



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

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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 ecosystems society relies on. Forests have become increasingly important in the international climate change dialogue, as seen in the Paris Agreement and the COP26 Glasgow Leaders' Declaration on Forests and Land Use (COP26 2021; Popkin 2019) to help reach net zero greenhouse gas (GHG) emission targets. Further, there is 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).

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 7890 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).

State governments can leverage the climate benefits of 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 impact that forests, forest management, and forest policies currently have on emissions levels, as well as the interaction with future impacts on forest health and climate benefits, to better inform decision-making and policy regarding forests and climate action. This report is designed to inform Michigan's future decision-making towards carbon stewardship (a management approach that seeks to explicitly and intentionally integrate carbon science into land management), 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 effects from using wood in place of other emissions-intensive materials.

Modeling Forest Management and Wood Utilization in Michigan

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 Michigan 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 Michigan;

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

3) Scenario modeling with i) a growth and yield-based forest ecosystem model - the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3; Kurz et al. 2009) - parameterized for conditions in Michigan, ii) a customized harvested wood products dynamics model (CBM-HWP-MI) built using the Abstract Network Simulation Engine framework (ANSE; CFS 2024), iii) potential leakage factors applied to changing harvest rates, iv) displacement factors to evaluate substitution effects 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 Michigan Department of Natural Resources (DNR), we identified several management priorities and concerns for forests in Michigan: **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 Michigan and have been recognized as concerns regionally and nationally. From these state priorities, we developed 13 modeling scenarios to cover a broad range of forest management, climate change impacts, and wood utilization scenarios, grouped into four categories representing similar management objectives and priorities: 1) Harvesting Practices; 2) Forest Health and Regeneration; 3) Climate Change Impacts; and 4) Wood Utilization and Markets (**Table E1**). For full scenario descriptions and parameters, see **Report Table 3**.

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

Table E1. Names, descriptions, objectives, and a results summary for the 15 scenarios and portfolio conducted in this analysis. Scenarios that are components of the Portfolio are marked with a † symbol. See Appendix for assumptions and data sources used to construct each scenario. Negative numbers for net ecosystem carbon flux and net carbon balance represent a net carbon sink and positive numbers represent a net carbon source. Negative numbers for % change from BAU indicate lower emissions than BAU, while positive numbers represent higher emissions than BAU.

	Scenario Name, Description, and Motivation	Average Annual Net Ecosystem Carbon Flux (MMT CO_2e yr^{-1})	Cumulative Net Carbon Balance 2021-2100 (MMT CO_2e)	Precent Difference in Cumulative Net Carbon Balance 2021-2100 from BAU
	Business-as-usual (BAU) Continuation of average historical rates of management, land-use change, and natural disturbance; establish a benchmark to assess scenarios against	-16.0	-1335.0	-
Harvesting Practices	**† Extended Rotations** Increase the average harvest age of stands to and increase ecosystem carbon stocks; explore the tradeoffs between altered harvest levels and increasing carbon stocks through deferred harvests	-16.2	-1347.8	-1%
Harvesting Practices	***Jack Pine Management** Decrease the average harvest age of jack pine stands and send jack pine carbon to a portfolio of commodities; quantify potential effects of altering jack pine management for Kirkland warbler habitat	-16.0	-1339.1	-0.3%
Forest Health and Regeneration	**† Increase Regeneration: Oak & NHW** Promote oak and northern hardwood (NHW) regeneration by increasing harvest intensity; quantify the impacts of shifting silvicultural regimes to increase regeneration	-16.8	-1393.8	-4%
Forest Health and Regeneration	**† Increase Regeneration: NHW** Promote regeneration of NHW by increasing harvest intensity; understand the relationship between larger harvest gaps, carbon stocks, and future regeneration	-17.0	-1418.7	-6%
Forest Health and Regeneration	**Increase Harvest Retention Size** Increase the reserve size following clearcuts and seed tree cuts; assess how leaving more standing timber affects forest carbon stocks and HWP carbon storage	-17.0	-1422.6	-7%
Forest Health and Regeneration	**† Enrichment Planting: NHW** Increase supplemental planting to restock understocked stands; quantify the effect of increasing tree plantings on carbon sequestration rates	-17.9	-1492.2	-12%
Forest Health and Regeneration	**† Red Pine Planting** Increase red pine planting targets; understand the effect of increasing red pine planting on carbon sequestration rates	-16.2	-1362.0	-2%
Climate change impacts	**Insect-Driven Mortality** Increase the effects of mortality caused by insect outbreaks; simulate the potential carbon loss from a lack of management to assess the impact of climate driven stressors	-15.9	-1334.8	0.01%
Climate change impacts	**Cover-Type Transition** Increase the rate of aspen stands transitioning to lowland fir/spruce, oak mix, or NHW cover types where advanced regeneration has already occurred; understand the potential carbon effects of letting certain forest types naturally transition, an expected outcome under future climate regimes	-16.1	-1350.5	-1.2%

Table E1, cont. Names, descriptions, objectives, and a results summary for the 15 scenarios and portfolio conducted in this analysis. Scenarios that are components of the Portfolio are marked with a † symbol. See Appendix for assumptions and data sources used to construct each scenario. Negative numbers for net ecosystem carbon flux and net carbon balance represent a net carbon sink and positive numbers represent a net carbon source. Negative numbers for % change from BAU indicate lower emissions than BAU, while positive numbers represent higher emissions than BAU.

	Scenario Name, Description, and Motivation	Average Annual Net Ecosystem Carbon Flux (MMT CO_2e yr^{-1})	Cumulative Net Carbon Balance 2021-2100 (MMT CO_2e)	Precent Difference in Cumulative Net Carbon Balance 2021-2100 from BAU
Wood utilization and markets	**Harvest Residue Utilization: BAU** Increase harvest residues sent to HWP from clearcuts; quantify how increasing wood utilization effects net carbon balance under business-as-usual practices	-15.7	-1312.0	1.7%
	Harvest Residue Utilization: Bioenergy Increase harvest residues sent to HWP from clearcuts; quantify emissions and substitution effects from increased production of bioenergy from woody biomass	-15.7	-1325.4	0.7%
	Harvest Residue Utilization: Biochar Increase harvest residues sent to HWP from clearcuts; quantify emissions and substitution effects from increased production of biochar	-15.7	-1328.3	0.5%
	Mass Timber Add mass timber as a novel product category; quantify carbon storage and substitution effects from production of mass timber	-16.0	-1338.4	-0.3%
Portfolio	**Portfolio** Ensemble of concurrent scenarios (marked with † above); illustrate the potential for Michigan to fully leverage its forests as natural climate solutions to explore tradeoffs and opportunities from implementing multiple CSF strategies concurrently	-17.7	-1484.5	-11%

Box 1. 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).

Climate-Smart Forestry in Michigan

Results of this study show that forests and the forest products sector already contribute strong climate mitigation benefits in Michigan, acting as a net carbon sink (**Box 1**), and that undertaking changes in land use and forest management could increase these benefits substantially. A key factor for successfully undertaking CSF in Michigan will be establishing and maintaining diverse and multi-age forest landscapes. Such landscapes help to balance the two key mechanisms through which forests mitigate climate change – carbon sequestration (removing carbon from the atmosphere and converting it into wood through photosynthesis) and carbon storage (holding that carbon in forests and wood products rather than emitting it to the atmosphere).

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

Box 2. CLIMATE-SMART FORESTRY PRACTICES IN MICHIGAN

- ✓ **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.
- ✓ **Maintain and increase forest extent** via increased *Red Pine Planting* and *Enrichment Planting* of northern hardwood species.
- ✓ **Support climate mitigation and adaptation by incorporating climate change considerations into forest management** through proactively promoting more adaptive *Forest-Type Transitions*, as well as shifts in the *Management of Jack Pine* forests.
- ✓ **Update harvesting practices** by *Extending Rotations* or promoting *Increased Regeneration* of oak and northern hardwood species post-harvest.
- ✓ **Bolster the climate mitigation potential of the forest products sector** through the introduction of *Mass Timber*, effectively increasing the carbon storage potential of the forest products sector while also providing substantial benefits from using wood in place of other emission-intensive materials.
- ✓ **Implement the suite of climate-smart forest practices** listed above as represented by the *Portfolio* scenario

The benefits of expanding climate-smart forestry in Michigan

Our results suggest that by continuing *Business-As-Usual* (BAU) practices, Michigan forests will have an average *Net Ecosystem Carbon Flux* (**Box 1**) of -16.0 MMT CO_2e yr^{-1} from 2021-2100 (**Table E1**), meaning that Michigan forests are sequestering and storing more carbon than they emit each year. Further, assuming BAU harvest practices are maintained, Michigan forests will transfer an average of 6.6 MMT CO_2e yr^{-1} to the forest products sector through 2100, a stable level which is consistent with historical (2007-2019) rates of harvest. Michigan's cumulative *Net Carbon Balance* (**Box 1**) shows that forest ecosystems and the forest product sector together will provide substantial climate mitigation, capturing and storing a total of -1335.0 MMT CO_2e from 2021-2100 (**Table E1**), 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 Michigan's forests to act as a net carbon sink throughout the end of the century, while still providing a steady stream of HWP.

When considering how alternative forest management could impact net carbon balance, we find that implementing a range of concurrent CSF management practices (including extended rotations, enrichment planting, and regeneration harvest), as represented by the *Portfolio* scenario, could strengthen Michigan's cumulative forest carbon sink by 11% in 2050 relative to BUA, with this level holding stable through 2100 (**Table E1**). This equates to an additional -64.6 MMT CO_2e of climate mitigation by 2050 and –149.5 MMT CO_2e of climate mitigation by 2100. 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 just some of the range of CSF actions encapsulated by the *Portfolio* scenario 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 (**Table E1**), indicating that Michigan's forests will be a reliable natural climate solution into the future. However, by examining the trends of individual scenarios we can glean additional information about the future climate mitigation potential of specific actions. For example, the *Extended Rotations* scenario, where the minimum harvest age is extended for all forest types, accumulates 2% more carbon (an additional -22.7 MMT CO_2e) in the forest ecosystem relative to BAU. However, because cumulative harvest volumes are lower than under BAU, the *Extended Rotations* scenario leads to net carbon leakage, where a fraction of the reduced harvest leaks out to adjacent regions, and so we credit the expected emissions from these harvests back to the *Extended Rotations* scenario. When this leakage and a reduction in HWP emissions are accounted for, *Extended Rotations* lead to just 1% additional climate mitigation (an additional –12.8 MMT CO_2e) as compared to BAU by 2100 (**Table E1**).

Under the theme of increasing forest extent, the *Enrichment Planting: NHW* scenario also leads to a cumulative increase of 12% more carbon (an additional –157.2 MMT CO_2e) captured and stored relative to BAU by 2100 (**Table E1**). In the *Enrichment Planting: NHW* scenario, 560,039 acres are targeted for supplemental planting to restock northern hardwood (NHW) forest types by the end of the century. Because NHW species are highly productive and cover a substantial portion of Michigan's forests, increasing the number of trees growing in this forest type yields strong climate mitigation benefits, especially from 2065 onwards when most of this new forest area is at its peak in growth and productivity. By contrast, *Red Pine Planting*, another tree planting focused scenario in which 226,744 acres are planted with red pine, results in a 2% increase (additional

−22.5 MMT CO_2e) in cumulative carbon sequestration and storage as compared to BAU by 2100 (**Table E1**). So, the *Enrichment Planting: NHW* scenario results in nearly seven times the climate mitigation from just double the amount of tree planting. Of all scenarios tested, the *Enrichment Planting: NHW* scenario results in the largest cumulative climate mitigation benefits relative to BAU (**Table E1**), surpassing the *Portfolio* scenario in terms of cumulative net carbon balance in 2092.

The *Cover-Type Transition* scenario, which simulates secondary succession aspen stands (approximately 2,063 ac yr^{-1}) into lowland spruce/fir, oak mix, and NHW cover types through natural processes, switches from cumulatively sequestering and storing less carbon than BAU (up until 2049) to cumulatively sequestering and storing more carbon than BAU from 2050 onward. The primary driver of this shift is the fact that these newly transitioned stands have substantially higher (more negative) net primary productivity than the aspen they are replacing, reducing net ecosystem carbon flux and net carbon balance. In addition, because northern hardwoods represent a forest type with high harvest rates, an increase in the area of these forest types leads to higher hardwood harvest levels. When harvest levels increase relative to BAU, we assume that the amount of commodities produced also increases, helping to displace emissions from more emissions-intensive alternative commodities such as lumber and composite panels. Overall, the *Cover-Type Transition* scenario contributes to a small 1.2% (−15.5 MMT CO_2e) increase in cumulative climate mitigation as compared to BAU by 2100 (**Table E1**).

The *Insect-Driven Mortality* scenario increases the annual rate of insect disturbance, to simulate potential future climate change impacts in Michigan. This scenario results in a slight reduction in cumulative net primary productivity because of higher tree mortality rates, and thus sequesters 0.01% less carbon (+0.2 MMT CO_2e in total) than BAU by 2100 (**Table E1**). Though small, this decrease in cumulative climate mitigation represents a potential climate-adjusted reality for future forests in Michigan, which may also experience other climate-driven impacts not modeled here.

The three *Harvest Residue Utilization* scenarios remain net carbon sinks yet lead to less climate mitigation by 2100 as compared to BAU. In these scenarios, harvest residues, tops and branches which would otherwise be left in the forest as coarse woody debris, are removed during the harvest process and sent to the HWP sector, resulting in higher cumulative harvest transfers and lower ecosystem carbon stocks as compared with the BAU scenario. The use of these harvest residues varies between the three scenarios, influencing their effects on HWP sector emissions and carbon storage. In the case of the *Harvest Residue Utilization: BAU* and *Harvest Residue Utilization: Bioenergy* scenarios, there is an increase in the production of certain commodities which substitute for more emissions-intensive alternatives, helping to displace emissions from other sectors, though overall HWP emissions for these two scenarios are still higher than under BAU. In the *Harvest Residue Utilization: Biochar* scenario, harvest residues are used exclusively in the production of biochar, a durable, low-emissions commodity, but not one which displaces other commodities. Across the three *Harvest Residue Utilization* scenarios, the *Harvest Residue Utilization: BAU* scenario leads to 1.7% less climate mitigation (+6.7 MMT CO_2e) than BAU by 2100 whereas the *Harvest Residue Utilization: Biochar* and the *Harvest Residue Utilization: Bioenergy* led to 0.7% and 0.5% (+9.6 MMT CO_2e and +23.0 MMT CO_2e) less climate mitigation than BAU by 2100, respectively (**Table E1**).

A final aspect to consider is how changes in the forest product sector may influence net carbon balance (Box 1) and thus climate mitigation. In the Mass Timber scenario, harvested wood products dynamics were altered to allocate 5% of softwood material away from pulp toward the production of mass timber each year. Importantly, unlike the three Harvest Residue Utilization

scenarios examined above, the Mass Timber scenario only differs from BAU in its HWP emissions and product substitution, as the ecosystem dynamics, and thus HWP transfer, are identical to BAU. When harvested wood is allocated to mass timber production rather than pulp, its carbon is emitted more slowly as mass timber has a longer in-use half-life than pulp. Further, less total carbon is emitted, as mass timber has a smaller landfill degradable fraction than pulp. Mass timber can also substitute for more emissions-intensive alternatives, displacing emissions from concrete and steel, and leading to overall emissions reductions relative to BAU. Collectively, these factors mean that the Mass Timber scenario results in a 0.3% increase (an additional –3.4 MMT CO2e) in climate mitigation as compared to BAU by 2100 (Table E1). While these altered HWP dynamics were not applied to other scenarios or the Portfolio, making such changes in combination with other CSF management strategies has the potential to lead to further synergistic effects on net carbon balance and thus climate mitigation potential in Michigan.

Other Considerations

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 Tree Planting (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 remain crucial to the future health and stewardship of natural and working forestlands. Our results suggest that current BAU practices could result in both a stable carbon sink and a sustainable future timber supply, and that Michigan's forests will continue to provide significant climate mitigation potential through the end of the 21st century. This analysis further demonstrates that various climate-smart forest management actions including maintaining or increasing the area of forestland, supporting forest health and regeneration, sustainable use of timber products, and managing for future impacts of climate change provide potential solutions to increase the climate mitigation benefits of Michigan'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 Michigan 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 Michigan's forests and forest products sector.

Introduction

Forests as a Natural Climate Solution

Climate change presents an unprecedented global challenge to society and the ecosystems society relies on. Forests have become increasingly important in the international climate change dialogue, as seen in the Paris Agreement and the COP26 Glasgow Leaders' Declaration on Forests and Land Use (COP26 2021; Popkin 2019) to help reach net zero greenhouse gas (GHG) emission targets. Further, there is 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 tCO2e) and cost of implementation. Results of these assessments at the international (Griscom et al. 2017) and United States (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 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 7890 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).

Assessing Forest Climate Benefits in Michigan

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

To achieve such ambitious climate targets, states need new information about the impact that forests and forest management currently have on emissions levels, as well as an understanding of their future impacts on forest health and climate benefits. State governments within the Lake States region (Minnesota, Wisconsin, and Michigan) desire to use this information to inform decision-making and shape policy regarding forests and climate action. Minnesota, Michigan, and Wisconsin collectively contain 54.66 million acres of forestland, and 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 an understanding that the issues, barriers, and opportunities across the region are similar.

This report is designed to inform Michigan'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 effects from using wood in place of other emissions-intensive materials.

The Context for Michigan Forests

Michigan contains 19.3 million acres of forest land (~53% of the state). With approximately 18.6 million acres of its forest classified as timberland, Michigan has the fifth most timberland in the US (USDA Forest Service, 2021). Michigan forests are dominated by deciduous hardwood forests but are home to a wide variety of forests including old-growth hemlocks, jack pine forests, and oak savannas. Tribes and First Nations have been managing forests in Michigan for millennia; however, European settlements brought a large change to forestry in the state (Dickmann and Leefers, 2018). Settlers converted large portions of forest land to agriculture and cities. The 19th century saw a drastic change when logging companies depleted many forests in Michigan and logging led to expansive fires in the late 1800s, shifting public sentiment to focus more on conservation. Throughout the 20th century, Michigan pivoted to more sustainably managing its resources which has led to a large recovery in forest land (MSU Extension, n.d.).

Currently, Michigan is dominated by Maple-beech-birch and Oak-hickory forest types; however, White-red-jack pine, spruce-fir, and aspen-birch are also relatively dominant. Young forests (1-20 years old) are just under ~10% of the area of the state and slightly declining. Middle-aged forests (20-80 years old) represent ~65% of the forest area and are also declining slightly. Mature forests (>80 years old) comprise ~25% of the forest area and are increasing (USDA Forest Service, 2021). Overall, natural vegetation cover decreased from 2006-2016. Non-native insects and diseases, weather extremes, and potential shifts to species ranges are some of the main threats and challenges facing Michigan forests, and are all expected to worsen with a changing climate. In particular, regeneration and other forest health concerns continue to grow in Michigan. Wildfire behavior, while highly variable, remains another area of concern from degradation of fire-adapted lands that may lead to increased risk of wildfire (Handler et al, 2014).

Forestry and the subsequent logging industries remain a key economic driver in Michigan. However, recent trends show that both industries are aging and practitioners are leaving the sector (Gc et al., 2020), leading to concerns about the future strength and viability of the workforce. As of 2022, the forestry, logging, and HWP industries employed 40,449 people with an economic impact of approximately $16.2 billion in direct output (Poudel, 2022). Additionally, Michigan forests serve as a key recreational activity for hunting, fishing, and other outdoor activities.

Michigan's forests are at a nexus for both climate change adaptation and mitigation. Forests in Michigan are situated at both the northern and southern extremes for several ecologically and economically important forest types and species. This report comes at a critical time to provide key insights and information to decision-makers about potential future ramifications of both management and policy decisions that directly and indirectly influence carbon storage and sequestration at the regional level.

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 Michigan 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 Michigan;

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

3) Scenario modeling with i) a growth and yield-based forest ecosystem model - the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3; Kurz et al. 2009) - parameterized for conditions in Michigan, ii) a customized harvested wood products dynamics model (CBM-HWP-MI) built using the Abstract Network Simulation Engine framework (ANSE; CFS 2024), iii) potential leakage factors applied to changing harvest rates, iv) displacement factors to evaluate substitution effects 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 Science

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 Michigan 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.

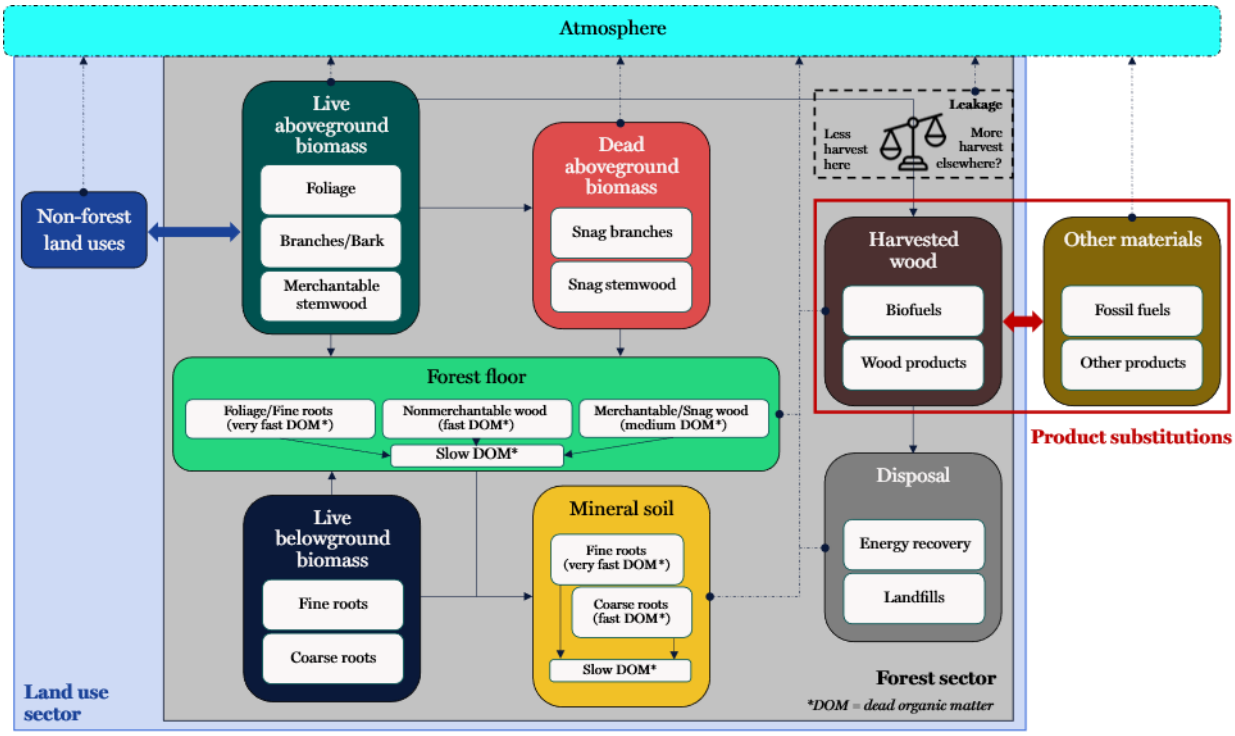


Figure 1. Simplified systems view of land uses and sectors influencing forest carbon stocks and sequestration. The forest sector (gray box) shows the forest carbon pools and transfers used in the CBM-CFS3 and CBM-HWP-MI models. For DOM (dead organic matter) pools, "very fast", "fast", "medium", and "slow" refer to various decomposition rates of dead organic matter in the forest ecosystem. Transfers between the land use sector (blue box) and the forest sector (gray box) represent land use changes (either forest loss or forest gain). Leakage (black dashed outline) represents the potential for harvest activities and associated emissions to leak outside of the accounting system boundaries (i.e. to the neighboring state) in response to decreased harvest within the system. Product substitutions (red outline) represent the use of harvested wood in place of other materials in the economy. Adapted from Kull et al. 2019 and Nabuurs et al. 2007.

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 effects 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 Michigan forests. We use the CBM-CFS3 for this study at the request of Michigan DNR Forest Resources Division staff, to expand on previous modeling efforts for state forests in the Lake States region.

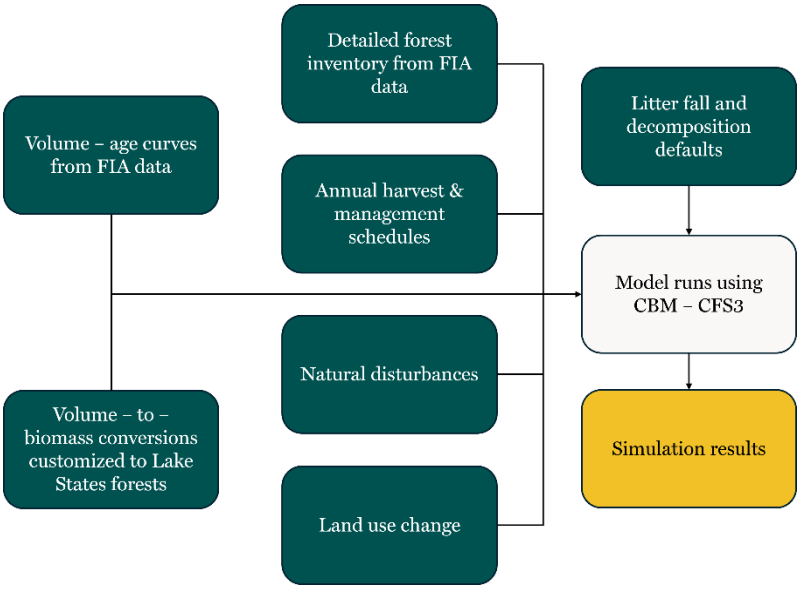


Figure 2. Modeling inputs and process for CBM-CFS3. Adapted from Kull et al. 2019.

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 tree species. Finally, process-based equations simulate dynamics between soil, dead organic matter, and forest processes like litter fall and decomposition in the model (Kurz et al. 2009).

Management and natural disturbance data are also necessary inputs – the CBM-CFS3 does not independently predict future events, but instead follows a user-determined schedule of annual management, disturbance, and land-use change (LUC) events (collectively termed disturbances) for the simulation period. For this analysis, our disturbance data come from FIA (USDA Forest Service 2019), Michigan Department of Natural Resources Fire Dashboard (MI DNR, 2023), and the National Land Cover Database (Wickham et al. 2021). See **Table 1** for BAU ecosystem disturbance parameters.

In addition to event schedules, the CBM-CFS3 utilizes disturbance matrices to represent specific impacts of disturbance events on mortality, the transfer of carbon between pools, the transfer of carbon to the forest products sector, and the emissions of carbon to the atmosphere (Kurz et al. 2009). See 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-MI 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-MI 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 Michigan 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-MI model. These carbon inputs are partitioned into various HWP streams based on current practices in the forest products sector in Michigan (**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 like mill residues can be used for fuel, additional commodity production, or remain unused, and fuelwood, which is burned for residential or industrial heating and energy production. Each domestic commodity produced from roundwood or other sources has a corresponding half-life that determines the longevity of the carbon in use before moving to a product retirement pathway (i.e., recycled, burned for energy, or sent to the landfill) and, eventually, being emitted back to the atmosphere. Emissions from landfilled wood and paper products are largely dictated by the proportion of their material assumed to be decomposable 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).

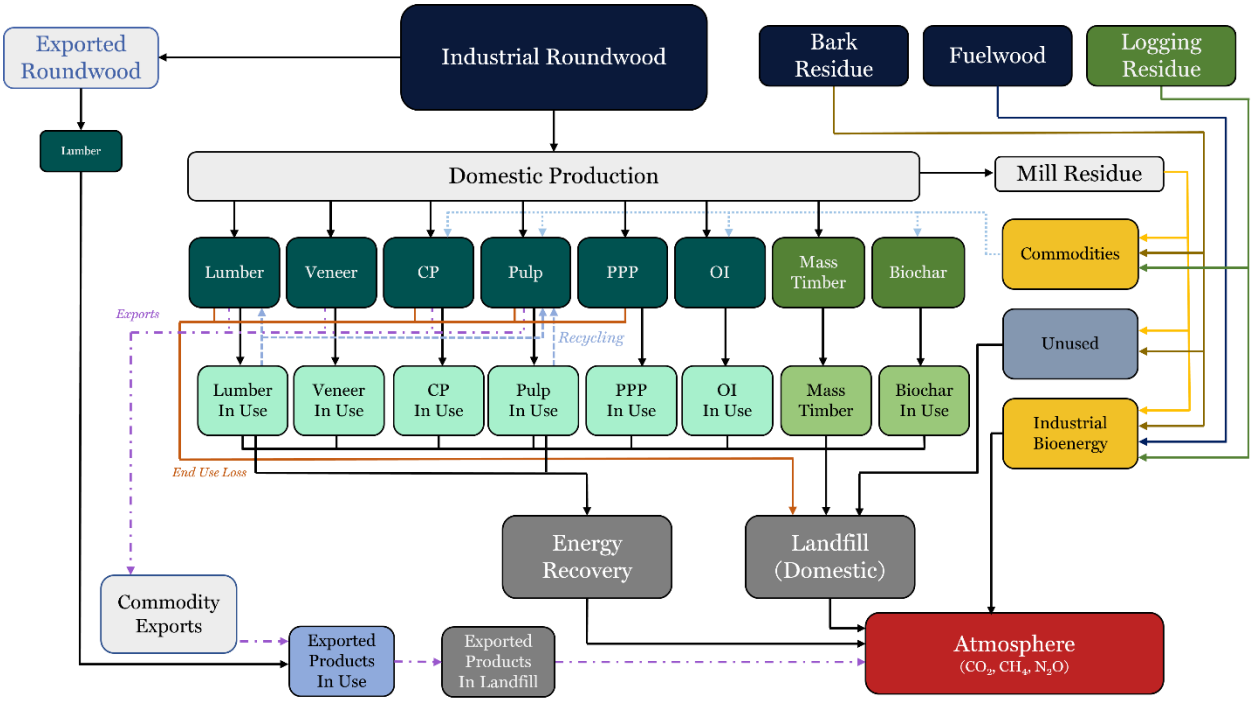


Figure 3. Pathways for carbon in harvested wood products in the CBM-HWP-MI model, which are used for analysis of the fate of harvested carbon in Michigan. CP stands for composite panels; PPP stands for poles posts and pilings, and OI stands for other industrial products. Logging residue inputs, biochar,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

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 substitutes 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 effects*. 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 effects, representing a reduction of atmospheric GHG emissions. Likewise, a decrease in harvest and commodity production may be associated with increased emissions in cases where more emissions-intensive products are assumed to replace the less emissions-intensive wood products. Substitution effects are applied only to saw log, composite

panel, mass timber, and bioenergy production. Note that substitution effects 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 effects 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 effects calculation methods.

To parameterize the CBM-HWP-MI 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 Michigan, 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 3** in the **Developing Modeling Scenarios** section for BAU HWP parameters and **Appendix** for more details on data and assumptions used in model parameterization.

Identifying Forest Management and Policy Priorities

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

- **Harvesting practices**. Forests in Michigan are managed for a range of ecological, social, and economic goals where tree cuttings and other silvicultural practices are a key tool to continue the provisioning of forest resources. Understanding the current conditions and future trends of timber management offers strategic guidance on the sustainable management of forests statewide. Recent evidence has suggested that many past silvicultural regimes no longer meet broader forest management goals of sustainably management forest under a changing climate and meeting future demands for timber (Kern et al., 2017; Walters et al., 2020; Helman et al., 2021), thus understanding future implications of current cutting regimes is paramount to achieving future sustainability priorities.

- **Forest health and regeneration**. Ensuring positive forest health outcomes requires management approaches that conserve or enhance biological diversity, promote ecosystem health and vitality, and foster net positive growth. Michigan has experienced challenges related to the regeneration of important species including sugar maple (Walters et al., 2020; Webster et al., 2018), white oak (Abrams, 2003; Hartman et al., 2005), and red pine (Drobyshev et al., 2008; Schilke et al., 2024), in addition to other regeneration challenges within northern hardwood forests (Walters et al., 2020; Henry and Walters, 2023a; Henry and Walters, 2023b).

- **Climate change impacts**. Michigan's forests are already coping with the negative effects of climate change. Michigan's forests are projected to become warmer and drier in the future, affecting current disturbance regimes and the distribution and composition of forest ecosystems (Handler et al., 2014). Spruce-fir, lowland deciduous, and northern hardwood forests are all projected to lose suitable habitat, with additional pressures from insect-related mortality events (Handler et al., 2014; Iverson et al., 2012; Peters et al., 2020). Furthermore, future growing conditions are expected to shift the current range and composition of Michigan's forests (Iverson et al., 2019; Peters et al., 2019), with some red pine and aspen stands already experiencing advanced regeneration of encroaching hardwood species.

- **Wood utilization and markets**. Wood products and their subsequent markets remain a vital part of Michigan's overall economic health and serve as an important source of financing to continue to fund sustainable forest management. Understanding downstream effects on forest products caused by a shift in forest management practices, e.g. shifts in the type, volume, and species being harvested, has important implications for Michigan's overall economy. Additionally, fostering innovative markets for harvest residues such as bioenergy and biochar (Bernes et al., 2016; Lehmann et al., 2021) and developing new markets for mass timber building systems (Pasternack et al., 2022; Nepal et al., 2024) offer additional economic, ecological and climate mitigation benefits.

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

Developing Modeling Scenarios

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

Business-as-Usual (BAU)

A core objective of this project is to estimate the differential carbon impacts of various forest management practices in Michigan. This requires the construction 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 burns), 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 quantification and projection of current practices into the future. Though this scenario construction does not account for changes in policies, climate, and economics, it is a useful exercise to explore how the continuation of current behaviors and disturbances may affect future forest dynamics and carbon cycling. This also allows for comparison to scenarios with different assumptions from BAU by estimating the difference in mitigation potential between scenarios.

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

Land-use change			
Forest loss	37,048.5 ac yr^{-1}	Forest Gain	40,535.1 ac yr^{-1}
Natural disturbances			
Fire (Low Intensity)	1,450.5 ac yr^{-1}	Abiotic (Low Severity)	3,061.6 ac yr^{-1}
Fire (Medium Intensity)	3790.6 ac yr^{-}	Abiotic (High Severity)	9,943.5 ac yr^{-1}
Fire (High Intensity)	161.0 ac yr^{-1}	Mortality (Low Severity < 10%)	27,871.0 ac yr^{-1}
Defoliator (Light Severity <10%)	110,955.1 ac yr^{-1}	Mortality (Moderate Severity <10-50%)	51,472.0 ac yr^{-1}
Defoliator (Moderate Severity 10 50%)	84,779.3 ac yr^{-1}	Mortality (High Severity >50%)	14,114.6 ac yr^{-1}
Defoliator (High Severity > 50%)	129,495.4 ac yr^{-1}		

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

Forest management practices			
Prescribed fire (~40% understory consumption)	838 ha yr^{-1}		
Federal forests			
Thinning (25% merchantable biomass removal)	11,840 tC yr^{-1} (21,12,419 ft^3 yr^{-1})	Clearcut (95% merchantable biomass removal)	80,556 tC yr^{-1} (13,685,082 ft^3 yr^{-1})
Group Selection (30% merchantable biomass removal)	3,721 tC yr^{-1} (549.284 ft^3 yr^{-1})	Single Tree Selection (30% merchantable biomass removal)	55,466 tC yr^{-1} (10,442,945 ft^3 yr^{-1})
Shelterwood / Seed Tree 50-70% merchantable biomass removal, 95% overstory removal)	4,644 tC yr^{-1} (673,698 ft^3 yr^{-1})		
State / County forests			
Thinning (25% merchantable biomass removal)	37,350 tC yr^{-1} (6,627,686 ft^3 yr^{-1})	Clearcut (95% merchantable biomass removal)	264,516 tC yr^{-1} (43,327,287 ft^3 yr^{-1})
Group Selection (30% merchantable biomass removal)	10,715 tC yr^{-1} (1,514,223 ft^3 yr^{-1})	Single Tree Selection (30% merchantable biomass removal)	82,690 tC yr^{-1} (12,182,935 ft^3 yr^{-1})
Shelterwood / Seed Tree 50-70% merchantable biomass removal, 95% overstory removal)	14,676 tC yr^{-1} (2,048,005 ft^3 yr^{-1})		
Private forests			
Thinning (25% merchantable biomass removal)	72,514 tC yr^{-1} (12,581,109 ft^3 yr^{-1})	Clearcut (95% merchantable biomass removal)	744,469 tC yr^{-1} (120,022,587 ft^3 yr^{-1})
Group Selection (30% merchantable biomass removal)	59,974 tC yr^{-1} (8,779,658 ft^3 yr^{-1})	Single Tree Selection (30% merchantable biomass removal)	606,885 tC yr^{-1} (89,623,093 ft^3 yr^{-1})
Shelterwood / Seed Tree 50-70% merchantable biomass removal, 95% overstory removal)	72,318 tC yr^{-1} (10,442,945 ft^3 yr^{-1})		

This analysis covers the period from 2021-2100, where historical averages from 2007-2019 (**Table 1**) are annualized and projected forward for 80 years. Note that this approach assumes the same acreage and intensity of disturbance each year, which does not allow for interannual variability (i.e., big fire, pest outbreak, or harvest years. BAU wood utilization, discard, and decay parameters (including landfill methane) are based on annualized historical averages from 1997-2020 (**Table 2**). See the **Systems-Based Forest Carbon Modeling** section for data sources and **Appendix** for methodology and additional scenario details.

Alternative Management, Disturbance, and HWP Scenarios

For this analysis, we construct alternative scenarios by changing default BAU parameters, representing potential changes in future management decisions or disturbance events. Scenarios relate to one specific practice or objective, where only one BAU practice is changed and the rest of the BAU remains the same. This allows us to examine the specific influences of each altered management practice on forest carbon dynamics and evaluate their relative power as climate mitigation actions. Our 13 scenarios cover a broad range of forest management, climate change impacts, and wood utilization practices, and are grouped into four categories representing similar management objectives and priorities: 1) Harvesting Practices; 2) Forest Health and Regeneration; 3) Climate Change Impacts; and 4) Wood Utilization and Markets (**Table 3**; see Appendix for additional scenario details).

While each individual scenario represents a potential alternative, these practices or impacts would rarely be implemented alone across the state. To better represent comprehensive forest climate action, we also construct a **Portfolio** scenario – an ensemble of practices that could be concurrently implemented on the landscape – to illustrate the cumulative potential of Michigan's forests to provide climate mitigation benefits.

We modeled two scenarios to assess the impacts of **Harvesting Practices** on carbon dynamics. The *Extended Rotations* scenario increases the minimum age of harvest for all even-aged managed forests by 10 years. The *Jack Pine Management* scenario decreases the minimum age of harvest in jack pine forest types by 20 years on state managed lands and 10 years on privately managed lands. The *Jack Pine Management* scenario also alters HWP dynamics, where proportions of jack pine biomass is used to generate bioenergy and pulp (for additional details see below).

Five scenarios were developed to assess the potential carbon implications of increasing **Forest Health and Regeneration**. The *Increase Regeneration: Oak & NHW* seeks to shift a proportion of single-tree-selection (STS) harvest systems for oak to clearcuts (45% of STS) and group selections (55% of STS harvests). Additionally, this scenario shifts 75% of STS harvests of northern hardwood (NHW) stands to clearcut. Alternatively, the *Increase Regeneration: NHW* scenario shifts 75% of STS harvests in NHW stands to group selection cuts. The *Increase Harvest Retention Size* scenario leaves behind an additional 10% of merchantable volume on site following clearcuts and seed tree cuts in all forest types. The final two scenarios in this category seek to boost regeneration through tree plantings. The *Enrichment Planting: NHW* scenario increases supplemental planting on understocked NHW stands by planting 7,000 ac yr^{-1}. The *Red Pine Planting* scenario increases the annual rate of red pine plantings by 2,843.3 ac yr^{-1}.

We developed two scenarios that seek to understand the potential implications of future **Climate Change Impacts**. The *Insect-Driven Mortality* scenario doubles the area affected by insect mortality events for spruce-fir, lowland deciduous, and northern hardwood forests. The *Cover-Type Transition* scenario models the conversion of aspen dominated stands through natural successional processes, assuming some level of advanced regeneration is already observed. This scenario transitions 263 acres of aspen to red pine and 4,934 acres of aspen to either lowland spruce/fir, oak mix, or NHW forests per year.

We developed four scenarios aimed at assessing the impact of **Wood Utilization and Markets** on carbon sequestration and storage, particularly in the HWP sector. One of these, the *Mass Timber* scenario, used BAU ecosystem assumptions paired with alternate HWP assumptions where 5% of the softwood roundwood that would normally be allocated toward pulp was instead allocated toward the production of mass timber (**Table 3**), thereby altering product retirement and landfill emissions, as well as substitution effects.

For the latter three HWP scenarios, ecosystem parameters were adjusted along with HWP model parameters. In each one, additional wood which would otherwise be left in the forest as coarse woody debris was removed during the harvest process and sent to the HWP sector. On average, this volume constituted 3% (53,468 tC yr^{-1}) of the BAU harvest removal volume, and was allocated

to one of three products depending on the scenario. In the *Harvest Residue Utilization: Biochar* scenario, 100% of this additional harvest removal volume was allocated to biochar production. In the *Harvest Residue Utilization: Bioenergy* scenario, 100% of this additional harvest removal volume was allocated to bioenergy production (with an assumed 60%-40% split between electricity and combined heat and power production). Finally, in the *Harvest Residue Utilization: BAU* scenario, this additional harvest removal volume was allocated identically to all other HWP inputs (i.e. using the BAU HWP assumption: **Table 2**).

We also developed a unique set of HWP assumptions for the *Jack Pine Management* scenario (see above for associated ecosystem parameter modifications). In this scenario, shorter rotation lengths to maintain younger stands for Kirtland warbler habitat led to an average of 1,663 tC yr^{-1} of additional harvest. From 2021-2030, this additional harvest is allocated 50% toward bioenergy production (with an assumed 60%-40% split between electricity and combined heat and power production), 25% toward mastication (modeled as a direct input to the landfill), and 25% toward pulp. From 2031-2050, this ratio shifts to 40% mastication and 60% pulp. From 2051-2100, 100% of the additional removals on Kirtland warbler habitat are allocated toward pulp. All other removals are processed using the BAU HWP assumptions (**Table 2**).

For the *Mass Timber, Harvest Residue Utilization: Biochar, Harvest Residue Utilization: Bioenergy,* and *Jack Pine Management* scenarios, novel product half-lives and/or substitution effects were calculated and applied to softwood mass timber, biochar, and bioenergy, respectively. See **Appendix** for additional scenario details.

Table 2. Michigan BAU HWP parameters. Values are based on 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	76.78%	Industrial Roundwood	73.44%
Fuelwood	8.85%	Fuelwood	12.28%
Bark Residue	14.37%	Bark Residue	14.28%
Roundwood exports			
Softwood exports	0%	Hardwood exports	0.14%
Commodity distribution (proportion of carbon distributed to various commodities)			
Softwood commodities			
Lumber	17.39%	Composite Panels from mill residue	12.45%
Veneer	0.11%	Unused mill residue	0.02%
Composite Panels	6.42%	Industrial Bioenergy from bark residue	12.16%
Pulp	26.08%	Other Industrial from bark residue	2.52%
Post, Poles, Pilings	7.63%	Composite Panels bark residue	0.90%
Other Industrial	1.73%	Unused bark residue	0.21%
Industrial Bioenergy from mill residue	8.41%	Lumber from exported roundwood	0%
Other Industrial from mill residue	3.99%		

Table 2, cont. Michigan BAU HWP parameters. Values are based on 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)			
Hardwood commodities			
Lumber	21.11%	Composite Panels from mill residue	3.37%
Veneer	0.71%	Unused mill residue	0.097%
Composite Panels	13.94%	Industrial Bioenergy from bark residue	11.05%
Pulp	29.49%	Other Industrial from bark residue	3.67%
Post, Poles, Pilings	0%	Composite Panels bark residue	1.32%
Other Industrial	3.06%	Unused bark residue	0.11%
Industrial Bioenergy from mill residue	3.63%	Lumber from exported roundwood	0.18%
Other Industrial from mill residue	4.36%		
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

Table 3. Ecosystem and wood utilization scenario parameters for Michigan. 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 a † symbol. All carbon measurements are in metric tons (tC). See ***Appendix*** *for assumptions and data sources.*

Harvesting Practices

Scenario Name	Objective	Parameter to Change	Parameter value change	Scenario impact, 2021-2100
† Extended Rotations	Increase average harvest age of stands to increase carbon stocks	Minimum age of allowable harvest	+10 years on all even-aged managed systems	Average age of even-age harvest: 74 years → 82 years
*Jack Pine Management	Decrease average harvest age of jack pine stands and send jack pine carbon to a portfolio of commodities	Minimum age of allowable harvest	-20 years on state managed lands	State managed jack pine rotations: 50 years → 30 years
			-10 years on private managed lands	Private managed jack pine rotations: 60 years → 50 years
		HWP allocation for wood removed from jack pine stands	2021 -2030: 50% bioenergy, 25% masticated (direct to landfill), 25% pulp	+1,663tC yr^{-1} of additional softwood inputs to HWP from jack pine
			2031 -2050: 60% pulp, 40% masticated (direct to landfill)	
			2051-2100: 100% pulp	

Forest Health and Regeneration

Scenario Name	Objective	Parameter to Change	Parameter value change	Scenario impact, 2021-2100
† Increase Regeneration: Oak & NHW	Promote oak and NHW regeneration from increasing harvest intensity	Harvest intensity rate	Shift 45% of single-tree-selection harvest of oak to clearcut (+200% increase in harvest intensity)	+ 192.7 ac yr^{-1} clearcut harvest with increased regeneration
			Shift 55% of single-tree-selection harvest of oak to group selection (+17% increase in harvest intensity)	+ 437.2 ac yr^{-1} group selection cuttings with increased regeneration
			Shift 75% of single-tree-selection harvest of NWH to clearcut (+200% increase in harvest intensity)	+ 19,889.3 ac yr^{-1} clearcut harvest with increased regeneration
† Increase Regeneration: NHW	Promote regeneration of NHW from increasing harvest intensity	Harvest intensity rate	Shift 75% of single-tree-selection harvest of NHW to group selection (+17% increase in harvest intensity)	+ 42,227.8 ac yr^{-1} group selection cuttings with increased regeneration
Increase Harvest Retention Size	Increase reserve size following clearcuts and seed tree cuts	Harvest intensity rate	100% increase in merchantable volume left standing	Merchantable volume left standing: 5% → 10%
† Enrichment Planting: NHW	Increase supplemental planting to restock understocked stands	Annual rate of supplemental planting in NHW	+7,000 ac yr^{-1}	+ 560,039 ac planted
† Red Pine Planting	Increase red pine planting targets	Annual rate of red pine planting	+2,834.3 ac yr^{-1}	+ 226,744 ac planted

Table 3, cont. Ecosystem and wood utilization scenario parameters for Michigan. 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 a † symbol. All carbon measurements are in metric tons (tC). See ***Appendix*** *for assumptions and data sources.*

Climate change impacts

Scenario Name	Objective	Parameter to Change	Parameter value change	Scenario impact, 2021-2100
Insect-Driven Mortality	Increase the effects of mortality caused by insect outbreaks	Annual area of forest affected by insect disturbance	+100% increase in spruce-fir area affected +100% increase in lowland deciduous area affected +100% increase in NHW area affected	+ 4589 ac yr^{-1} insect outbreaks in spruce-fir forests + 398 ac yr^{-1} insect outbreaks in lowland deciduous forests + 1,129 ac yr^{-1} insect outbreaks in NHW forests
Cover-Type Transition	Increase rate of aspen stands that transition to Lowland spruce/fir, oak mix, and NWH stands where advanced regeneration has already occurred	Annual rate of cover type transitions	1% of eligible aspen stands on state and private managed lands	4835 ac yr^{-1} transitioned into lowland spruce/fir, oak mix, or NWH stands

Wood utilization and markets

Scenario Name	Objective	Parameter to Change	Parameter value change	Scenario impact, 2021-2100
Harvest Residue Utilization: BAU	Increase harvest residues sent to HWP from clearcuts	Rate of harvest residuals left on site post cutting	Assume harvest residue is treated as any other HWP input	On average 4,672 tC yr^{-1} of additional softwood inputs and 48,796 tC $yr^{-1}$of additional hardwood from harvest residue
Harvest Residue Utilization: Bioenergy	Increase harvest residues sent to HWP from clearcuts	Rate of harvest residuals left on site post cutting HWP allocation for carbon removed from logging residue	Assume harvest residue goes 100% toward bioenergy (60% electricity and 40% CHP)	On average 4,672 tC yr^{-1} of additional softwood inputs and 48,796 tC $yr^{-1}$of additional hardwood from harvest residue
Harvest Residue Utilization: Biochar	Increase harvest residues sent to HWP from clearcuts	Rate of harvest residuals left on site post cutting HWP allocation for carbon removed from logging residue	Assume harvest residue goes 100% toward biochar production	On average 4,672 tC yr^{-1} of additional softwood inputs and 48,796 tC $yr^{-1}$of additional hardwood from harvest residue
Mass Timber	Add mass timber as a novel product category	No change in HWP inputs Change HWP allocation for carbon from softwood harvest	Softwood pulp production: 57.07% -> 52.07% Softwood Mass Timber production: 0% -> 5%	

Table 3, cont. Ecosystem and wood utilization scenario parameters for Michigan. 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 a † symbol. All carbon measurements are in metric tons (tC). See ***Appendix*** *for assumptions and data sources.*

Portfolio				
Scenario Name	**Objective**	**Parameter to Change**	**Parameter value change**	**Scenario impact, 2021-2100**
Portfolio	Ensemble of concurrent scenarios (marked with † above) to illustrate potential for Michigan to fully leverage its forests as natural climate solutions	Minimum age of allowable harvest	+10 years on all even aged managed systems	Average age of even-age harvest: 74 years → 82 years
		Harvest intensity rate	Shift 45% of single-tree-selection harvest of oak to clearcut (+200% increase in harvest intensity)	+105 ha yr^{-1} clearcut harvest with increased regeneration
			Shift 55% of single-tree-selection harvest of oak to group selection (+17% increase in harvest intensity)	+156 ha yr^{-1} group selection cuttings with increased regeneration
			Shift 37.5% of single-tree-selection harvest of NWH to clearcut (+200% increase in harvest intensity)	+ 4990 ha yr^{-1} clearcut harvest with increased regeneration
			Shift 37.5% of single-tree-selection harvest of NWH to group selection (+17% increase in harvest intensity)	+ 7760 ha yr^{-1} group selection cuttings with increased regeneration
		Annual rate of supplemental planting in NWH	+2833 ha $year^{-1}$	+ 226640 ha planted NHW
		Annual rate of red pine planting	+1147 ha $year^{-1}$	+ 91760 ha planted red 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 Michigan and will continue to do so with thoughtful implementation of CFS management strategies. As discussed in the **Forest Carbon Science** section above, this mitigation potential can be influenced by both carbon sequestration and carbon storage dynamics across the landscape, and climate-smart practices strive to balance both factors. Our results indicate that favoring one of these attributes over the other comes with important tradeoffs that can significantly impact future forest health, resilience, and climate mitigation potential.

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

In the BAU scenario, Michigan's forests remain a net carbon sink from 2021-2100, represented by a net ecosystem carbon flux below zero (**Figure 4a**). *Net ecosystem carbon flux (NECF)* refers to the yearly net 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 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).

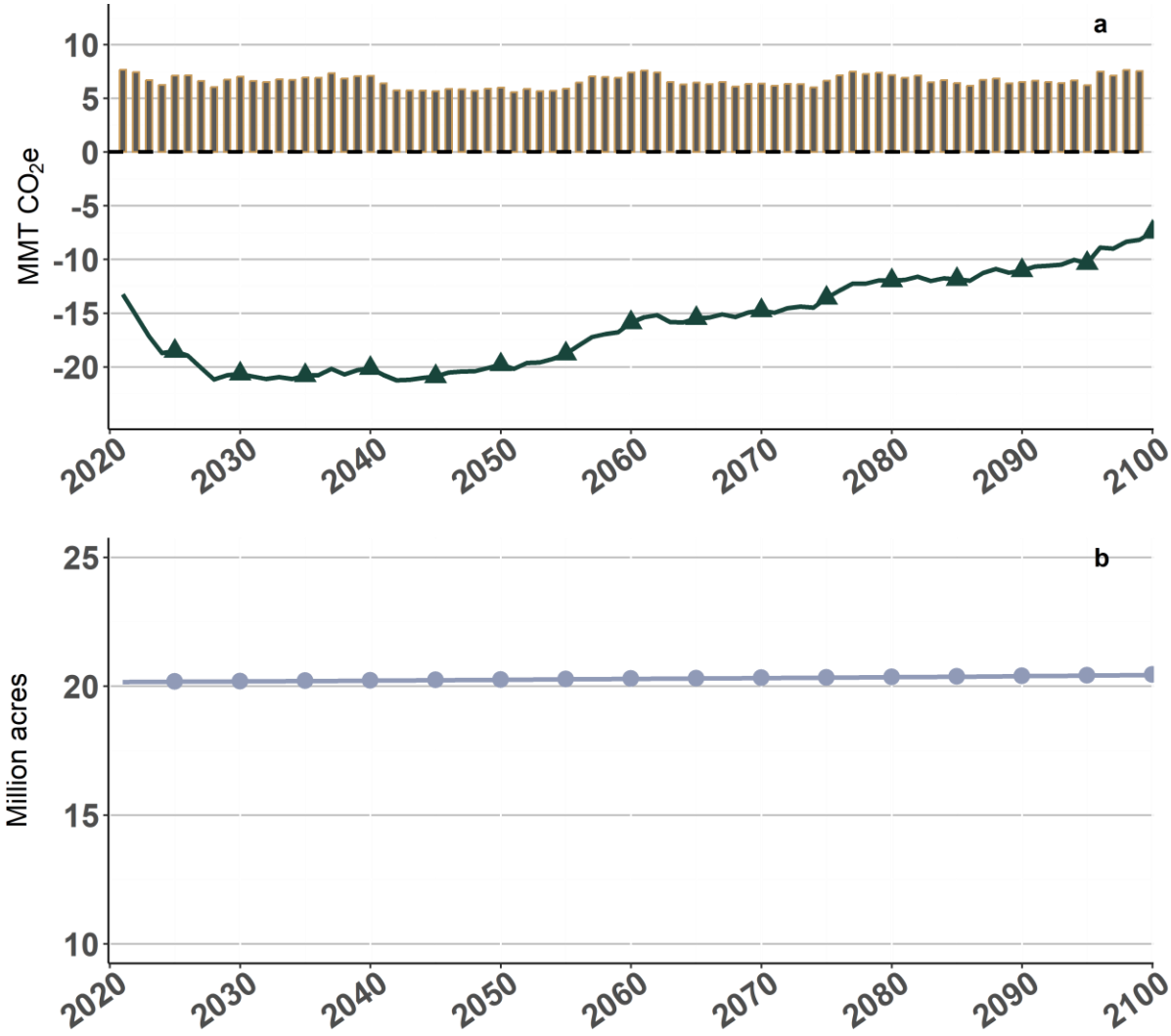


Figure 4. BAU scenario results showing a) annual net ecosystem carbon flux (green line) in MMT CO_2e yr^{-1} and transfers to HWP (dark brown bars) in MMT CO_2e yr^{-1}, and b) forest area (million acres) from 2020-2100. Net ecosystem carbon flux refers to the net yearly sequestration of carbon by forests after accounting for decomposition and wood product removals. Negative numbers for net ecosystem carbon flux represent a net carbon sink.

The strength of this BAU carbon sink increased at the beginning of the simulation until 2028, after which it remained relatively stable, gradually weakening beginning in 2045 due to a slight trend of increasing annual ecosystem emissions until the end of the century. Across the 80-year simulated period, NECF was on average -15.95 MMT CO_2e yr^{-1} after accounting for the 6.63 MMT CO_2e yr^{-1} which is transferred to HWP. Ecosystem carbon stocks per acre increased throughout the duration of the simulation (**Figure 5**), indicating that the carbon density of forests increased (i.e., growth outpaced mortality, removals, and LUC) with an additional increase in total forest area (**Figure**

4b). Carbon density increased the most in aboveground biomass, with relatively smaller amounts of increasing carbon density in other pools.

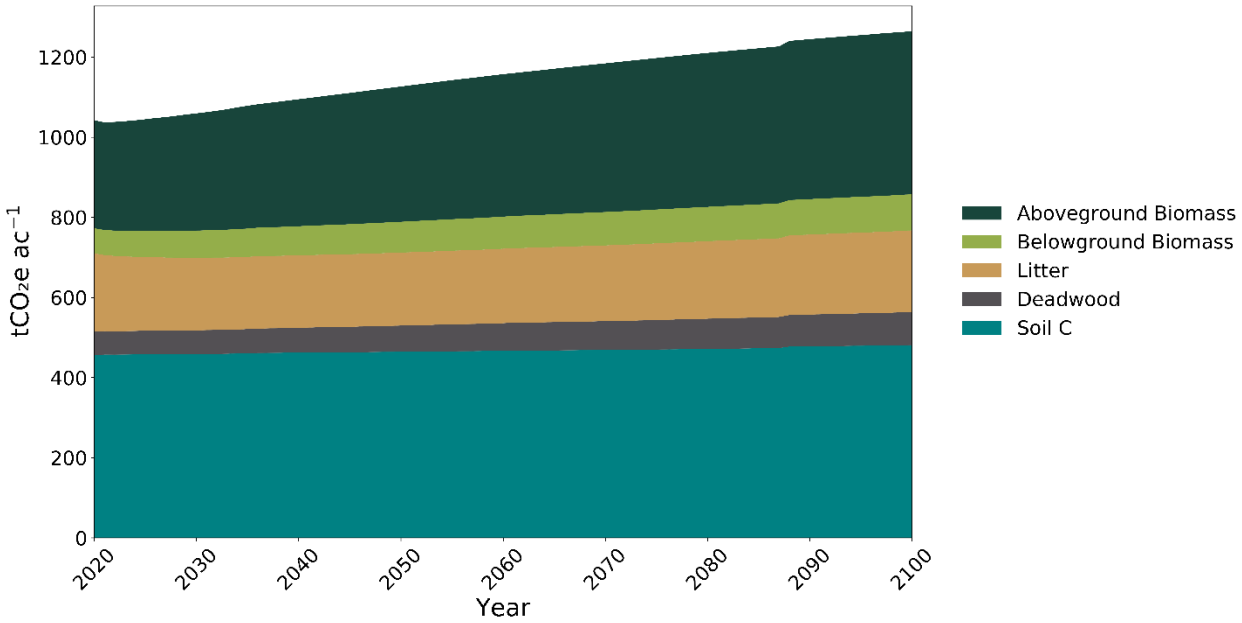


Figure 5. BAU scenario results for per acre carbon stocks (tCO2e ac^{-1}) in IPCC reporting pools from 2020-2100. Positive numbers represent accruing carbon stocks. Litter layer includes carbon in the L horizon, fine and small woody debris including dead coarse roots in the forest floor, and carbon in the F, H, and O horizons (i.e., soil carbon above the mineral layer)

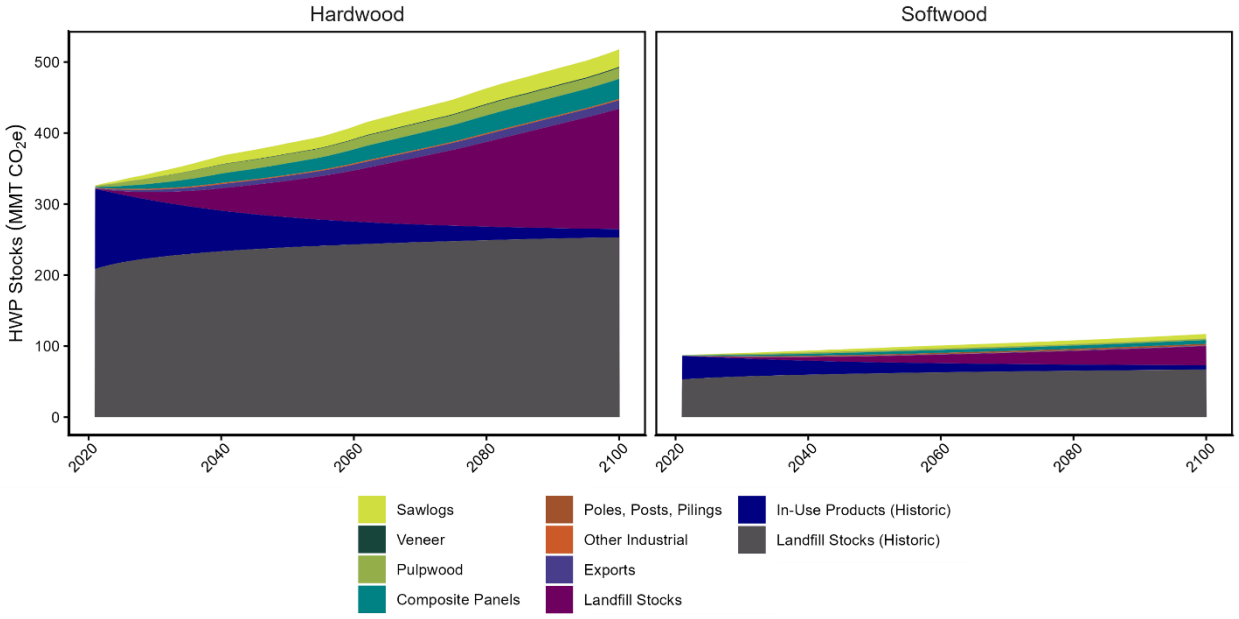


Figure 6. HWP carbon stocks (MMT CO2e) by primary product for hardwood and softwood from 2021-2100. Positive numbers denote accruing carbon stocks. Historic in-use stocks and landfill stocks represent materials cut prior to the beginning of the simulation. Historic in-use stocks transfer to historic in-use landfill stocks when they reach end of life.

The amount of carbon transferred to HWP also remained stable, 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 S2, Figure 4a**). Assuming static future HWP demand, Michigan's forests will be able to maintain current timber supplies while staying a net carbon sink through 2100. Carbon stocks in both hardwood and softwood HWP increased over time in the BAU scenario (**Figure 6**), though hardwood stocks increased by a larger extent than softwood stocks (+59% for hardwood stocks vs +34% for softwood stocks) and hardwood stocks were on average 4.1 times larger than softwood stocks. By 2100, HWP carbon storage is dominated by the landfill categories, comprising 82% and 80% of hardwood and softwood stocks respectively (**Figure 6**). Of the in-use categories, the largest components are lumber (33% of total in-use hardwood, and 28% of total in-use softwood stocks in 2100), and composite panels (32% of total in-use hardwood, and 24% of total in-use softwood stocks in 2100).

HWP carbon emissions for both hardwood and softwood species declined over the simulation, dropping to 82% of 2020 levels for hardwoods in 2100, and 57% of 2020 levels for softwood in 2100. Products produced and in landfills prior to 2020 shifted from being the dominant source of emissions (70% and 75% of hardwood and softwood HWP emissions, respectively, in 2021) to being the smallest source of emissions (6% and 11% of hardwood and softwood HWP emissions, respectively, in 2100), replaced by contemporary landfill emissions (48% and 46% 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) were also a large emission category (representing 38% and 34% 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, the net of

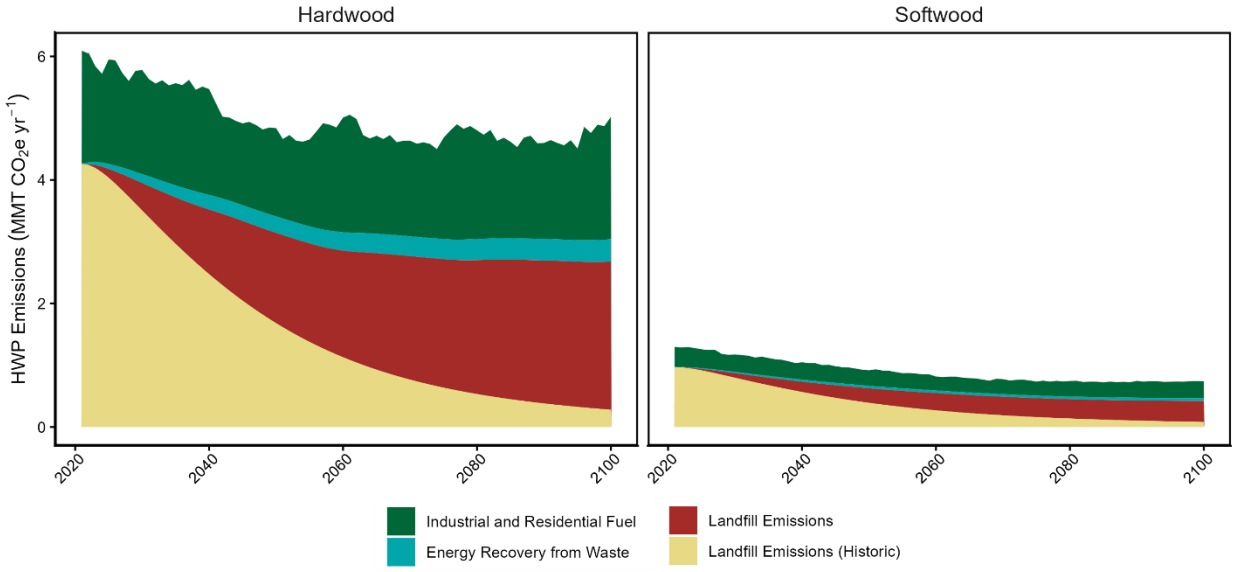


Figure 7. Annual HWP emissions distribution (MMT CO_2e yr^{-1}) for hardwood and softwood from 2021-2100 for the BAU scenario. Emissions are the result of woody material that is cut and removed from the forest and do not include any residues or other materials left on site. Historic landfill emissions 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.

HWP inputs minus HWP emissions, accrued additional carbon (-0.73 MMT CO_2e yr^{-1}on average) meaning that HWPs represent a growing carbon storage pool for Michigan.

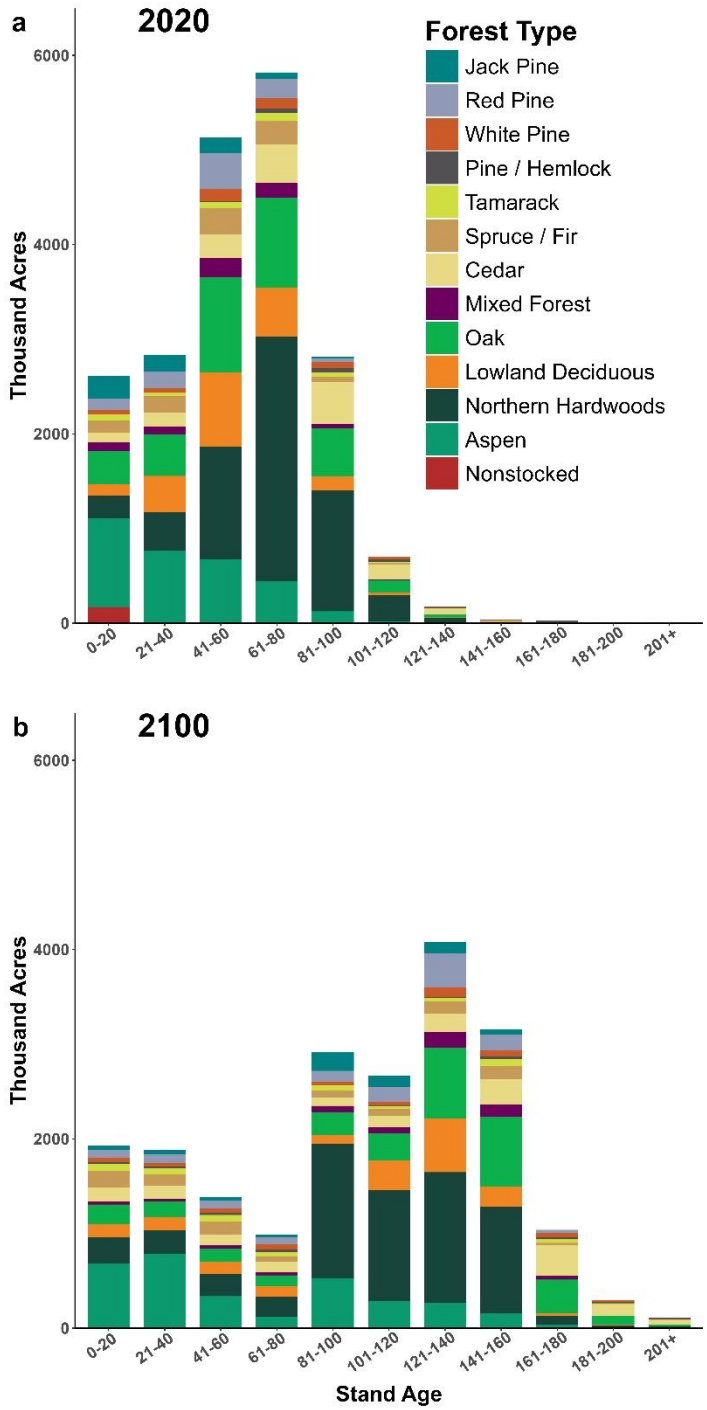


Figure 8. BAU scenario age-class distribution by forest type in a) 2020 and b) 2100.

Forest age and other age-dependent successional dynamics are key factors influencing both current and future net carbon balances. In 2020, roughly 81.3% of Michigan's forest area was younger than 80 years (**Figure 8a**), indicating strong near-term mitigation potential since younger forests typically accumulate carbon more rapidly. By 2100, however, only about 30.2% of forestland will remain under 80 years old, while an additional 42.5% will exceed 120 years, reflecting a significant shift in age demographics.

As forests mature, their productivity per unit area generally declines (Coomes et al., 2012). If this aging trend continues, overall productivity could decrease, potentially weakening the carbon sink, though our BAU projections indicate that overall growth will still outpace emissions from decomposition and removals, meaning that the forest is not at immediate risk for becoming a net carbon source. The current age-class distribution at the state level largely reflects historical land-use legacies, including agricultural clearing and subsequent land abandonment. By 2100, under the BAU scenario (**Figure 8b**), this distribution shifts toward a more balanced structure, with forests increasingly aging into mature classes (escaping both natural or anthropogenic disturbances) while younger age classes stabilize.

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**). Eight scenarios sequester and store additional carbon (have a lower NECF) as compared to BAU: *Enrichment Planting: NHW*, the *Portfolio*, *Increased Regeneration: Oak & NHW, Increased Harvest Retention Size, Increased Regeneration: NHW, Extended Rotations, Red Pine Planting,* and *Cover-Type Transition.* The remaining three scenarios - *Jack Pine Management*, *Insect-Driven Mortality,* and *Harvest Residue Utilization: BAU* - sequester and store less carbon (have a higher NECF) relative to BAU. It is important to note that the reduction in carbon storage for scenarios with increased levels of harvest residue utilization, including *Harvest Residue Utilization: BAU,* is primarily driven by the fact that these additional removals appear as losses of carbon from the forest when they are in fact transfers to the HWP sector. While this ultimately means that decomposition emissions are lower for the harvest residue scenarios

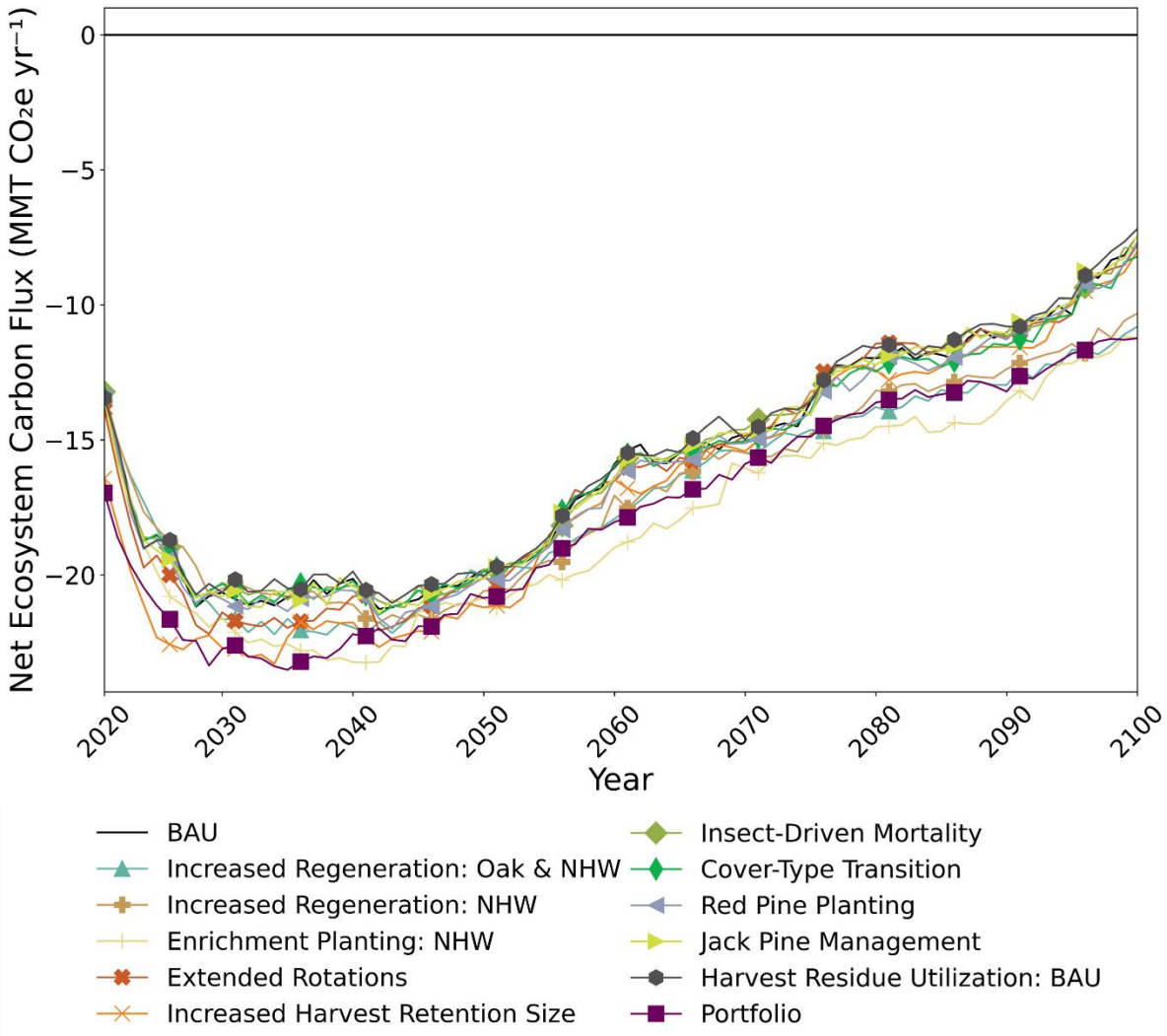


Figure 9. Annual net ecosystem carbon flux for selected scenarios, 2020-2100. Net ecosystem carbon flux includes net growth minus emissions from respiration and decomposition and all disturbance related emissions including carbon transferred to HWP. Negative values denote carbon sequestration (a net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

than for the BAU scenario, the net transfer of carbon means less carbon storage in the forest ecosystem and a higher NECF value. Other important trends to highlight include the *Cover-Type Transition* scenario, initially performing worse, but eventually switching to increased mitigation potential as compared to BAU as forests continue to mature, sequestering additional carbon. All scenarios also exhibit a similar pattern to BAU of increasing annual sequestration until the mid-2030's before sequestration declines, and in some cases weakens past 2020 levels by 2100. As in the BAU simulation, aging forests and increases in annual ecosystem emissions are the primary drivers of this decline of sequestration rates through time.

Annual Mitigation Potential in Forests and Forest Products Sector

When considering both forests and the forest product sector, all scenarios remain a net carbon sink from 2021-2100, indicated by a net carbon balance less than zero (**Figure 10**). *Net carbon balance*

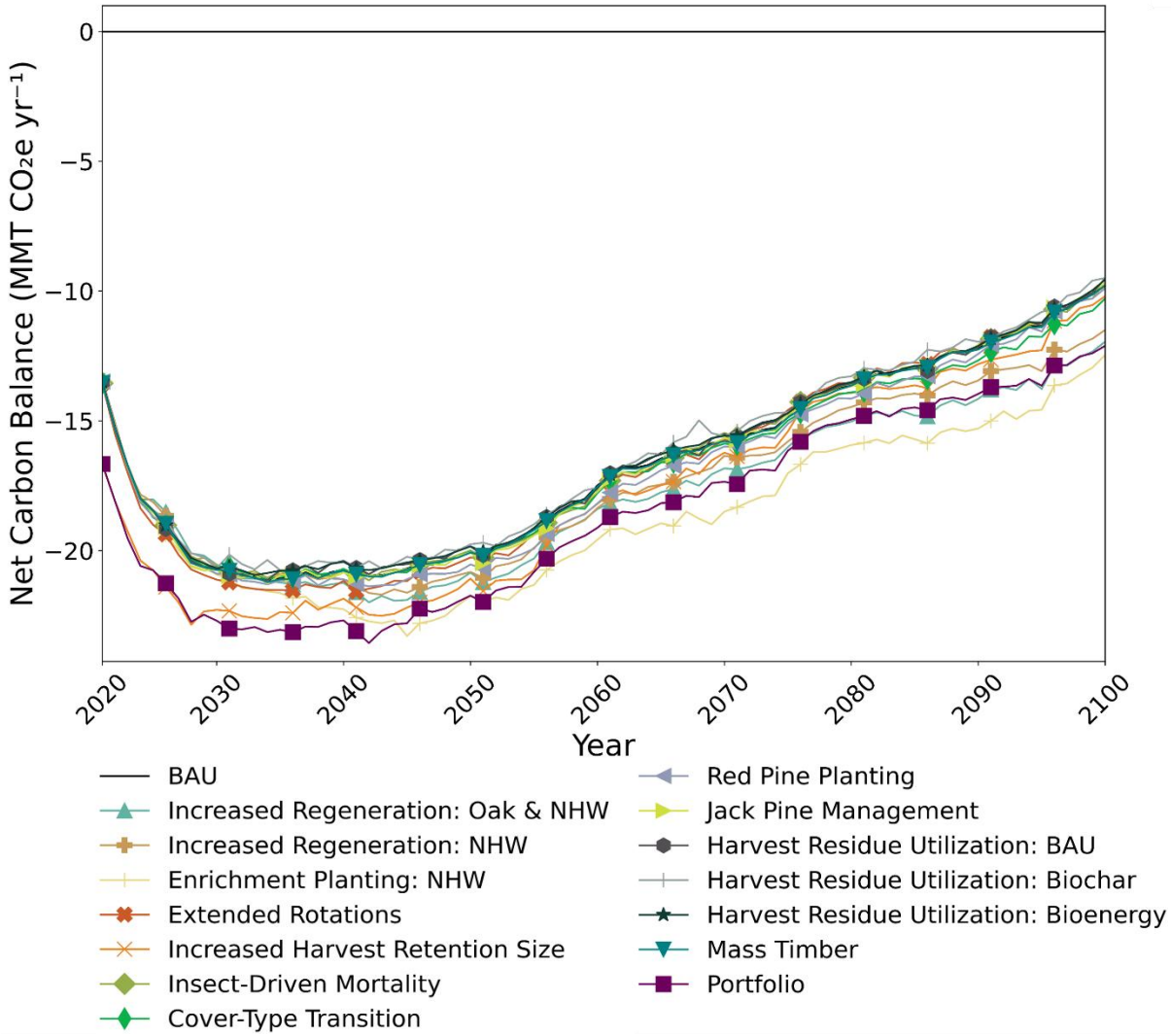


Figure 10. Annual net carbon balance for selected scenarios (2021-2100). Net carbon balance includes net ecosystem carbon flux in the forest, transfers to HWP, emissions from wood products in use and in landfills, substitution effects in years where harvest is different than BAU, and leakage in years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

includes net ecosystem carbon flux in the forest, transfers to HWP, emissions from wood products in use and in landfills, substitution effects (which can be increase or decrease emissions) 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).

The *Portfolio* scenario, which includes *Extended Rotations*, *Increase Regeneration: Oak & NHW*, *Enrichment Planting: NHW*, and *Red Pine Planting*, presents the best opportunity for increasing annual forest carbon sink strength, with an average annual net carbon balance 14% stronger than BAU by 2030, 11% stronger by 2050, and 12% stronger by 2100 (**Figure 10**). These values help boost the annual net carbon balance to +136.9% of its current (2021) level in 2030. However, due to a decline in net carbon balance across all scenarios, this value drops to 73% of the current (2021) level in 2100. The *Enrichment Planting: NHW* scenario also provides opportunities for additional climate mitigation potential, matching and surpassing the *Portfolio* scenario in annual net carbon balance from about 2050 to the end of the century (**Figure 10**). This suggests that increasing supplemental planting to restock understocked northern hardwood stands provides significant long-term mitigation potential, but that this benefit, which arises from increased growth and net primary productivity in these stands, can take years to decades to fully manifest. Other scenarios with an improved net carbon balance relative to BAU include both increased regeneration scenarios (*Increased Regeneration: NHW*, *Increased Regeneration: Oak & NHW),* as well as the *Increased Harvest Retention Size* and *Red Pine Planting* 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 *Harvest Residue Utilization: Bioenergy* scenario sequesters and stores 1.6% less carbon (+23.0 MMT CO_2e) than BAU, while the *Enrichment Planting: NHW* scenario sequesters and stores 12% more carbon (−157.2 MMT CO_2e) than BAU over the same timeframe (**Figure 11**). This range illustrates the potential spread of carbon outcomes for Michigan's forests and forest products sector, depending on future management decisions. The *Portfolio* scenario, which has the second lowest cumulative net carbon balance (11% lower or -149.5 MMT CO_2e, relative to BAU) demonstrates the potential for future climate mitigation potential from implementing multiple concurrent climate-smart forest management practices in Michigan. The majority of the remaining scenarios modeled fall within +9 to −25 MMT CO_2e (0.7% more to 1.1% less) of cumulative net carbon balance relative to BAU by 2100, indicating more modest climate mitigation impacts of these scenarios when implemented alone.

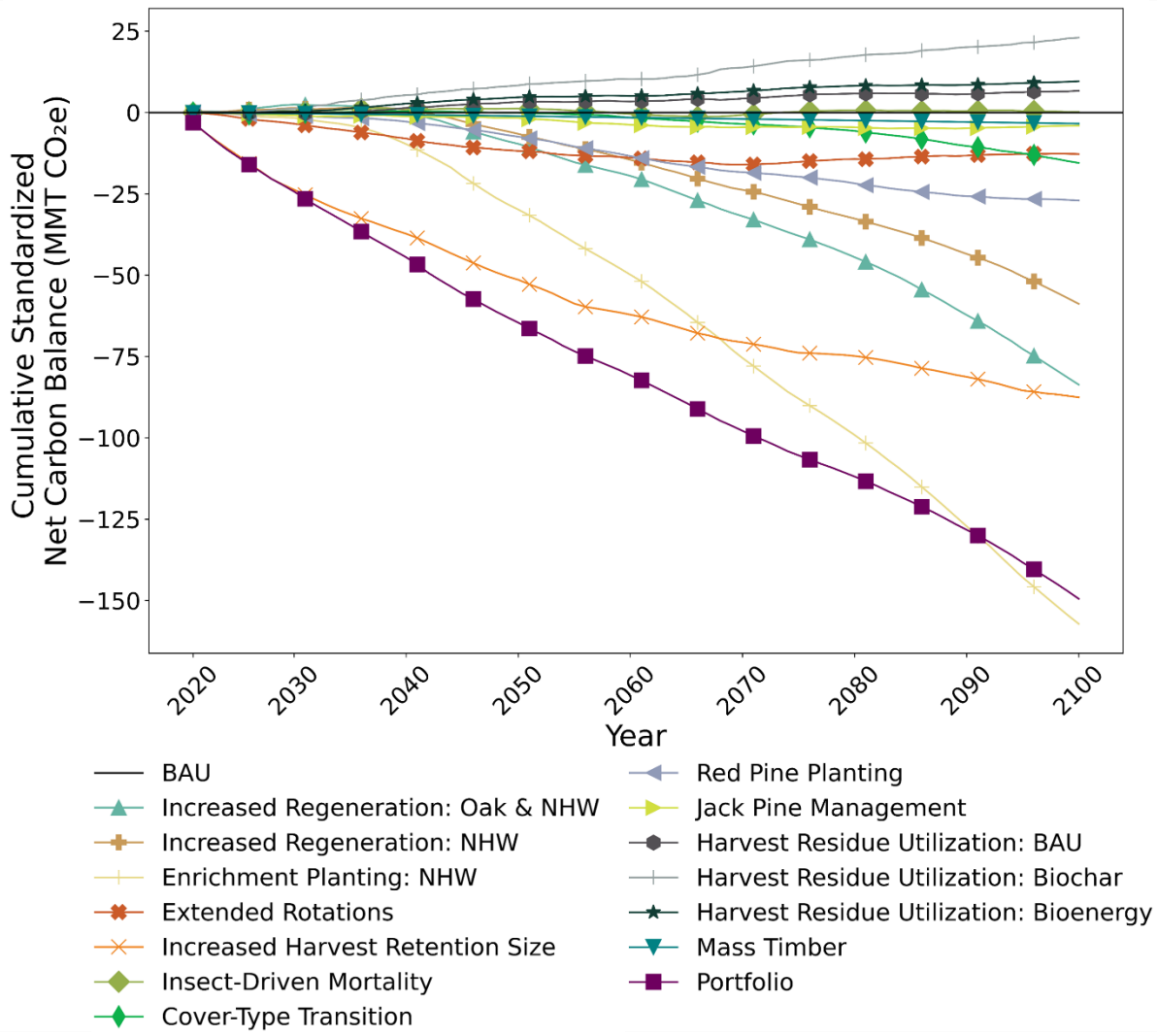


Figure 11. Cumulative net carbon balance for selected scenarios (2021-2100) standardized to BAU. Net carbon balance includes net ecosystem carbon flux in the forest, transfers to HWP, emissions from wood products in use and in landfills, substitution effects in years where harvest is different than BAU, 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).

We can further examine the components of cumulative net carbon balance 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 a large amount of additional carbon in the forest ecosystem relative to BAU (-22.7 MMT CO_2e) by 2100, but also has a substantial amount of forgone HWP transfers (+13.6 MMT CO_2e) and leakage (+7.1 MMT CO_2e) which almost fully offset the net gain in carbon in the forest ecosystem (**Figure 12**). That said, the *Extended Rotations* scenario also benefits from cumulative product substitution (-2.1 MMT CO_2e) where across all years, the production of certain HWP commodities exceeds BAU levels, leading to displaced emissions from using wood to in place of more emissions-intensive alternatives. Further, because of reduced HWP transfers, cumulative HWP emissions are lower

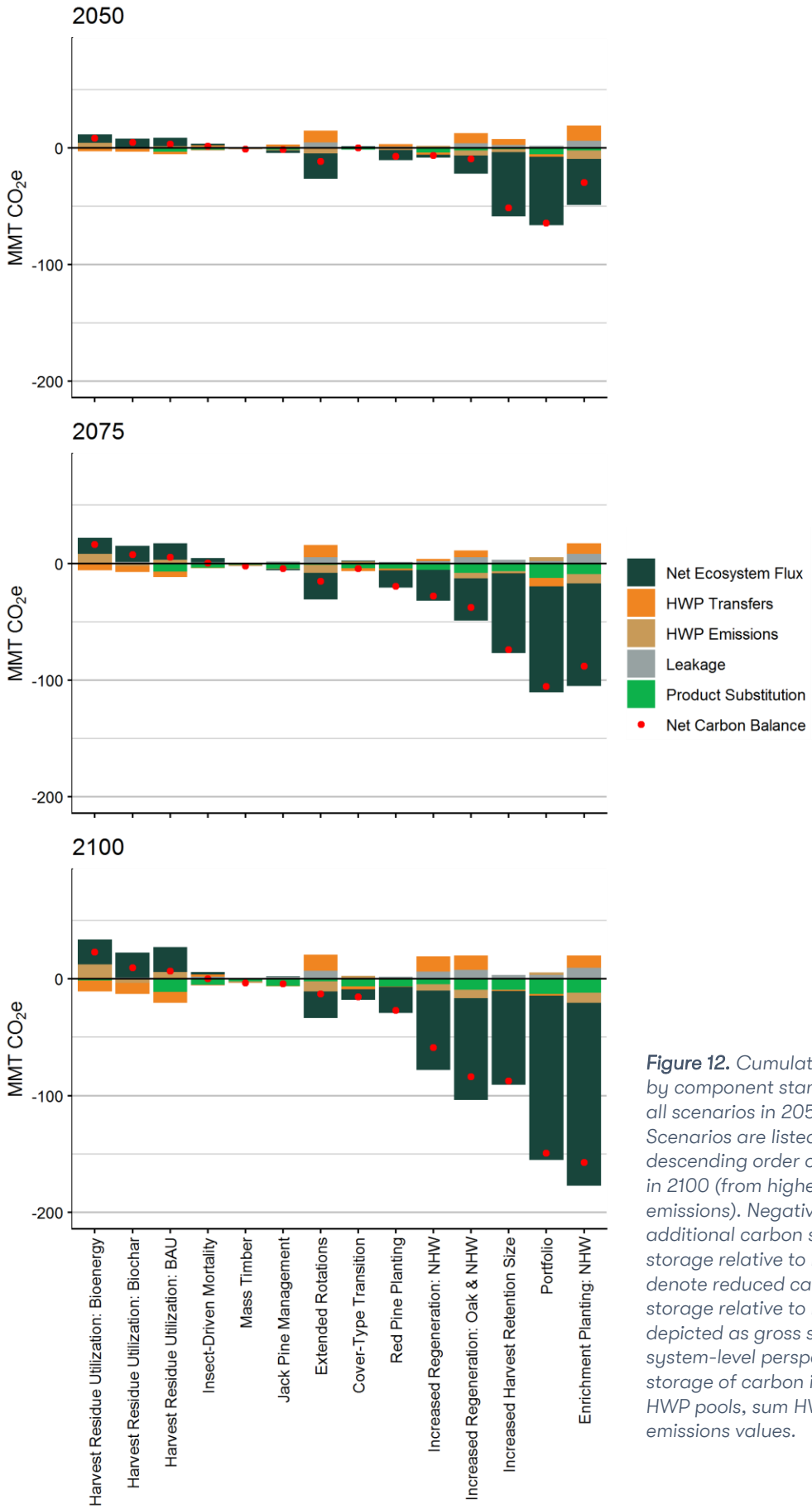


Figure 12. Cumulative mitigation potential by component standardized to BAUs for all scenarios in 2050, 2075, and 2100. Scenarios are listed from left to right in descending order of net carbon balance in 2100 (from higher emissions to lower emissions). Negative values denote additional carbon sequestration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

(-8.7 MMT CO_2e) relative to BAU (**Figure 12**). 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 stagnates and decreases (becomes less negative) from 2070 onwards (**Figure 11**), once the majority of harvest deferrals have ended. This difference amounts to a 1.9% (-11.8 MMT CO_2e), a 1.5% (-15.2 MMT CO_2e), and a 1.0% (−12.8 MMT CO_2e) lower cumulative net carbon balance (more carbon sequestered and stored) than BAU by 2050, 2075, and 2100, respectively (**Figure 12**).

The other scenario affecting harvest rotation lengths, the *Jack Pine Management* scenario, exhibits similar tradeoffs between ecosystem and HWP carbon, though to a much smaller degree because this scenario only targets a subset of total harvest (**Figure 11**). In the *Jack Pine Management* scenario, the average harvest age of jack pine stands is reduced as a mechanism to promote growth and regeneration in Kirtland's warbler habitat, with additional harvested material sent to bioenergy and pulp production. Through 2100, less carbon is stored in the forest ecosystem (+0.2 MMT CO_2e) and more carbon is transferred to HWP (-0.3 MMT CO_2e) relative to BAU, with a proportionally small amount of increased cumulative HWP emissions (+0.1 MMT CO_2e; **Figure 12**). The leakage and substitution effects for the *Jack Pine Management* scenario are much larger, with +1.9 MMT CO_2e of cumulative leakage and −5.9 MMT CO_2e of cumulative substitution (**Figure 12**). This occurs as annual harvest removals from the *Jack Pine Management* scenario are variable, higher than BAU in some years and lower than BAU in other years. Leakage only accumulates in one direction (always a net loss of carbon, i.e., a positive flux), while substitution effects can occur in either direction (i.e., fewer emissions the atmosphere in years where production of certain commodities exceeds BAU production or more emissions to the atmosphere in years when production is lower than BAU). Overall, the *Jack Pine Management* scenario leads to a higher level of harvest, and due to the allocation of this additional harvest toward bioenergy, substitution effects from displacing fossil fuels are larger than the loss of carbon to leakage. Collectively, these effects lead to a relatively moderate 0.2% decrease (−1.7 MMT CO_2e) in cumulative net carbon balance (more carbon sequestered and stored) relative to BAU by 2050, growing to 0.4% (−4.5 MMT CO_2e) by 2075, but falling to 0.3% (−4.1 MMT CO_2e) by 2100 (**Figure 12**).

Like the two altered-rotation scenarios, the three alternative harvest-regime scenarios (*Increase Regeneration: Oak & NHW*, *Increase Regeneration: NHW*, and *Increased Harvest Retention Size*) also exhibit tradeoffs between ecosystem and HWP carbon. Both variations of the *Increase Regeneration* scenario aim to promote forest regeneration by increasing harvest intensity, switching from single tree selection to group selection or clearcut style harvesting. By 2100, these changes in harvest regime lead to an accumulation of additional ecosystem carbon relative to BAU, -87.3 MMT CO_2e and −67.8 MMT CO_2e for the *Oak & NHW* and *NHW* only versions, respectively (**Figure 12**). Much of this increase is driven by higher growth rates in stands that have undergone regeneration harvests. However, despite increased harvest intensity, cumulative HWP transfers are lower than BAU (+12.3 MMT CO_2e for *Oak & NHW* and +12.7 MMT CO_2e for *NHW* only), which, in part, contributes to the accumulation of additional ecosystem carbon relative to BAU (**Figure 12**). Initially (through 2058), this reduction in harvest is concentrated in oak stands; by 2100, both oak and NHW stands show lower harvest levels, primarily because modeled age restrictions limit the eligible harvest area each year. As is the case when harvest volumes are reduced, cumulative HWP emissions are lower than BAU for both scenarios (-7.5 MMT CO_2e for *Oak & NHW* and -5.5 MMT CO_2e for *NHW* only), and both scenarios experience leakage (+7.9 MMT CO_2e for *Oak &*

NHW and +6.4 MMT CO_2e for *NHW* only; **Figure 12**). Although cumulative harvest volumes are lower than BAU, both scenarios include years when harvest and thus commodity production exceed BAU levels, resulting in reduced emissions due to substitution effects (-9.1 MMT CO_2e for *Oak & NHW* and -4.7 MMT CO_2e for *NHW* only; **Figure 12**). Overall, both *Increased Regeneration* scenarios sequester and store more carbon than BAU and thus lead to additional net climate mitigation, as denoted by a cumulative net carbon balance less than BAU. The *Increase Regeneration: Oak & NHW* scenario leads to a 2% lower cumulative net carbon balance (-9.6 MMT CO_2e) than BAU by 2050, a 4% lower (-37.9 MMT CO_2e) cumulative net carbon balance by 2075, and a 6% lower (-83.7 MMT CO_2e) cumulative net carbon balance by 2100. The *Increase Regeneration: NHW* scenario leads to a 1% lower (-6.6 MMT CO_2e) cumulative net carbon balance than BAU by 2050, dropping to 3% (-28.1 MMT CO_2e) lower by 2075, and 4% (-58.8 MMT CO_2e) lower by 2100 (**Figure 12**).

Impacts of the *Increased Harvest Retention Size* scenario, which increases reserve size following clearcuts and seed tree cuts, are more straightforward. In this scenario, there is a large increase in cumulative ecosystem carbon (-80.4 MMT CO_2e) relative to BAU, but much smaller relative impacts on HWP dynamics. Cumulative HWP transfers are higher than BAU (-0.8 MMT CO_2e), cumulative HWP emissions are lower, (-0.4 MMT CO_2e), a small amount of leakage occurs, (+3.3 MMT CO_2e), and substitution effects lead to a reduction in emissions (-9.2 MMT CO_2e; **Figure 12**). When summed together, cumulative net carbon balance is 9% (–51.4 MMT CO_2e) less than BAU by 2050, 7% (-73.8 MMT CO_2e) less by 2075, and 6.5% (–87.6 MMT CO_2e less) by 2100 (meaning this scenario leads to more carbon sequestration and storage; **Figure 12**).

Under the theme of forest health and regeneration, two scenarios relate directly to tree planting. The *Enrichment Planting: NHW* and *Red Pine Planting* scenarios both lead to cumulative increases in the forest ecosystem's mitigation potential (-157.8 MMT CO_2e and –22.5 MMT CO_2e, respectively) relative to BAU by 2100 (**Figure 12**). Each scenario here increases overall forest area, 560,039 acres of supplemental planting to restock NHW in the *Enrichment Planting: NHW* scenario, and 226,744 acres of additional red pine planting in the *Red Pine Planting* scenario. Interestingly, though the area of supplemental planting to restock NHW is close to double that of additional red pine planting, its effect on net ecosystem carbon flux is over seven times greater. This reflects the fact that growth and thus net primary productivity is much higher for NHW stands than red pine stands, meaning that each additional NHW acre restocked will have a larger proportional climate mitigation benefit. The annual additional climate mitigation benefit of the *Red Pine Planting* scenario also begins to saturate around 2075, while the annual additional climate mitigation benefit of the *Enrichment Planting: NHW* scenario increases from 2065 onward (**Figure 11**), further reflecting growth and productivity dynamics for these two forest types. Both scenarios also experience small changes in HWP transfers from altered land-use change activities, and thus increased emissions from leakage (when harvest removals are reduced) and reduced emissions from substitution effects (when harvest is increased). The resultant cumulative net carbon balance for the *Enrichment Planting: NHW* scenario is 5% (–29.8 MMT CO_2e) lower (meaning greater carbon sequestration and storage) than BAU by 2050, 9% (-87.9 MMT CO_2e) lower than BAU by 2075, and 12% (–157.2 MMT CO_2e) lower than BAU by 2100. For the *Red Pine Planting* scenario, cumulative net carbon balance is 1% (–7.4 MMT CO_2e) lower than BAU by 2050, 1.9% (-19.7 MMT CO_2e) lower than BAU by 2075, and 2% (–27.0 MMT CO_2e) lower than BAU by 2100 (**Figure 12**).

Two scenarios are categorized by the theme of climate adaptive management: the *Cover-Type Transition* scenario, which simulates secondary succession of aspen stands into either lowland spruce/fir, oak mix, or NHW cover types through natural processes, and the *Insect-Driven Mortality* scenario, which increases the annual rate of tree mortality by increasing the annual area impacted by insect disturbance. The *Cover-Type Transition* scenario switches from cumulatively sequestering and storing less carbon than BAU (up until 2049) to cumulatively sequestering and storing more carbon than BAU from 2050 onward (**Figure 11**). This scenario assumes that approximately 2,063 ac yr^{-1} of red pine or aspen stands begin to naturally transition into stands comprised of longer-lived species. This initially results in an increase in net ecosystem carbon flux, but as these new stands age, net primary productivity increases, lowering net ecosystem carbon flux levels below BAU (**Figure 12**). In addition, because northern hardwoods represent a forest type with high harvest rates, an increase in the area of these forest types leads to higher cumulative HWP transfers (-2.7 MMT CO_2e), and HWP emissions (+1.6 MMT CO_2e) relative to BAU (**Figure 12**). Because of this increase in hardwood harvest, this scenario also displaces emissions (-6.4 MMT CO_2e) from more emissions-intensive alternatives to hardwood products like lumber and composite panels. Even with the overall increase in harvest transfers, there is a small amount of leakage (+1.0 MMT CO_2e) which occurs in years when harvest is less than BAU. Overall, the cumulative net carbon balance for the *Cover-Type Transition* scenario is just 0.01% (-0.01 MMT CO_2e) lower (meaning more carbon sequestration and storage) than BAU by 2050, before improving to 0.4% (-4.3 MMT CO_2e) lower than BAU by 2075, and 1% (–15.5 MMT CO_2e) lower than BAU by 2100 (**Figure 12**).

In contrast to the *Cover-Type Transition* scenario, the *Insect-Driven Mortality* scenario leads to a cumulative net carbon balance greater than BAU, meaning less carbon sequestration and storage and thus less climate mitigation. The increase in tree mortality from insect disturbances associated with this scenario drives a slight reduction in cumulative net primary productivity, and thus carbon sequestration, leading to cumulatively less carbon in the forest ecosystem relative to BAU (+2.3 MMT CO_2e), lower cumulative transfers of carbon to the HWP sector (+1.6 MMT CO_2e), lower cumulative HWP emissions (-0.6 MMT CO_2e) and some leakage (+2.1 MMT CO_2e; **Figure 12**). However, as with other scenarios where annual harvest volumes are variable, this scenario also has net emissions reductions from substitution effects (-5.1 MMT CO_2e). The *Insect-Driven Mortality* scenario has a higher net carbon balance (emits additional carbon) relative to BAU: 0.2% (+1.2 MMT CO_2e) by 2050, 0.02% (+0.2 MMT CO_2e) by 2075, and 0.01% (+0.2 MMT CO_2e) by 2100 (**Figure 12**). However, it should be noted that even with these impacts, the forest and forest products sector still remain a net carbon sink through 2100.

In addition to the scenarios above, we also tested four scenarios using alternate HWP model parameters. One of these scenarios, the *Mass Timber* scenario, was based on the BAU ecosystem model, with the HWP model updated to allocate 5% of softwood material away from pulp toward the production of mass timber. This scenario only differs from BAU in its HWP stocks, emissions, and product substitution, as the ecosystem dynamics, and thus HWP transfer, are identical to BAU (meaning no leakage is assessed). When wood is allocated to mass timber rather than pulp, this carbon is emitted more slowly, as mass timber has a longer in-use half-life than pulp (73.3 vs 3 years). In addition, less of the overall carbon is emitted, as mass timber has a smaller degradable fraction (10%) than pulp (50%) in landfills. Finally, mass timber will substitute for more

emissions-intensive alternatives, displacing emissions, and leading to overall emissions reductions relative to BAU. Collectively, these factors lead the *Mass Timber* scenario to have a cumulative net carbon balance 0.18% (–1.1 MMT CO_2e) lower (meaning more carbon sequestration and storage) than BAU by 2050, 0.21% (-2.2 MMT CO_2e) lower by 2075, and 0.25% (–3.4 MMT CO_2e) lower by 2100 (**Figure 12**).

The other three HWP scenarios each have alterations in both their ecosystem and HWP parameters. Each of these are based on the concept of *Harvest Residue Utilization,* where harvest residues, tops and branches which would otherwise be left in the forest as coarse woody debris, are removed during the harvest process and sent to the HWP sector. All other aspects of these scenarios, including the harvest intensity (acres per year), are identical to BAU. In the *Harvest Residue Utilization: BAU* scenario, wood that is removed as harvest residue is treated identically to any other harvest removal (i.e., it is treated as additional harvest). Cumulatively, these extra removals lead to less carbon in the forest ecosystem relative to BAU (+21.3 MMT CO_2e) and cumulatively more carbon is allocated to HWP (-9.6 MMT CO_2e), accompanied by emissions reductions from substitution effects (-11.0 MMT CO_2e), and a small amount of leakage (+0.6 MMT CO_2e; **Figure 12**). However, this additional transfer of carbon to the HWP sector leads to cumulative HWP emissions which are higher than BAU (+5.4 MMT CO_2e; **Figure 12**). When these factors are summed, cumulative net carbon balance is 0.54% (+3.2 MMT CO_2e) higher (meaning less carbon sequestration and storage) than BAU by 2050, 0.51% (+5.3 MMT CO_2e) higher than BAU by 2075, and 0.05% (+6.7 MMT CO_2e) higher than BAU by 2100 (**Figure 12**).

In the *Harvest Residue Utilization: Bioenergy* scenario, wood that is removed as harvest residue is allocated 100% toward bioenergy, while in the *Harvest Residue Utilization: Biochar* scenario, wood that is removed as harvest residue is allocated 100% toward biochar. For both of these scenarios, ecosystem carbon and harvest transfers are identical to the *Harvest Residue Utilization: BAU* scenario, but they each differ in HWP emissions, substitution effects, and overall net carbon balance.

We assume that 100% of the carbon in wood allocated to bioenergy will be emitted in the same year that it is harvested, and as such, cumulative HWP emissions for the *Harvest Residue Utilization: Bioenergy* scenario are substantially increased relative to BAU (+11.9 MMT CO_2e; **Figure 13**). At the same time, we assume that energy produced from these fuel sources displaces fossil energy sources (see **Appendix** for details on calculation of displacement factors), thus reducing overall emissions (-1.2 MMT CO_2e; **Figure 12**). The net effect is that the cumulative net carbon balance for the *Harvest Residue Utilization: Bioenergy* scenario is 1.4% (+8.3 MMT CO_2e) higher (meaning less carbon sequestration and storage) than BAU by 2050, 1.7% (+16.0 MMT CO_2e) higher by 2075, and 1.6% (+23.0 MMT CO_2e) higher by 2100 (**Figure 12**).

Unlike the other two *Harvest Residue Utilization* scenarios, the additional harvest transfer in the *Harvest Residue Utilization: Biochar* scenario does not lead to any product substitution, since biochar does not displace a more emissions-intensive alternative product. However, biochar has a long in-use half-life (100 years) and very little of the carbon allocated to biochar will reach end of life during the 80-year simulation period. Accordingly, this scenario has similar cumulative HWP emissions to BAU, despite higher overall harvest transfers (**Figure 12**). This results in a cumulative

net carbon balance 0.78% (+4.7 MMT CO_2e) higher (meaning less carbon sequestration and storage) than BAU by 2050, 0.74% (+7.6 MMT CO_2e) higher by 2075, and 0.72% (+9.6 MMT CO_2e) higher by 2100 (**Figure 12**).

Representing a concurrent suite of climate-smart forest management actions (**Table 3**), the *Portfolio* scenario (which combines the *Extended Rotations*, *Increase Regeneration: Oak & NHW*, *Enrichment Planting: NHW*, and *Red Pine Planting* scenarios) illustrates compounding climate mitigation potential when these actions are taken together. The *Portfolio* scenario results in a cumulative net carbon balance 10.8% (–64.4 MMT CO_2e) less (meaning more carbon sequestration and storage) than BAU by 2050, 10.3% (–105.4 MMT CO_2e) less by 2075, and 11.2% (–149.5 MMT CO_2e) less by 2100, while still supporting a sustainable timber supply (**Figure 12**). Interestingly, the portfolio does not result in the largest amount of potential climate mitigation benefits of all the scenarios modeled, being surpassed in terms of cumulative net carbon balance by the *Enrichment Planting: NHW* scenario in 2092 and cumulatively capturing and storing 7.7 MMT CO_2e less carbon by 2100. This occurs, as even though *Enrichment Planting: NHW* is included in the *Portfolio*, the total land area available for restocking NHW species is reduced when the other management actions in the *Portfolio* are concurrently applied across the state. As such, cumulative net primary productivity (the primary driver of carbon sequestration) for the *Portfolio* is 135.7 MMT CO_2e less than the *Enrichment Planting: NHW* scenario, explaining much of the difference in cumulative net carbon balance. Nonetheless, the *Portfolio* presents an opportunity for maintaining a strong forest carbon sink across Michigan while accomplishing multiple climate-smart forestry and management goals. The *Portfolio* also helps to highlight significant opportunities for additional climate benefits from ambitious state action on a wide range of forest management practices.

The Influence of Age Class on Mitigation Potential

As in 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 81.3% of Michigan's forests under 80 years old in 2020, dropping to 30.2% under 80 years in 2100 (**Figure 6**). The average forest age subsequently changes from 56 years old in 2020 to 99 years old in 2100 (**Figure 13**), reflecting a shift toward a more mature forest 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 tends to be the lowest in the very youngest stands, while the middle-aged and older stands hold more carbon per area (**Figure 13**).

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 stock densities increase through time, going from 344.84 $tCO_2e\ ac^{-1}$ in 2030 to 390.05 $tCO_2e\ ac^{-1}$ in 2100 (**Figure 13**). Over the same time, average per-acre net ecosystem productivity increases (less carbon capture per acre) from –1.38 $tCO_2e\ ac^{-1}\ yr^{-1}$ in 2030 to -0.77 $tCO_2e\ ac^{-1}\ yr^{-1}$ in 2100 (**Figure 13**), after reaching a peak value of –1.39 $tCO_2e\ ac^{-1}\ yr^{-1}$ in 2034. Among the alternate scenarios tested, none substantially deviated from this BAU trend. In the *Increased Regeneration: Oak & NHW* scenario, average age still increases (from 61 to 96 years from 2030-2100) but is lower than BAU, as the result of a slightly higher harvest intensity each year meant to promote oak and NHW regeneration (**Table 3**). Similarly, carbon stock densities still increase through time in the *Increased Regeneration: Oak & NHW* scenario, going from 344.84 $tCO_2e\ ac^{-1}$ in 2030 to 390.05 $tCO_2e\ ac^{-1}$ in 2100. However, due to the regeneration harvest and larger proportion of younger stands in the *Increased Regeneration: Oak & NHW* scenario, carbon stock densities are lower than BAU (–0.09% and –0.26% of BAU levels in 2030 and 2100, respectively; **Figure 13**). Per-acre net ecosystem productivity rises (capturing less carbon per acre) from –1.38 $tCO_2e\ ac^{-1}\ yr^{-1}$ in 2030 to -0.76 $tCO_2e\ ac^{-1}\ yr^{-1}$ in 2100. However, this increase is less than BAU by 2100, with per-acre net ecosystem productivity values for the *Increased Regeneration: Oak & NHW* scenario +4% and -9% of BAU in 2030 and 2100, respectively (**Figure 13**).

The *Extended Rotations* scenario provides another slight contrast from BAU, with a mean stand age on average 0.55 years older than BAU (+0.31 years in 2030 and +0.76 years in 2100; **Figure 13**). While small, this increase in stand age reflects the fact that harvest deferrals like those implemented in the *Extended Rotations* scenario keep working forests active for longer, expanding the proportion of the forest age class distribution in the middle-aged range (40-80 years). This harvest deferral also has implications for carbon stocks, with the *Extended Rotations* scenario having an average carbon stock density of 363.81 $tCO_2e\ ac^{-1}$ (+0.33% relative to BAU) in 2050, 379.51 $tCO_2e\ ac^{-1}$ (+0.36% relative to BAU) in 2075, and 390.05 $tCO_2e\ ac^{-1}$ (+0.32% relative to BAU) in 2100 (**Figure 13**). Per-acre net ecosystem productivity values for the *Extended Rotations* scenario are more similar to BAU, -1.29 $tCO_2e\ ac^{-1}\ yr^{-1}$ (-1% relative to BAU) in 2050, -0.99 $tCO_2e\ ac^{-1}\ yr^{-1}$ (+1% relative to BAU) in 2075, and -0.77 $tCO_2e\ ac^{-1}\ yr^{-1}$ (-1% relative to BAU) in 2100, primarily driven by the relative age difference from BAU at each stage of the simulation (**Figure 13**). When mean forest age for the *Extended Rotations* scenario is at its largest difference from BAU (+0.81 years), per-acre net ecosystem productivity is at its weakest point relative to BAU (+2%).

In the *Portfolio* scenario, carbon stock densities are initially lower than BAU (361.23 $tCO_2e\ ac^{-1}$ or -0.37% relative to BAU in 2050), before increasing to 380.21 $tCO_2e\ ac^{-1}$ (+0.19% relative to BAU) in 2075 and 392.71 $tCO_2e\ ac^{-1}$ (+0.68% relative to BAU) in 2100 (**Figure 13**). This increase in carbon stock densities is likely driven by the deferred harvest (*Extended Rotations* scenario) and increase in tree planting (*Red Pine Planting* and *Enrichment Planting: NHW* scenarios) included in the *Portfolio*, which each independently increase carbon stock densities (**Figure 13**). The age distribution of the *Portfolio* scenario is largely similar to BAU, in line with other single effect scenarios. The *Portfolio* scenario also leads to relatively large decreases (meaning more carbon sequestration) in per-acre net ecosystem productivity, -1.07 $tCO_2e\ ac^{-1}\ yr^{-1}$ (-7% relative to BAU) in 2075, and -0.89 $tCO_2e\ ac^{-1}\ yr^{-1}$ (-15% relative to BAU) in 2100 (**Figure 13**), as the result of tree planting and regeneration treatments which promote growth and productivity, especially in the younger age classes.

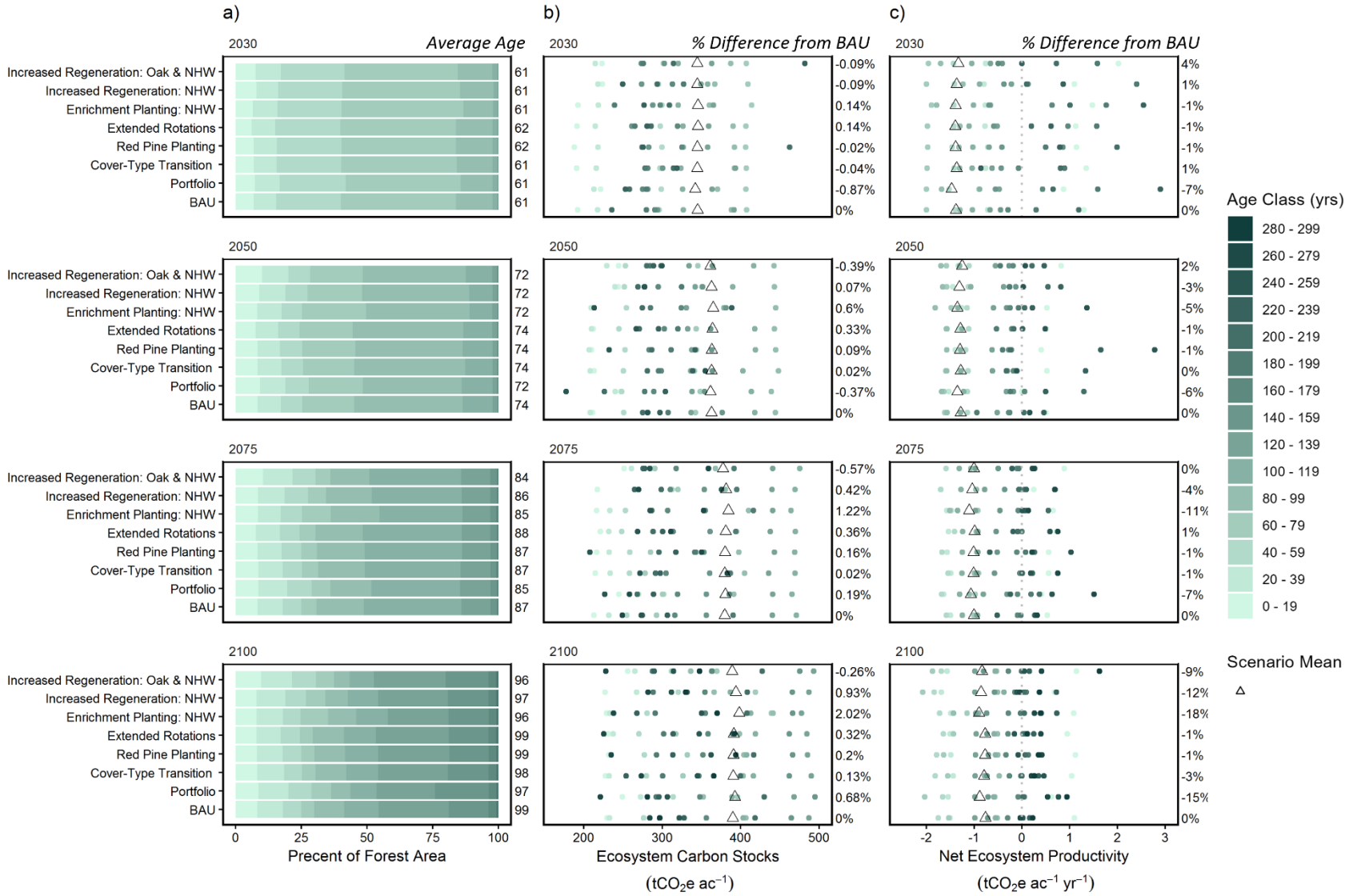


Figure 13. a) Age class distribution, b) ecosystem carbon stock density ($tCO_2e\ ac^{-1}$), and c) per-acre net ecosystem productivity ($tCO_2e\ ac^{-1}\ yr^{-1}$) for selected scenarios in 2030, 2050, 2075, and 2100. Net ecosystem productivity refers to the net yearly sequestration of carbon per acre 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.

Other scenarios like *Red Pine Planting, Enrichment Planting: NHW,* and *Cover-Type Transition* have similar forest age trends to BAU, with comparable average ages and age class distributions through time. Of this group, the *Enrichment Planting: NHW* scenario generates the best long term carbon storage gains relative to BAU by increasing supplemental planting to restock understocked stands, thus boosting forest carbon density. As such, carbon stock densities increase from just +0.14% (345.32 $tCO_2e\ ac^{-1}$) relative to BAU in 2030 to +2.02% (397.93 $tCO_2e\ ac^{-1}$) relative to BAU in 2100 (**Figure 13**). The *Enrichment Planting: NHW* scenario also provides substantial improvements in net ecosystem productivity via its restocking treatments, with per-acre net ecosystem productivity values -11% and -18% lower (meaning more carbon sequestration per acre) than BAU in 2030 and 2100, respectively (**Figure 13**). These differences demonstrate the additional potential of CSF management practices to increase forest carbon sequestration and storage in Michigan 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 Michigan. 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 Michigan'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 Michigan. 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 the 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 effects 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 effects 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 play a critical role in nature-based climate solutions (Griscom et al., 2017; Fargione et al., 2018). They capture and store atmospheric carbon while supporting the forest bioeconomy through wood product supply (Skog, 2008; Smyth et al., 2014; Lempriere et al., 2013). Our analysis shows that Michigan's forests already provide strong climate mitigation benefits, and that implementing key climate-smart forest management practices in Michigan can significantly enhance climate mitigation beyond business-as-usual approaches, strengthening the forest carbon sink through the end of the century. These practices also help meet broader management objectives by promoting forest health, supporting climate adaptation, and ensuring a sustainable supply of timber and other ecosystem services. The climate-smart forest management practices identified include (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.

- **Maintain and increase forest extent** via increased *Red Pine Planting* and *Enrichment Planting* of northern hardwood species.

- **Support climate mitigation and adaptation by incorporating climate change considerations into forest management** through proactively promoting more adaptive *Forest-Type Transitions*, as well as shifts in the *Management of Jack Pine* forests.

- **Update harvesting practices** by *Extending Rotations* or promoting *Increased Regeneration* of oak and northern hardwood species post-harvest.

- **Bolster the climate mitigation potential of the forest products sector** through the introduction of *Mass Timber*, effectively increasing the carbon storage potential of the forest products sector while also providing substantial benefits from using wood in place of other emission-intensive materials.

- **Implement the suite of climate-smart forest practices** listed above as represented by the *Portfolio* scenario.

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 Michigan's forest carbon sink by 10.8% in 2050 and 11.2% 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.

Despite a gradual projected decline in annual net ecosystem carbon flux across all of our scenarios, annual growth and sequestration still outpaces all emissions from timber harvests, natural disturbances, and LUC meaning that in the forest will remain a net carbon sink through the end of the century. The *Red Pine Planting, Enrichment Planting: NHW*, both *Increase Regeneration*, and the *Extended Rotations* scenarios all represent potential CSF opportunities to increase the climate mitigation potential of Michigan'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 three *Harvest Residue Utilization* scenarios, while providing less climate mitigation potential as compared to BAU (though still remaining net carbon sinks through 2100), represents a an intriguing option should the desire to increase HWP production increase while keeping harvest acreage static. Further, our results suggest that investments in the production of *Mass Timber* a durable and longer-lived wood product may provide 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 develop and promote policies and incentives that encourage the adoption of climate-smart forest management practices to help reduce greenhouse gas emissions. Sustaining Michigan's forestlands depends on incentivizing practices that meet diverse management goals while discouraging actions that increase forest vulnerability and risk. There is no universal approach to climate-smart forest management. Effective strategies require site-specific knowledge combined with broader-scale insights to guide future mitigation and adaptation efforts.

Opportunities exist to incentivize the maintenance or expansion of forest cover on privately managed lands through mechanisms such as tax programs, stewardship and management plans, voluntary carbon offset projects, and cost-share programs that encourage climate-informed practices and adoption of CSF management strategies. Technical assistance programs tailored for small, non-industrial landowners can also provide essential support for sustainable forest management. Additionally, continuously integrating new data and insights allows decision-makers to refine management objectives and GHG reduction targets over time. Establishing flexible, data-driven decision-making processes will strengthen forest stewardship in Michigan, ultimately fostering healthier, more resilient forests and the communities that depend on them.

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Appendix

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

Past and future carbon (C) stocks and stock changes were modeled using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) (Kull et al., 2019; Kurz et al., 2016). The CBM-CFS3 model was selected to analyze the forest ecosystem, management practices, and land-use change components within our systems-based approach. The CBM-CFS is fully consistent with IPCC guidelines for estimation and reporting utilizing tier III methodologies. Other empirically based models such as the USFS Forest Vegetation Simulator (FVS) (Anderson et al., 2020), Carbon Calculation Tool (CCT) (Smith et al., 2007; Woodall et al., 2011), or LANDIS-II (Scheller et al., 2007), offer some potential strengths for analyzing landscape to stand-level scales 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 carbon 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 site 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 utilizes the single inventory as opposed to estimate stock change across multiple inventory windows. **Figure 2** provides a conceptual graphic representing model inputs and processes within the CBM-CFS3.

Table S1. List of Classifiers and descriptions

Code	Name	Description	ID	Value
UNITCD		Biogeographic unit that contains minor variation in physiographic, macroclimatic, and vegetation conditions	1 2 3 4	Eastern Upper Peninsula
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 20 30 40	Forest Service Other Federal State / County 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 101p 102 102p 103 103p 105 121 122 126 171 104 127 401 503 505 525 520 701 801 901 902 999 0	Natural Jack Pine Planted Jack Pine Natural Red Pine Planted Red Pine Natural White Pine Planted White Pine Hemlock Upland Spruce/Fir Lowland Spruce/Fir Tamarack Cedar Upland Conifers Lowland Conifers Upland Mixed Forest Oak Mix Northern Red Oak Black-Red Hybrid Oak Mixed Upland Deciduous Lowland Deciduous Northern Hardwood Aspen Lowland Aspen/Balsam Poplar Nonstocked Nonforest
SITECLCD	Site Class Code	Measure of site productivity in terms of growth as a function of cubic feet per acre per year.	1 2 3	171-201+ cu ft/ac/yr 81-170 cu ft/ac/yr 1-80 cu ft/ac/yr

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 Michigan. The purpose of the BAU is to not forecast future climate states or economic trends in forest products, but to develop a plausible simulation of just one potential future outcome by projecting longer-term averages of activity data into the future. This does not account for changes in policies, climate, or economics, but nonetheless, remains a useful exercise to explore how the continuation of current behaviors and disturbances may affect future ecosystem and carbon cycling dynamics to inform current understanding of management practices and forest dynamics. Additionally, projecting current practices and disturbances into the future allows for a counterfactual comparison of alternative forest management, climate, and wood utilization scenarios in contrast to the BAU. Allowing for a quantification of the carbon mitigation potential of specific management practices or actions. Modeling each practice individually allows for the assessment and analysis of each practice in isolation.

To properly account for forest carbon dynamics, information regarding forest growth, forest management, natural disturbances, and land-use change is necessary to capture relevant factors that impact net carbon balances within the forest ecosystem. Harvest practices were identified and validated heuristically with direct input and participation from our state partners including definitions of common harvest regimes (**Table S3**). Utilizing a participatory approach with our state-partners, we were able to incorporate direct feedback from both model assumptions and preliminary results to ensure accuracy within both the forest ecosystem and forest products sector. Further, the active participation of partners allows us to prioritize and model both concerns and opportunities of forest management currently ongoing within the BAU.

The BAU scenario initially uses historical data from 2007-2019 and then projects onwards starting in 2020 until 2100. **Table 1** provides the BAU ecosystem disturbance parameters for Michigan. The purpose of projecting until 2100 is to try and capture longer. Harvest removals simulated in the BAU simulation removed approximately 86% annually of the initial inputted targets primarily due to lack of eligible forest records driven by changes in the forest age distribution and rule-based harvest events, whereas both LUC and natural disturbances were represented as 100% of target parameters.

The 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. 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 spatially referenced rather than spatially explicit, 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.

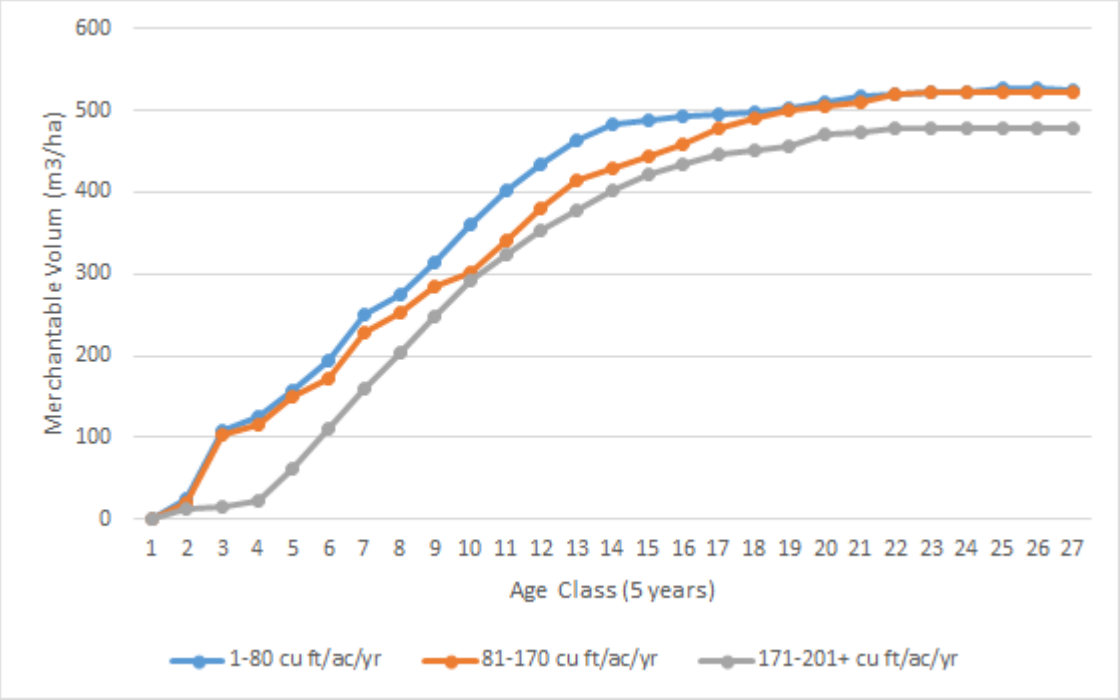


Figure S1. Example of yield curves for Northern Hardwoods (FORTYPCD=801) for the three productivity classes

In the CBM-CFS3 modeling framework, forest productivity and regeneration are represented by empirically derived growth and yield curves which represent the rate of biomass accumulation as a function of stand age and site productivity (quantified as MAI) and post-disturbance transition rules. Growth-yield curves were derived for each unique combination of forest type group and site class representing a range in growth characteristics and productivity indices using the USFS Forest Vegetation Simulator (Anderson et al., 2020) where FIA plots within Michigan were grown for a period of 200 years under a variety of management and growth conditions to estimate volume, site class, and biomass of each stand as a function of stand age. The yield curves were derived from

natural resource consultancy firm Mason, Bruce, and Girard, and were provided by the Michigan DNR. 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. Figure S1 represents growth curves for northern hardwood stands for each site class represented in the inventory.

Activity Data

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. Stand age was utilized to group harvesting into broad categories for harvest type and harvest intensity with direct input from state partners (Table S2). Table S3 outlines the average harvest intensity represented by percentage removals of merchantable volume as a product of stand age and forest type group.

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.

Table S2. Harvest Type and intensity by forest type group and average stand age with upper and lower ranges in Michigan for BAU simulation. Harvest intensity refers to the proportion of merchantable biomass removed during harvest. Average stand age at time of harvest was estimated using the BAU simulation results.

Forest Type	Average stand age at time of harvest with minimum and maximum age ranges	Harvest Type
101: Natural Jack Pine	30 (20-40) 70 (60-100)	Thinning Clearcut
101p: Planted Jack Pine	45 (40-60)	Clearcut
102: Natural Red Pine	60 (40-70) 120 (80-150)	Thinning Clearcut
102p: Planted Red Pine	30 (20-40) 105 (80-150)	Thinning Clearcut
103: Natural White Pine	60 (40-70) 90 (80-120)	Thinning Clearcut
105: Hemlock	140 (80-200)	Clearcut
121: Upland Spruce/Fir	80 (60-115)	Clearcut
122: Lowland Spruce/Fir	50 (50-80)	Clearcut
126: Tamarack	75 (60-100)	Clearcut
127: Cedar	130 (105-250)	Clearcut
171: Upland Conifers	105 (80-135)	Clearcut
503: Oak Mix	90 (80-100)	Clearcut

Table S2, cont. Harvest Type and intensity by forest type group and average stand age with upper and lower ranges in Michigan for BAU simulation. Harvest intensity refers to the proportion of merchantable biomass removed during harvest. Average stand age at time of harvest was estimated using the BAU simulation results.

Forest Type	Average stand age at time of harvest with minimum and maximum age ranges	Harvest Type
505: Northern Red Oak	135 (130-160)	Clearcut
	130 (80-200)	Group Selection
	130 (80-165)	Shelterwood / Seed Tree
	80 (70-85)	Thinning
	120 (90-190)	Single Tree Selection
515: Black / Red Hybrid Oak	85 (80-95)	Clearcut
	90 (85-95)	Shelterwood / Seed Tree
520: Mixed Upland Deciduous	85 (70-120)	Clearcut
	90 (70-120)	Shelterwood / Seed Tree
701: Lowland Deciduous	110 (90-170)	Clearcut
	110 (90-170)	Group Selection
	120 (90-170)	Shelterwood / Seed Tree
	70 (60-70)	Thinning
	110 (90-170)	Single Tree Selection
801: Northern Hardwoods	125 (100-170)	Clearcut
	120 (100-220)	Group Selection
	120 (100-170)	Shelterwood / Seed Tree
	80 (70-80)	Thinning
	105 (90-210)	Single Tree Selection
901: Aspen	60 (40-170)	Clearcut
902: Lowland Aspen / Balsam Poplar	45 (40-90)	Clearcut
999: Nonstocked	45 (40-60)	Clearcut

To estimate merchantable carbon from the volumetric removals, we applied as the following equation:

$$C = ((Volume * SW_{proportion} * SW_{sg}) + (Volume * HW_{proportion} * HW_{sg})) * 0.5$$

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.

This method of estimating total volumetric harvest removals does not allow for attribution to specific management practices because the FIA database does not contain such information. To assign a harvest type and intensity to each record of volumetric removal, stand age at the time of removal was calculated by taking the mid-point average between time t_1 and t_2 (Bechtold and Patterson, 2005) where t_1 is the year the unharvested stand was measured (from the 2007-2013 survey cycle) and t_2 is the repeat interval measurement year post-harvest (from the 2014-2020 survey cycle). Stand age at the time of harvest can then be calculated by taking the time between t_1 and t_2 divided by 2 added to the stand age in t_1. These harvest ages from FIA data were binned into

20-year age classes to reduce uncertainty around stand age at time of harvest, especially for uneven-aged management systems. Then, we used information on typical management practices with direct input from state partners to estimate the average age and harvest intensity (in terms of percent merchantable biomass removed) corresponding to each harvest type for each forest type group. Finally, we attributed volumetric removals from FIA for those age + forest type group combinations to a specific harvest type. Post simulation validation was conducted both at the stand level and state-level to validate harvest regimes accurately depict carbon dynamics.

Harvest intensity is modeled through disturbance matrices that describe the flux of carbon between various ecosystem pools in response to a disturbance, including treatment of harvest residues and removals for HWP (see **Figure 1** for the carbon pools included in the CBM-CFS3). The CBM-CFS3 provides default disturbance matrices for over 200 disturbance types; following accuracy assessments with our state partners, we assigned default disturbance matrices for disturbances where relevant or created new disturbance matrices to more accurately represent forest dynamics in Michigan.

Table S3. Description of each harvest regime and harvest event schedule rules

Harvest Regime	Description
Thinning	Removal of approximately 25% of merchantable carbon via cutting. Stand age does not reset.
Clearcut	Removal of approximately 95% of merchantable carbon. Stand age resets to zero.
Group Selection	Removal of approximately 30%. Area harvested resets stand age to zero while the rest of the stand continues to grow unaltered.
Shelterwood / Seed Tree	Initial removal of approximately 70% of merchantable carbon followed by a 10-20 year reentry delay to remove remaining canopy species. Following mature harvest, stand age resets to zero.
Single Tree Selection	Removal of approximately 25% of merchantable carbon with age being reset to next youngest cohort ~65 years. Requires a 20-year period before reentry. BAU simulation decreases site index to 1-80 cu ft/ac/yr to simulate growing concerns over regeneration of stands from both herbivory and non-beneficial diameter limit cuts (also known as high grading).

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 from 2005-2020. Annual estimates of LUC were validated and 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 Michigan DNR Fire Management Dashboards (MI DNR, 2023) as GIS and other derived estimates of prescribed fire generally underestimate areas burned in low severity fires.

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 Michigan 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).

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

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 Michigan, 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 2013-2019. 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

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

record back to age zero to simulate regeneration determined by regional specific literature reviews. The shelterwood / seed tree disturbance type would initially remove between 50-70% of biomass followed by complete removal of remaining biomass after a 20-year period. Single tree selection harvests would reset stand age to the next youngest cohort following disturbance to mimic on average 20-year re-entry intervals in stands.

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-MI 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 Michigan, we multiplied the national total by the portion of Michigan 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 Michigan, 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 Michigan 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 Michigan roundwood production exported internationally, assumed that all exported roundwood was going toward the production of lumber, and applied corresponding product half-lives.

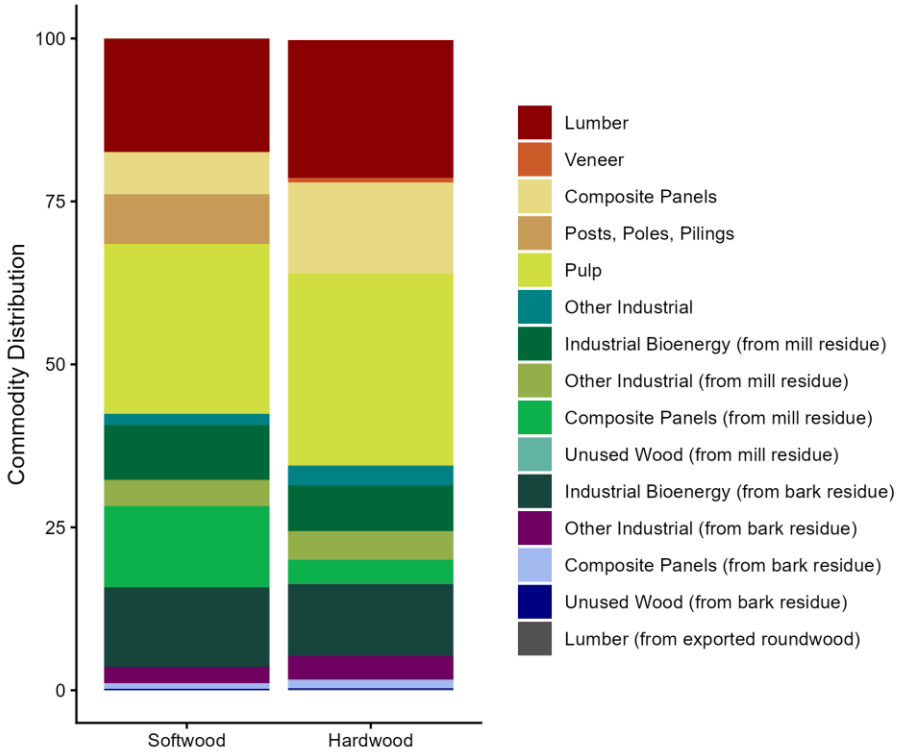


Figure S2. Primary product ratios for commodities produced in Michigan, differentiated by softwood and hardwood inputs.

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-MI. 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 Michigan mills have an average mill efficiency of 70.5% for softwoods and 81.8% for hardwoods, meaning that the remaining material – 29.5% and 18.2% of total harvest after export for softwoods and hardwoods, respectively – becomes mill residue during the commodity production process. We differentiated between softwood and hardwood inputs, as these wood types differ in their exports and commodities produced, as well as their associated product half-lives and displacement factors (described below). We then assigned mill residues, including bark from exported roundwood, to four commodity pools using proportions from TPO data in 2018 and the 2021 and 2023 Michigan Mill Survey Reports (Michigan Department of Natural Resources -

Forest Resources Division 2023; 2025): composite panels, bioenergy, other industrial, and unused residues (see **Table 3 for proportions for softwoods and hardwoods**).

Primary Product Ratios

As noted above, the CBM-HWP-MI 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-MI 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 Michigan 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 had calculated exports, mill residues, and primary products from annual harvest volumes, we determined end-uses for those products and their associated half-lives. We used end-use product half-life (Dymond 2012) and product use data (Howard et al. 2017) to calculate softwood- and hardwood-specific half-lives for Michigan 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 Michigan 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 effects* and *leakage* for this change in HWP supply. Substitution effects, or *displaced emissions*, were estimated following Smyth et al. (2017), with emissions reductions from substitution occurring when additional wood products are manufactured and used in place of alternative emissions-intensive materials, and additional emissions from substitution effects occurring when wood supply falls short and other emissions-intensive materials are assumed to be used instead. We applied substitution effects only to saw log, composite panel, bioenergy, and transport fuel products.

Substitution effects 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 effects associated with timber product substitution, we coupled Michigan-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: 2.07; hardwood: 2.63) and composite panels (softwood: 2.65; hardwood: 1.78), 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).

To account for substitution effects associated with bioenergy, we first assumed that 60% of biomass would go toward electrical production and 40% would go toward combined heat and power (CHP) production. Then, using data from the U.S. Energy Information Administration (2024), we calculated the proportion of electrical and CHP production coming from fossil sources (coal, oil, and natural gas), and used these proportions and the LCAs from Smyth et al. (2017) to estimate a weighted composite LCA. Then, based on the assumption that wood used in bioenergy has an energy density of 2 MWh tC^{-1} (Federal Energy Management Program 2004), we calculated displacement factors for electric (0.49 tC tC^{-1}) and CHP (0.15 tC tC^{-1}) bioenergy. Because Michigan has a 100% clean energy goal by 2060, we assumed that from 2061 onward electrical bioenergy would no longer displace any fossil carbon fuel sources. The rationale here is that wood products, including bioenergy, displace emissions associated with more emissions-intensive products. If the alternative products can achieve zero emissions in their production, the counterfactual scenario is zero emissions, meaning there are no longer any emissions to displace. As such, we applied a decreasing displacement factor to the electrical proportion of the bioenergy such that it decreases linearly until reaching zero in 2060.

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

Increased Regeneration: Oak & NHW

Increase Regeneration 1

Broadly speaking, silviculture seeks to control the establishment, growth, composition, health, and quality of forests through a variety of management practices. Silvicultural prescriptions, or site-specific plans, used to meet specific objectives are informed by the ecology of a specific forest systems along with site-specific factors. Current efforts are underway to assess alternative silvicultural regimes on the recruitment of economically important species such as red oak (*Acer rubrum*), white oak (*Quercus alba*), and sugar maple (*Acer saccharum*) (Izbicki et al., 2020; Henry & Walters, 2023; Walters et al., 2022; Walters et al., 2020). This scenario increases the harvest intensity in an effort to increase regeneration of specific species. While the CBM-CFS3 does not include species level quantification, the alteration to harvest intensity (i.e., removal of merchantable carbon) does have downstream effects for regeneration and carbon storage. This scenario shifts 45% of single-tree-selection harvest of oak to group selection and 55% of single-tree-selection cuttings of oak to clearcut. Additionally, this scenario shifts 75% of NHW single-tree-selection cuttings to clearcuts. This scenario assumes the successful regeneration of stands and that these new harvest regimes result in stands regenerating at an increased site class. Altered harvest regimes were implemented from 2020-2100.

Increased Regeneration: Oak

Similarly to above, this scenario changes 75% of single-tree-selection cutting regimes in NHW to group selection as a way to more aggressively regenerate sugar maple. Likewise, this scenario assumes the successful regeneration of NHW stands and that the group selection harvest regimes result in stands regenerating at a higher site class. Altered harvest regimes were implemented from 2020-2100.

Enrichment Planting

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., 2006b). Generally, enrichment planting is seen as a way to both increase the stocking of secondary forests as well as increase carbon sequestration rates (Paquette et al., 2009, Paquette et al., 2006a; Paquette et al., 2006b). This scenario models the planting of trees on 2833 ha of NWH in the upper-lower peninsula on state management lands for understocked stands for 30 years (2020-2050). This scenario assumes successful regeneration of stands are transitioned to a higher site class after enrichment planting treatment.

Altered Rotations

Changing rotation lengths, specifically extending the average length of rotations before harvesting is a popular management tool for increasing carbon storage (D'Amato et al., 2011; Fargione et al., 2018; Ontl et al., 2020). This scenario increased the rotation length by 10 years on all even aged managed systems. Uneven aged stands remained the same due to harvest regimes being implemented by basal area targets. Rotation lengths were implemented from 2020-2100.

Increased Reserve Size

Human management on forests has drastic implications for forest carbon storage and sequestration. Where, the intensity of harvest and cutting practices across a range of silvicultural systems directly affects the maintenance and levels of forest carbon stored *in situ* in the forests (Harmon and Marks, 2002; Nunery and Keeton 2010; Ray et al. 2009) and increase other ecosystem services (Marshalek et al., 2014). This scenario sought to estimate the effects on both carbon storage and sequestration in managed stands by increasing the size of post-harvest retention on clearcut stands. The BAU simulation currently leaves about 3% of the merchantable carbon on site following a clearcut harvest whereas this scenario increases that reserve size to ~10% of merchantable carbon being left on site. This scenario was modeled from 2020-2100.

Insect- Driven Mortality

Assessing the future potential effects of climate change impacts on forest carbon dynamics has strong implications for carbon storage and sequestration. Mortality caused by insect and diseases in the Midwest is project to increase (Handler et al., 2014). This scenario desired to coarsely capture what that might look like. This scenario doubled the area effected by mortality events from both disease and insect outbreaks for the following forest types: Spruce-fir, elm-ash-cotton, and northern hardwoods. The increased area of mortality was modeled from 2020-2100.

Cover-Type Transition

Climate change is expected to alter forest recruitment and regeneration (McDowell et al., 2020) Additionally, planted forests do not necessarily regenerate as the same forest type due to human intervention. Currently, Michigan has a large amount of maturing red pine that was planted by the Civilian Conservation Corp (CCC), mostly in the 1930s (Cook, 2020). The red pine was planted predominantly on abandoned agricultural land along the west side of the state. The most common cutting or harvest regime is to clearcut red pine, especially since these stands have remained largely unmanaged. However, the best estimates assume that without replanting red pine, these stands

will largely regenerate as northern hardwood stands. This scenario models the impacts of clearcut red pine stands in western Michigan regenerating as NHW until 2100.

Further, climate change is expected to alter successional dynamics of forests (McDowell et al., 2020). Where certain new and novel forest types might be ill suited for future growing regimes leading to mismatches in vegetation and climate. This scenario models the additional practice of letting aspen stand naturally succeed into a new novel forest type consisting of a split between NHW, Oak mix, and lowland spruce/fir forest types after the aspen stand reach age 100 as advanced regeneration of other species has already been observed in aspen forests across Michigan suggestion that transitions are already underway. This scenario shifts 100% of stands that meet these criteria to new cover types on only state and private managed lands until 2100.

Red Pine Planting

Reforestation remains a highly cost-effective method of increasing forest's contribution to net-zero GHG emissions target goals (Fargione et al., 2018). This scenario models the impact of converting 106 ha yr^{-1} of Nonstocked forest on federal managed lands, 786 ha yr^{-1} on state managed lands, and 255 ha yr^{-1} on privately managed lands until year 2050 which equates to ~10% of the total Nonstocked land at the simulation start period.

Jack Pine Management

Jack pine (*Pinus banksiana*) remains a key species in Michigan and serves as habitat for the federally endangered Kirtland's warbler (*Setophaga kirtlandii*). Fire suppression in the early- to mid- 1900s led to widespread habitat loss as Kirtland's warbler require early successional jack pine forests (MDNR 2014; Tucker et al., 2016). Currently, the Michigan DNR manages jack pine forests on a 50-year rotation to simulate the critical early successional habitat required for Kirtland's warbler. However, recent research has shown rotation lengths in jack pine plantations could be substantially reduced allowing for reductions in the total land area dedicated to warbler habitat and increasing the diversification of management regimes across the landscape (Gadoth-Goodman and Rothstein, 2020).

This scenario reduces the jack pine plantation rotations from 50 to 30 years (-20 years per rotation) on state managed land and rotation from 60 to 50 (-10 years per rotation) on private lands to simulate the effects of new and novel management regimes to optimize both warbler habitat and boost other ecosystem services (Gadoth-Goodman and Rothstein, 2020).

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 five such alternative wood utilization models.

The *Mass Timber* scenario retained BAU harvest transfer rates, however, in this scenario we allocated a fraction of the material going to the production of softwood pulp toward the production of mass timber. This change means that softwood pulp production dops from 57.07% of softwood

roundwood to 52.07% of roundwood, and mass timber production increases from 0% of softwood roundwood to 5% of softwood roundwood.

Increasing wood utilization through increased removal of harvest residues has strong potential for climate change mitigation specifically through derivation of bioenergy (Gustavsson et al., 2017; Smyth et al., 2016). The three *Harvest Residue Utilization* scenarios increased the amount of harvest residues removed following clearcut harvest by an average of 48,796 tC yr^{-1}. Here, wood residues that would normally be left on site after harvest were instead allocated to the wood products sector for use in one of three pathways. In the *Harvest Residue Utilization: BAU* scenario, additional harvest input from logging residue was treated as if it were any other harvest input, and thus commodity production splits were not altered. In the *Harvest Residue Utilization: Bioenergy* scenario, additional harvest input from logging residue was allocated 100% toward the production of bioenergy, with an assumed 40%-60% split between electricity and combined heat and power production (see **Appendix B** for calculation of displacement factors). Finally, in the *Harvest Residue Utilization: Biochar* scenario, additional harvest input from logging residue was allocated 100% toward the production of biochar.

We also developed a unique set of HWP assumptions for the *Jack Pine Management* scenario. In this scenario, shorted rotation lengths on Kirtland warbler habitat led to an additional 1,663 tC yr^{-1} of additional harvest, relative to harvest volumes for this forest type in the BAU. From 2021-2030 this additional harvest is allocated 50% toward bioenergy production (with an assumed 60%-40% split between electricity and combined heat and power production), 25% toward mastication (model as a direct input to the landfill), and 25% toward pulp. From 2031-2050 this ratio shifts to 40% mastication and 60% pulp. From 2051-2100, 100% of the additional removals on Kirtland warbler habitat are allocated toward pulp. All other removals are processed using the BAU HWP assumptions.