak
			516	Cherry / white ash / yellow-poplar
			517	Elm / ash / black locust

Table S1, cont. *List of Classifiers and descriptions*

Code	Name	Description	ID	Value
FORTYPCD	Forest Type	Code indicating the specific forest cover type defined by a leading species (See: FIADB User Guide for Phase 2 (version 9.0.1) for more information)	*519*	Red maple / oak
			520	Mixed upland hardwoods
			701	Black ash / American elm / red maple
			702	River birch / sycamore
			703	Cottonwood
			704	Willow
			705	Sycamore / pecan / American elm
			706	Sugarberry / hackberry / elm / green ash
			707	Silver maple / American elm
			708	Red maple / lowland
			709	Cottonwood / willow
			801	Sugar maple / beech / yellow birch
			802	Black cherry
			805	Hard maple / basswood
			809	Red maple / upland
			901	Aspen
			902	Paper birch
			904	Balsam poplar
			905	Pin cherry
			962	Other hardwoods
			995	Other exotic hardwoods
			999	Nonstocked
			0	Nonforest
TYPGRPCD	Forest Type Group	Code indicating the forest type group of each forest record by predominate species groupings ((See: FIADB User Guide for Phase 2 (version 9.0.1) for more information)	100	White / red / jack pine group
			120	Spruce / fir group
			170	Other softwoods group*
			400	Oak / pine group
			500	Oak / hickory group
			700	Elm / ash / cottonwood group
			800	Maple / beech / birch group
			900	Aspen / Birch group
			960	Other hardwoods group*
			999	Nonstocked
			0	Nonforest
SITECLCD†	Site Class Code	Measure of site productivity in terms of growth as a function of cubic feet per acre per year.	1	165-225+ cubic feet/acre/year
			2	85-164 cubic feet/acre/year
			3	20-84 cubic feet/acre/year
			4	0-19 cubic feet/acre/year

*Reclassified any TYPGRPCD of small area/sample size to just be 'other' HW and SW groups and by productivity class

†Reclassified FIA SITECLCD to be 1-4 as opposed 1-7 to increase sample size of plots for development of growth-yield relationships.

Framework selection & BAU 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 Wisconsin. 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 S2). 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.

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. Both the forest inventory and growth-yield relationships were derived from data in the Forest Inventory and Analysis (FIA) database (USDA Forest Service, 2019). 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 (accessed 3/5/2021). 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).

The forest inventory utilized in the CBM-CFS3 is a spatially referenced rather than a spatially explicit inventory, meaning that forest records are tracked via sub-regional classifiers rather than geolocated pixels or spatial data points. The forest inventory is estimated as a function of total area (hectares) for each unique combination of classifiers (Table S1). Additionally, the CBM-CFS3 requires information for each inventory record on UNFCCC land class, historic disturbance type (the most common disturbance type over the last 500+ years), and last disturbance. We used the rFIA package (Stanke et al., 2020) in the R programming environment (R Core Team, 2020) to run spatio-temporal queries on the FIA database and format data inputs. Historic disturbance and last disturbance data for each inventory record were derived from LANDFIRE (USGS, 2016) and FIA (USDA Forest Service, 2019), respectively.

In the CBM-CFS3 model, forest productivity and regeneration are empirically driven by growth and yield curves which represent the rate of biomass accumulation as a function of stand age and site productivity (quantified as MAI). To estimate the yield curves, we utilized a Chapman-Richards growth equation to model the relationship between merchantable volume (excluding bark, in cubic meters per hectare) and average stand age from FIA data (USDA Forest Service 2019). To estimate tree volume, we estimated gross merchantable volume for all trees (live and dead) for all forestlands. The Chapman-Richards growth curve takes the following form:

$$y(t) = a(1 - e^{-bt})^p \qquad \textbf{(Eq. S1)}$$

Where y is the merchantable volume at time t measured as average age of the dominant tree cohort within a forest record, a is the asymptote, b controls the rate of approach to the asymptote, and p is a growth modifier that reduces the maximum growth rate to its state at time t. The Chapman-Richards curve is a generalization of the yon Bertalanffy's growth model (Piennar and Turnbull, 1973) which is a common estimation procedure for forest growth within a flexible distribution of shapes with straightforward parameter estimation (Gove et al., 2019).

We derived growth-yield curves for each unique combination of forest type group and stocking class representing a range in growth characteristics and productivity indices. Growth-yield relationships represent a theoretical curve starting from stand establishment until canopy closure. Because the relationship models age versus stand-level volume, processes such as density driven mortality or stem exclusion are inherently accounted for within the total volume. The asymptote estimate with each curve represents an average maximum merchantable volume once a forest stand has reached its ecological maturity point. This assumption, common throughout the literature about older forests (>120 years), represents that in absence of stand replacing disturbances mortality of older cohorts and growth of younger cohorts generally balance each other out (Keeton 2018; Xu et al., 2014). However, some studies do indicate that forests may accumulate soil carbon in at least some old-growth situations (Zhou et al., 2006). **Figure S1** represents growth curves for Maple-Beech-Birch forest types for each site class represented in the inventory.

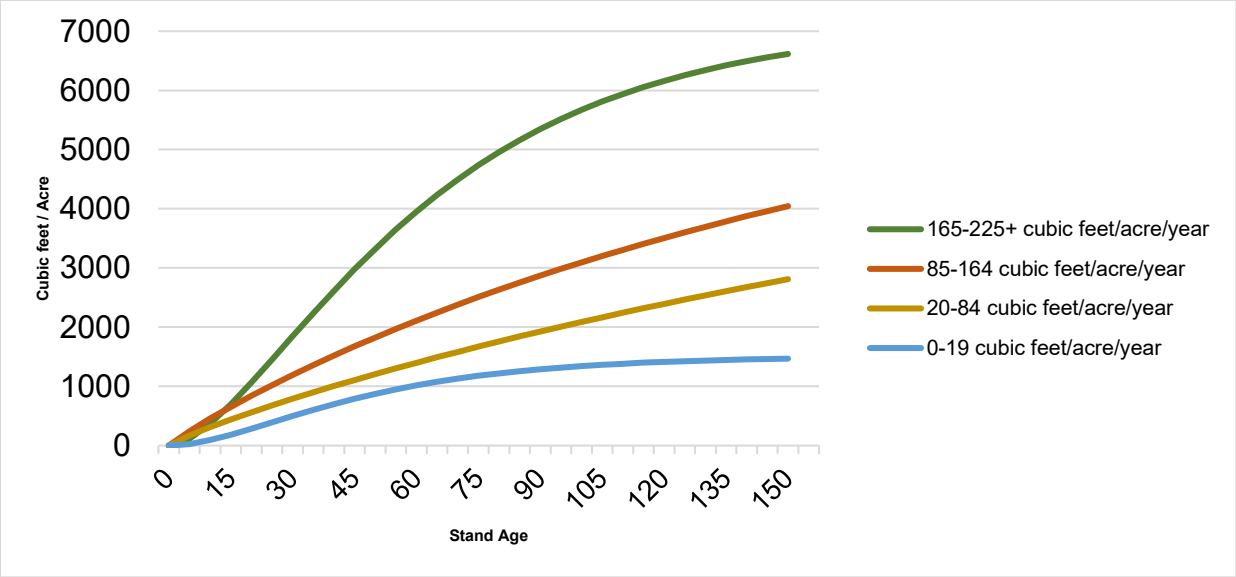


Figure S1. Growth-yield curves estimated using a Chapman-Richards growth equation for Maple-Beech-Birch forest types by site indices

Activity Data

Activity data for harvest removals, land-use change, and other disturbance events where estimated across a 12-year period from 2007-2019 where averaged rates were held constant through the simulation from 2020-2100.

Harvest Removals

Harvest volumes were estimated utilizing methods from Bechtold & Patterson, (2005) to estimate annual averages of volumetric removals in cubic feet by classifiers (i) forest type, (ii) ownership, and (iii) unit code as a function of stand age. Harvest regimes were developed utilizing the Wisconsin DNR silviculture handbook (WI DNR, 2020a) in addition to direct input from state partners. **Table S2** outlines the major harvest regimes developed represented by the percentage of merchantable carbon removed. Individual harvest events are inputted using a rule-based approach with specific carbon targets by ownership and forest type constrained by stand age and time since most recent disturbance. **Table S3** reports average age of each harvest by forest type as well as minimum and maximum ages from 2020-2100 rounded to the nearest 5-year age class.

Harvest events in the CBM-CFS3 model must be inputted as either an area, amount of merchantable carbon, or proportion of area of all eligible records. We estimated merchantable removals as a function of forest type group and stand age. Volumetric removals were converted to carbon following methods in GTR-343 (Smith et al., 2006). When a forest type group was not represented in GTR-343, a weighted specific gravity (SG) was calculated using species dominance as a function of basal area. To estimate merchantable carbon from the volumetric removals, **Eq. S2** was applied as the following:

$$C = ((Volume * SW_{proportion} * SW_{sg}) + (Volume * HW_{proportion} * HW_{sg})) * 0.5 \qquad \textbf{(Eq. S2)}$$

where carbon (C) was calculated individually for both softwood (SW) and hardwood (HW) proportions of the forest record by multiplying harvest volume by the representative $SW_{proportion}$ and

$HW_{proportion}$ and then by the respective specific gravity (sg) for each portion of the stand. A carbon fraction of 0.5 was then applied to convert biomass to carbon. Default values for logging residues post-harvest from the CBM-CFS3 were applied following discussion with state partners to ensure residuals left on site were being accurately represented within the simulation results.

Table S2. Descriptions of harvest types and average harvest intensity in terms of removal of merchantable carbon. Adapted from the Wisconsin DNR Silviculture handbook (WI DNR, 2020a).

Harvest Type	Description	Intensity
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	30% removal
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% removal
Overstory removal	A silvicultural method in which the stand overstory is removed in one cut to provide release of established seedlings and saplings. This method has also been referred to as a natural shelterwood or a one-cut shelterwood. Overstory removal results in an even-aged stand structure as opposed to uneven-aged. It differs from the clearcut and the coppice regeneration methods in that seedling and sapling regeneration is established prior to overstory removal. It differs from the shelterwood and seed tree methods in that no manipulation of the overstory is needed to establish regeneration.	95% removal
Shelterwood	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. The method is designed to regenerate an even-aged stand and normally involves removal of most of the overstory, in two or more cuttings, after the new stand is established. The overstory serves to modify understory conditions, create a favorable environment for reproduction, and provide a seed source. A secondary function of the overstory is to allow further development of quality overstory stems during seedling establishment to increase the efficient use of growing stock. The system is characterized by a preparatory cut (optional), seeding cut(s), and overstory removal. The most vigorous trees are normally retained and less vigorous trees removed.	50% removal
Coppice cut	A silvicultural method designed to naturally regenerate a stand using vegetative reproduction. Stump or root sprouts form the majority of the new stand although some seed origin reproduction may be present. Methods results in even-aged stands where a complete harvest is applied to the entire stand to be regenerated.	95% removal

Table S2. Descriptions of harvest types and average harvest intensity in terms of removal of merchantable carbon. Adapted from the Wisconsin DNR Silviculture handbook (WI DNR, 2020a).

Harvest Type	Description	Intensity
Single-tree selection	A silvicultural method designed to regenerate and maintain uneven-aged stands by removing some trees at regular intervals. 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. Individual trees of various size and age classes are periodically removed to provide space for regeneration and to promote growth of remaining trees. To recruit and release regeneration, trees are removed singly and in small groups, creating canopy gaps <0.1 acres in size. Each regeneration opening (canopy gap) covers an area equivalent to the crown spread of a one to several large trees. The spacing of regeneration gaps is irregular, based on the location of large harvested trees and small groups of undesirable trees (risk, vigor, quality, species). Residual stand stocking is regulated by age (or size) class and generally maintained at a specified level to promote development of quality boles (timber) and fully utilize the site. Regeneration cuts, thinning, and harvesting usually occur simultaneously.	25% removal

Table S3. Average stand age at time of harvest by forest type and harvest type from 2020-2100 (rounded to nearest 5-year age class). Values in the parentheses represent minimum and maximum values.

Forest Type	Average stand age at time of harvest with minimum and maximum age ranges	Harvest Type
101: Jack Pine	40 (35-45) 110 (70-160)	Thinning Clearcut
102: Red Pine	40 (20-45) 80 (45-160)	Thinning Clearcut
103: Eastern White Pine	60 (40-80) 140 (120-220)	Thinning Clearcut
105: Hemlock	205 (175-270)	Clearcut
121: Balsam fir	40 (25-45) 115 (75-155)	Thinning Clearcut
122: White spruce	40 (35-45) 85 (70-115)	Thinning Clearcut
125: Black Spruce	40 (20-45) 130 (110-160)	Thinning Clearcut
126: Tamarack	145 (120-200)	Clearcut
127: Northern white-cedar	70 (30-130) 190 (170-210)	Thinning Clearcut
401: Eastern white pine / northern red oak / white ash	55 (30-60) 115 (100-150)	Thinning Clearcut
409: Other pine / hardwood	40 (35-45) 90 (65-150)	Thinning Clearcut
503: White oak / red oak / hickory	60 (35-65) 95 (60-105) 135 (90-170)	Thinning (group selection) Shelterwood Overstory removal
504: White oak	55 (20-80) 105 (95-115) 170 (150-190)	Thinning (group selection) Shelterwood Overstory removal
505: Northern red oak	55 (30-65) 130 (80-155) 130 (100-190)	Thinning (group selection) Shelterwood Overstory removal
509: Bur oak	60 (50-65) 95 (70-105) 150 (130-175)	Thinning (group selection) Shelterwood Overstory removal

Table S3, cont. *Average stand age at time of harvest by forest type and harvest type from 2020-2100 (rounded to nearest 5-year age class). Values in the parentheses represent minimum and maximum values.*

Forest Type	Average stand age at time of harvest with minimum and maximum age ranges	Harvest Type
512: Black walnut	40 (35-45) 80 (40-160)	Thinning (group selection) Clearcut
513: Black locust	55 (40-65)	Thinning (group selection)
515: Chestnut oak / black oak / scarlet oak	60 (55-80) 95 (60-125)	Shelterwood Overstory Removal
516: Cherry / white ash / yellow-poplar	55 (40-65) 90 (60-100) 120 (95-145)	Thinning (group selection) Shelterwood Overstory Removal
517: Elm / ash / black locust	85 (60-100) 90 (80-115)	Shelterwood Overstory Removal
519: Red maple / oak	55 (40-60) 85 (60-100) 125 (80-165)	Thinning (group selection) Shelterwood Overstory removal
520: Mixed upland hardwoods	45 (20-60) 100 (90-105) 130 (110-150)	Thinning (group selection) Shelterwood Overstory removal
701: Black ash / American elm / red maple	60 (55-65) 95 (65-100) 145 (120-200)	Thinning (group selection) Shelterwood Overstory removal
703: Cottonwood	105 (70-150)	Shelterwood
705: Sycamore / pecan / American elm	35 (20-45)	Thinning (group selection)
706: Sugarberry / hackberry / elm / green ash	40 (35-45) 90 (80-85) 155 (115-190)	Thinning Shelterwood Overstory removal
708: Red maple / lowland	40 (35-45) 80 (75-85) 130 (95-160)	Thinning Shelterwood Overstory removal
709: Cottonwood / willow	135 (105-165)	Shelterwood
801: Sugar maple / beech / yellow birch	60 (55-65) 90 (85-95) 175 (155-210) 110 (100-120)	Thinning Shelterwood Overstory removal Single tree selection
802: Black cherry	60 (40-65) 80 (60-90) 130 (90-160) 100 (80-120)	Thinning Shelterwood Overstory removal Single tree selection
805: Hard maple / basswood	60 (55-65) 90 (75-95) 130 (100-160) 110 (80-120)	Thinning Shelterwood Overstory removal Single tree selection
809: Red maple / upland	60 (55-65) 85 (60-90) 115 (100-135) 90 (80-120)	Thinning Shelterwood Overstory removal Single tree selection
901: Aspen	35 (30-40) 70 (30-160)	Thinnings (group selection) Coppice
902: Paper birch	60 (50-65) 95 (60-145)	Thinning Clearcut
962: Other hardwoods	60 (40-110) 60 (40-110)	Thinning (group selection) Clearcut
999: Nonstocked	25 (20-80)	Clearcut

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. Afforestation estimates were 47,778 ac yr^{-1} while deforestation estimates were 51,712 ac yr^{-1} leading to a net loss of 3,934 ac yr^{-1} from 2021-2100. Annual estimates of LUC were in general agreement with other remotely-sensed 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. Additionally, the FIADB was utilized to estimate total annual extent of wildfire. Three severities were assigned an acreage of area burned based on mortality following proportion determined in the Monitoring Trends in Burn Severity database (MTBS, Eidenshink et al., 2007). Prescribed fire was estimated using the Wisconsin DNR Fire Management Dashboards (WI DNR, 2023) as GIS and other derived estimates of prescribed fire generally underestimate areas burned in low severity fires.

Table S4. Impacts of prescribed fire on carbon pools in the CBM-CFS3 in Wisconsin, based on literature review

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

We created a new disturbance matrix for prescribed fire, to represent and accurately capture the lower intensity fire as compared to other default stand-replacing wildfire matrices in the CBM-CFS3. Based on literature review, we determined that prescribed fires in Wisconsin consume roughly 40% of understory material with no significant impact on the overstory, though impacts differ by carbon pool (see Table S4; Archuleta, 2020, Clark et al., 2015, Elliott & Vose, 2010, Hartman, 2004, Hubbard et al., 2004, Hutchinson et al., 2005, Joers, 2016, Ralston and Cook, 2013, 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).

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 Wisconsin, we also collected data on the historical occurrence (in terms of volumetric removals per year for harvesting, or acres per year for natural disturbances and land-use change) of these events from 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 2020-2100.

Post-Disturbance Transition Rules

Post disturbance transition rules define 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 regional specific literature reviews (Cleland et al, 2004, Gough et al, 2007, 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-WI tracks carbon in the HWP sector, 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 historic national scale roundwood volumes reported in Howard & Liang (2019). To estimate the amount of roundwood attributable to Wisconsin, we multiplied the national total by the portion of Wisconsin production as reported in periodic USDA Forest Service reports (USDA Forest Service 2001; 2004; 2009; 2014; 2023). Since the data from Howard & Liang (2019) are reported in a volume (MCF) we converted these volumes to a carbon mass (including bark) using expansion and conversion factors from (Smith et al. 2006), and wood-type (i.e., hardwood or softwood) specific gravities based on species typically harvested in Wisconsin, the latter of 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. Due to the high degree of interstate trade in the Lake States region, it is exceedingly difficult to estimate total international trade and final export destination. After conversations with state partners, it was determined that the majority of WI roundwood export flows to Asian markets and the European Union, where this wood is processed into lumber, veneers, and other aggregated wood products. We then used TPO data from 1997, 2002, 2007, 2017, and 2018 (USDA Forest Service 2019b; 2023a) to determine the percent of total

WI roundwood production exported internationally, assumed that all exported roundwood was going toward the production of lumber, and applied corresponding product half-lives.

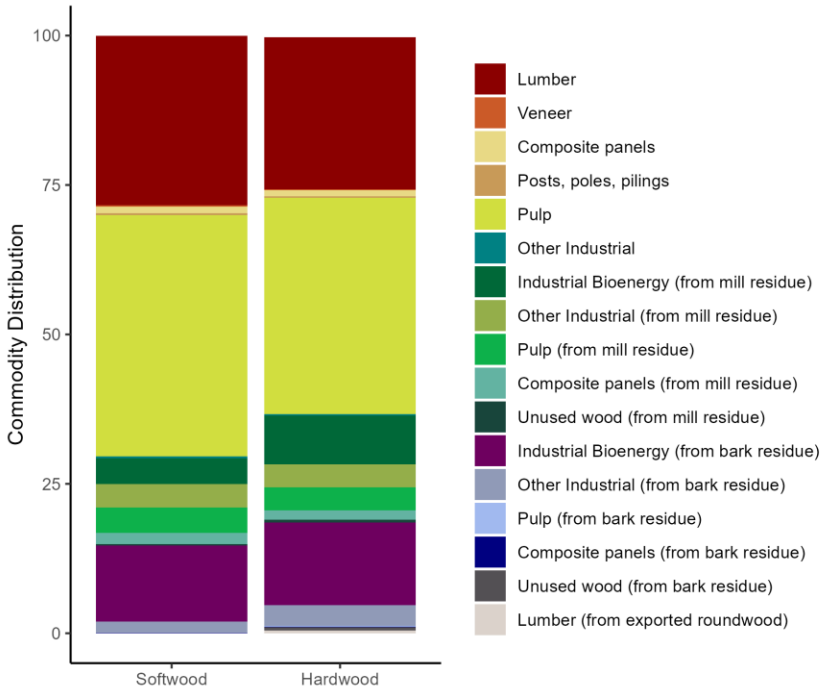


Figure S2. Primary product ratios for commodities produced in Wisconsin, differentiated by softwood and hardwood inputs.

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 primary products, so they need to be tracked separately in the CBM-HWP-WI. 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 Wisconsin mills have an average mill efficiency of 82.9% for softwoods and 77.9% for hardwoods, meaning that the remaining material – 17.1% and 22.1% 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-WI works by tracking proportions of carbon as they move through the HWP stream. These proportions come from *primary product ratios*, which partition harvest volume inputs into various commodities based on their relative historic production. Upon entering the CBM-HWP-WI 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 Wisconsin from RPA data, 1997-2017 (**Table 3**, **Figure S2**; USDA Forest Service 2023a). Again, we differentiated between 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 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 Wisconsin 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; 2017b 2022b; Howard and Liang 2019). Due to data limitations, we assumed recycling and energy recovery occurred only for sawlogs and pulpwood – all other commodities were assumed to retire exclusively to landfills. Recycled products were moved back into the appropriate commodity pool and stayed there according to the half-life determined for that commodity (see **Figure 3** for recycling pathways modeled). Energy recovery pathways were assumed to result in immediate emissions to the atmosphere.

To accurately model landfill dynamics, we utilized information on biodegradable proportions of landfilled material (Zhao 2019) to determine that 50% of carbon in 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 Wisconsin from 1981-2010 (Midwestern Regional Climate Center 2024). 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 Wisconsin-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: 2.00; hardwood: 2.619) and composite panels (softwood: 2.888; hardwood: 1.984), as each is associated with a different commodity and end-use mix. For mass timber, we used the displacement factor for glulam (0.94) as reported by Cabiyo et al. (2021). These values represent the amount of carbon reduction from other products per unit of carbon used in additional wood products (tC/tC).

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; we assume that 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.

C. Scenario Description / Development

While the results show just one simulation per scenario, the majority of scenarios have additional simulations run to assess sensitivity. The results of those sensitivity simulations are represented below.

Extended Rotation

Altering rotation lengths, specifically extending rotations, serves as one strategy to boost the climate mitigation potential of forests. This scenario targeted four forest types including red pine, white pine, oak, and northern hardwoods. **Table S5** provides a detailed description of changes to rotation age by forest type, ownership, and treatment. Three additional extended rotation simulations were run to test sensitivity to the initial simulation where each subsequent simulation increased the extended rotation age by an additional 10 years.

Table S5. Changes to rotation ages implemented as part of the Extended Rotations scenario

Forest Type	Ownership	Treatment	BAU Rotation Age	Extended Rotation Age	Sensitivity
102: Red Pine	10/20: Federal	Clearcut	60	175	+10/20/30 years
	30: State	Clearcut / Overstory removal	40-80+	120	+10/20/30 years
	40: Private	Clearcut	40-80+	120	+10/20/30 years
103: White Pine	10/20: Federal	Clearcut	80+	200	+10/20/30 years
	30: State	Clearcut	80+	180	+10/20/30 years
	40: Private	Clearcut	80+	200	+10/20/30 years
503: Oak	10/20: Federal	Shelterwood / Overstory removal	60-80+	100+	+10/20/30 years
	30: State	Shelterwood / Overstory removal	60-100+	110-150+	+10/20/30 years
	40: Private	Shelterwood / Overstory removal	80-100+	110-150+	+10/20/30 years
801: Maple – Beech - Birch	10/20: Federal	Shelterwood / Overstory removal	90-120+	140+	+10/20/30 years
	30: State	Shelterwood / Overstory removal	90-120+	140+	+10/20/30 years
	40: Private	Shelterwood / Overstory removal	90-120+	140+	+10/20/30 years
	10/20: Federal	Single-tree-selection	90-120+	140+	+10/20/30 years
	30: State	Single-tree-selection	90-120+	140+	+10/20/30 years
	40: Private	Single-tree-selection	90-120+	140+	+10/20/30 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. Additionally, the remaining reserve trees continue to store carbon that otherwise would be transferred to HWP or left on site to decompose. The scenario serves to represent increasing the average reserve size of clearcuts to 15% as opposed to the current 3% in the BAU scenario which is a 5X increase in reserve size for stand replacing harvests or cuts.

Shelterwood increased the reserve size by 10% increasing the average reserve size from 50% to 55%. Finally, Single-tree-selection increased reserves

Table S6. Changes in the reserve size (%) implemented in each of the Reserve Size scenarios

Treatment	BAU	Patch1	Patch2	Patch3	Patch4
	Reserve Size (%)	Reserve Size (%)	Reserve Size (%)	Reserve Size (%)	Reserve Size (%)
Clearcut	3	15	11	8	4
Overstory removal	3	15	11	8	4
Shelterwood	50	55	55	55	50
Coppice cut	3	15	11	8	4
Single-tree-selection	70	85	85	80	75

Increased Regeneration

Managers have a few methods for increasing stand productivity two of which are underplanting and regeneration cuts. Enrichment planting, as a management activity, introduces desired species to secondary or regenerating forests (Aide et al., 2000; Dalle et al., 2006). Enrichment planting can include both natural or artificial regeneration through silvicultural cuttings by mimicking natural gap dynamics or the planting of desired species (Paquette et al., 2006a; Paquette et al. 2006b). Underplanting has also shown promise to increase terrestrial carbon stocks (Paquette et al. 2009). Alternatively, cutting or harvesting provides another way to artificially increase stand vigor by such techniques as removal of old trees or cohorts or by increasing favorable conditions to establish reproduction and regeneration. This simulation implemented two techniques simultaneously to increase the stocking levels of underperforming stands by underplanting and regenerative cuts (WI DNR, 2020a).

Table S7. Changes in the type and amount of regeneration implemented in the Increased Regeneration scenario

Forest Type	Prescription	Amount (ha)	Sensitivity	Eligible area (ha)
Red Pine – 102	Underplanting	200	+25/50/75%	87908.8
White Pine – 103	Underplanting	200	+25/50/75%	93832.4
Oak Pine – 401	Underplanting	200	+25/50/75%	79509.3
Central Hardwood – 503	Underplanting	500	+25/50/75%	718112.8
Elm / Ash – 701	Regenerative cut	300	+25/50/75%	282251.9
Maple/Beech/Birch – 801	Regenerative cut	1200	+25/50/75%	603394.2

Afforestation

Increasing forest extents is one of the most cost-effective methods for climate change mitigation. To implement the afforestation scenario, we first estimated the amount of current idle farmland using the FIADB. FIA estimated 348,013 ac available for afforestation from idle farmland. To estimate new afforestation rates, we proportionally distributed 1% of the idle farmland available across the four ownership classes by the annual BAU afforestation rates. **Table S7** provides increases in afforestation rates by ownership class and providing values for the four sensitivity simulations.

Table S8. Changes in the amount of reforestation implemented in the Afforestation scenarios

Simulation Name	Ownership group	BAU afforestation rate (ha)	Increase in annual rate of afforestation (ha)	New annual rate of afforestation (ha)
Affor1	10: USFS	122	+ 9	131
	20: Other federal	161	+ 12	173
	30: State / Municipal	2452	+ 178	2631
	40: Private	16600	+ 1209	17809
Affor2	10: USFS	122	+ 18	140
	20: Other federal	161	+ 24	185
	30: State / Municipal	2452	+ 356	2808
	40: Private	16600	+ 2418	19018
Affor3	10: USFS	122	+ 4.5	126.5
	20: Other federal	161	+ 6	167
	30: State / Municipal	2452	+ 89	2541
	40: Private	16600	+ 605.5	17205.5
Affor4	10: USFS	122	+ 2	124
	20: Other federal	161	+ 3	164
	30: State / Municipal	2452	+ 45	2497
	40: Private	16600	+ 302	16902
Affor5	10: USFS	122	+ 9	131
	20: Other federal	161	+ 11	172
	30: State / Municipal	2452	+ 178	2630
	40: Private	16600	+ 5000	21600

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 Wisconsin 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, with an increase in prevent harvest on all mature harvesting (not thinnings or other intermediate treatments) by 10% with a sensitivity of 25%, 50%, 75% of that increase. Additionally, partners were interested in the effects of additional wood utilization of the increased removals using BAU product splits.

Forest-Type Conversion

Climate change is expected to shift and alter habitat regimes throughout the US. Aspen is predicted to be increasingly vulnerable as the Lake States comprise its most southern extent. Transitioning vulnerable cover-types is another option to protecting forest structure and function. This scenario transitioned 30% of the available aspen stands across the 80 year simulation resulting in 9,783 ac yr^{-1} of aspen being transitioned to longer lived northern hardwood forests, oak dominated forests, and pine dominated forests as these forests are predicted to increase in habitat suitability across the 21st century. The scenario had two sensitivities of 33% and 66% of area targets from 2020-2100.

Coarse Woody Debris Enhancement

Coarse woody debris (CWD) is a term used to describe wood from dead trees that meets a specific size definition of at least 10 cm in decimate and 1 m in length. CWD mainly consists of coarse parts of the dead tree such as trunks, branches, stumps, and larger roots, but remains distinct from

standing dead trees or snags. CWD plays a very important role in forest carbon cycling through decomposition processes. Additionally, this woody material provides habitat for numerous faunal species such as rodents, snakes, salamanders. The material also provides habitat for mosses, lichens, fungi, insects, and other invertebrates (Stahl and Dollof, 2002). Simple techniques or methods can be performed to increase the amount of material left over from harvest to change the stand structure. This scenario increased the amount of CWD left on site following clearcut, coppice cut, overstory removal treatments, shelterwoods, and single-tree selection systems to explore increasing dead biomass in the residual stands and enhance wildlife habitats.

Table S9. Changes in the amount of CWD left in the forest associated with each of the Coarse Woody Debris Enhancement scenarios

Harvest Type	CWD1	CWD2	CWD
Clearcut/Coppice/OSR	16.5% of AG live merch biomass goes to Medium DOM, 50% of stem snags	18% of AG live merch biomass goes to Medium DOM, 50% of stem snags	19.5% of biomass goes to Medium DOM, 50% of stem snags
Shelterwood	5% of total AG live merch biomass	10% of total AG live merch biomass, 50% of stem snag	15% of total AG live merch biomass, 50% of stem snag
STS	3% of total biomass	6% of total biomass	9% of total biomass

Wood Utilization and Markets

Changes in wood utilization and/or changes in commodity production can have a large impact on overall net carbon balance via changes in emissions (both in the ecosystem and the HWP sector), leakage, and product substitution. We investigated four such alternative wood utilization models.

The Composite Panels from Pulpwood scenario retained BAU harvest transfer rates, however in this scenario we adjusted the production of softwood pulp and paper and composite panels commodities by 1% per year from 2028 through 2037. In 2027 pulp and paper and composite panel production accounted for 57.07% and 1.56% of softwood commodity production respectively. After this change had gone into effect in 2038 pulp and paper and composite panel production accounted for 47.07% and 11.56% of softwood commodity production respectively.

For the Increased Harvest Residue Utilization Scenario, wood residues that would normally be left on site after harvest were instead allocated to the wood products sector for use in biochar. To calculate the amount of residues sent to HWP, we converted 1200 MCF of harvest residue (determined by agency partners) to units of carbon. To do so, we first converted 1200 MCF to cubic meters and then calculated a statewide averaged specific gravity of 0.462 using basal area by species as a proxy for abundance. We then multiplied the cubic meters of harvest residents by the statewide average and a carbon fraction of 0.5 to convert to metric tons of carbon, applying these changes to harvest targets and harvest disturbance matrices.

For the Increased Softwood Utilization Scenario, harvest targets are increased by 8.5% for all softwood harvest allotments. This results in an average annual increase of 5.6% softwood harvest (+22,631 tC yr^{-1}), 100% of which is allocated to mass timber.

For the Increased Hardwood Utilization Scenario, harvest targets are increased by 6% for all hardwood harvest allotments. This results in an average annual increase of 3.0% softwood harvest (+ 75,413 tC yr^{-1}), 100% of which is allocated to long-living products, to which we apply the same in-use and in-landfill parameters as lumber.