ESTIMATING CURRENT AND FUTURE CARBON STOCKS AND EMISSIONS IN MINNESOTA FORESTS AND FOREST PRODUCTS

A REPORT PREPARED FOR THE MINNESOTA FOREST RESOURCES COUNCIL | DECEMBER 13, 2024

MINNESOTA FOREST RESOURCES COUNCIL

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December 13, 2024

Eric Schenck
Executive Director
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Dear Mr. Schenck:

This letter accompanies the submission of the final report in partial fulfillment of the deliverables for the Minnesota Forest Resources Council (MFRC) grant, "*Estimating current and future carbon stocks and emissions in Minnesota forests and forest products under multiple management scenarios*." The report details team efforts over the past 20 months to describe current Minnesota forest sector carbon storage, sequestration, and emissions (in the forest and in harvested wood products) and to project those baselines into the future under alternative silvicultural scenarios. Results include descriptions of historical carbon flux on the landscape and in harvested wood products (HWPs), current baselines in all carbon pools, and simulations of future flux associated with different management prescriptions and resulting HWPs. These include detailed carbon life cycle assessments that describe the storage and emissions associated with different HWPs in Minnesota under each scenario. Unique and innovative compared to similar carbon studies, in-forest and LCA results were integrated and expanded statewide to provide study implications for forest management and policy across Minnesota.

The final version of the report reflects revisions from many meetings, presentations, and several rounds of feedback requests, including from an ad hoc peer review committee comprising regional experts. We believe this final report satisfies the grant requirements and desired information requested by the Council.

Another required deliverable is an online Minnesota forest carbon dashboard that provides interactive and readily digestible summary information from study results. Revisions to the integration analysis required partial restructuring of the dashboard, but these updates should be completed and a final version of the dashboard launched by December 6.

The results from this project will inform and assist the Council when developing climate related policy recommendations for the Governor and federal, state, and local governments. In addition, the scope and methods of this study further elevate Minnesota as a national leader in comprehensive forest carbon assessment.

I would like to particularly thank the project team members (see below) for their extraordinary effort and response to the continual feedback. Their collective work went above and beyond expectations in order to provide a superior product. Many, many thanks to them. We would like to thank you, MFRC chair Pete Aube, Research Advisory Committee chair Mike Kilgore, Council members, and the ad hoc peer review committee for the engagement and feedback throughout the project period. This final report represents a truly collaborative effort.

If you have any questions or concerns related to the final report, please feel free to let us know. We anticipate continued collaboration through dissemination of results and potential future research motivated by this study. Thank you!

Sincerely,

John Zobel

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Principle Investigator

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Estimating current and future carbon stocks and emissions in Minnesota forests and forests products under multiple management scenarios

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CONTENTS

1 EXECUTIVE SUMMARY

1.1 INTRODUCTION

Forestry represents the only economic sector in Minnesota where carbon sequestration and storage significantly exceed carbon dioxide (CO_2) emissions into the atmosphere (Figure 1.1). Fundamentally, carbon sequestration and storage within the forestry sector occurs both within forests and within forest products. Minnesota's 17.7 million acres of forest and a diverse forest product industry creates a unique opportunity for the strategic management of Minnesota's forests and support of forest product markets that have the potential to further mitigate the impacts of a changing climate through increased carbon sequestration and storage.

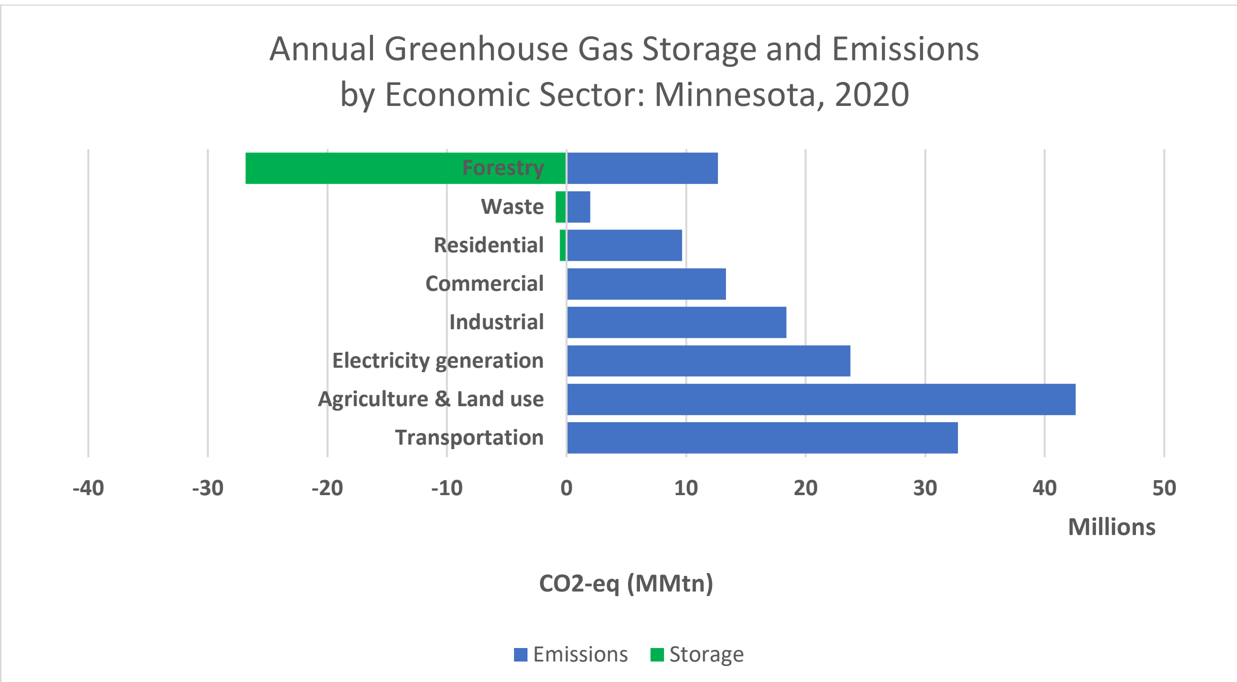

Figure 1.1. Forestry is the only economic sector that has "net negative" emissions in Minnesota. Graph generated from following data sources: 1. Minnesota Pollution Control Agency. "Greenhouse Gas Emissions (CO2-e Tons) by Sector, Activity, Source, GHG and Year." Greenhouse Gas Emissions Data, Tableau.com, 23 August. 2024, GHG emissions data | Tableau Public. Accessed 23 Aug. 2024, 2. Minnesota Department of Natural Resources Forest Resources Reports (1985-2020), 3. USDA-FIA, and current MFRC research.

To provide insights to the overall potential of the forestry sector to mitigate climate change, the Minnesota Forest Resources Council (MFRC) commissioned the University of Minnesota (UMN) Department of Forest Resources to complete an assessment of forest carbon baselines, and to model future outcomes of alternative forest management strategies and forest products. In doing so, MFRC identified two specific information needs:

Information Need #1: Understanding Minnesota's current forestry sector carbon storage and emissions baselines, including products; and developing, improving, and reporting this information for both forests and forest products in a form that is accessible, understandable, and useful to broad audiences.

Information Need #2: Life cycle assessments (LCA) of forest management intensities and strategies and harvested timber for products with focus on carbon storage, and emission reductions – understanding adaptation strategies, substitution effects, opportunities and tradeoffs.

To understand the forestry sector's carbon storage and emissions baselines, and the long-term carbon consequences of different forest management scenarios, including forest carbon stored in harvest wood products, the UMN team combined the forest carbon baseline and simulation modeling with a life-cycle assessment (LCA) evaluation conducted by the Consortium for Research on Renewable Industrial Materials (CORRIM). The full LCA was needed to account for harvest and manufacturing emissions associated with different harvested wood products, as well as substitution effects (i.e., using wood (carbon sink) in place of other carbon intensive products (carbon source)) related to trade-offs inherent to the different forest management scenarios. Results of this effort will inform future prioritization of research, development of policy positions, and strategic decision making by land managers and forest product industries focused on utilizing the Minnesota forestry sector to reduce emissions and improve carbon sequestration and storage associated with forests and forest products.

1.2 Forest Carbon Baselines

1.2.1 Background

Minnesota's forests and forest products play an essential role in sequestering and storing atmospheric carbon. Sequestration is the photosynthetic process of removing carbon dioxide from the atmosphere, releasing oxygen back into the air, and storing the carbon in the biomass of live trees and other plants in the forest. Carbon also is stored in forest soils, as well as in dead trees and woody debris until the wood decays or burns whereby carbon is released back into the atmosphere as CO_2. When trees and woody biomass are harvested, some of the carbon remains stored in forest products such as lumber or paper, and some ends up stored in solid waste disposal sites. Eventually, forest products and solid waste disposal sites decay and the stored carbon is released back into the atmosphere.

Carbon baselines for forests and forest products establish a historic record of carbon storage and carbon sequestration trends over time. For the purposes of this report, sequestration is measured by the change in carbon stocks resulting from growth, mortality, or harvest. This change in carbon stocks is formally referred to as "net carbon flux". When reporting "carbon stock (C)" amounts, this report often uses the standard convention of "carbon dioxide equivalent (CO_2-eq)" as the metric. Both carbon stocks (C) and carbon dioxide equivalent (CO_2-eq) metrics are presented as million metric tonnes (MMT or MMtn) (one metric tonne (MT or Mtn) = 1,000 kg. or 2,204.6 lbs.) of CO_2-eq. As a general reference, 1 dry cord of wood equals approximately 1.5

MT of CO_2-eq. Also, although carbon dioxide is only one of several greenhouse gases (GHG) of concern for climate change, for the purposes of this report CO_2, CO_2-eq, and GHG are used interchangeably in reporting of research results. Finally, because forests remove CO_2 from the air, related CO_2-eq data are often presented on report graphs and figures as a negative number.

Forest inventory and analysis (FIA) program data were used as the basis for establishing a statewide forest carbon baseline and for comparing alternative forest management scenarios. Minnesota's FIA database is part of a nationwide program administered by the U.S. Forest Service that monitors and reports forest land carbon, carbon dioxide and other greenhouse gas emissions across all states consistent with the protocols of the Intergovernmental Panel on Climate Change (IPCC). FIA compiles data into separate forest carbon "pools" that include live trees, dead wood, forest floor litter, below ground roots, and soil. It also allows forest carbon data to be sorted by land ownership, geographic regions, or forest cover types.

Uniquely, this report also incorporates harvested wood from Minnesota's forests in its baseline, tracking carbon storage and emissions over time. This presents an added challenge. The length of time carbon remains stored in harvested wood varies significantly depending upon how the wood is used. For example, harvested wood used as firewood emits its stored carbon in a short period of time while the emission of carbon in sawtimber that is cut into dimensional lumber used in a building may not be emitted for decades or longer. This report uses forest product life cycle assessments (LCA) which are a widely accepted analytical approach for determining how and when carbon emissions should be incorporated into a forest carbon baseline. LCA's also incorporate the emissions of harvesting and transporting wood, as well as the manufacturing emissions associated with creating different forest products.

1.2.2 Carbon in Forests

Over the last 32 years (1990-2022), total carbon stocks associated with all forest biomass "pools" in Minnesota have increased from 4,150 MMT CO_2-eq in 1990 to 4,506 MMT CO_2-eq in 2022, an increase of 8.6% (Figure 1.2). Across all component pools, the largest increase has occurred in the aboveground biomass pool, where carbon stocks have increased from 741 MMT CO_2-eq in 1990 to 974 MMT CO_2-eq in 2022, an increase of 31.5%. In relative terms, the largest percent increase in carbon stocks has been in dead wood pools (+37.0%). Carbon stocks have also increased in belowground biomass (+32.5%), litter (+2.6%), and mineral soil (+0.62%), with a slight decrease in organic soil (-0.02%). In 2022, carbon stocks in belowground biomass represented 19.6% of the aboveground component. Carbon stocks in mineral and organic soil represented 63.6% of total forest ecosystem carbon in 2022 (Walters et al. 2023).

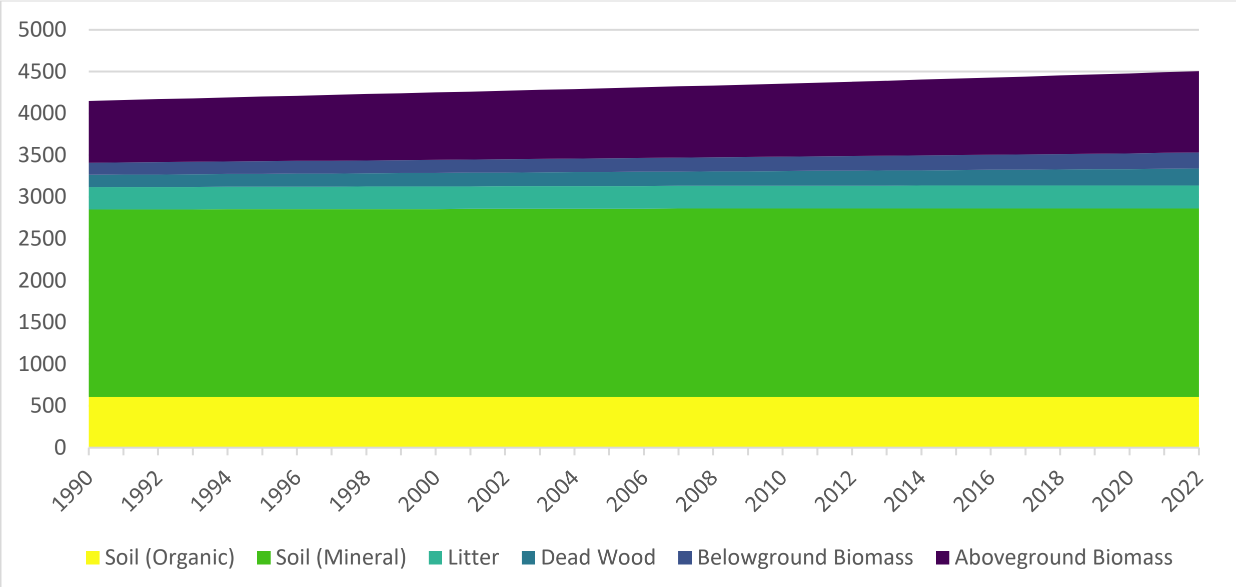

Figure 1.2. Carbon (MMT CO_2-eq) is distributed across several storage pools in Minnesota's forests. FIA and EPA report the total carbon stocks in these pools on an annual basis from 1990-2022.

1.2.3 Carbon in Harvested Wood

Additional analysis of historic timber product output from Minnesota's forests (Figure 1.3) was conducted to better understand the relationship of harvested wood and in-service wood products with total emissions from the forestry sector. Annual contributions of carbon to the HWP pool were tracked and can be displayed with annual storage in recycled and SWDS pools as well as end-of-life emissions (Figure 1.4). Tracking annual storage and emissions for all carbon pools also enables the display of stored carbon remaining in in-service HWP, recycled HWP, and SWDS over time (Figure 1.5). While cumulative HWP end-of-life emissions are substantial (~700 MMT CO_2-eq since 1821), remaining in-service HWP (including recycled content) also stores approximately 110 MMT CO_2-eq as of 2020.

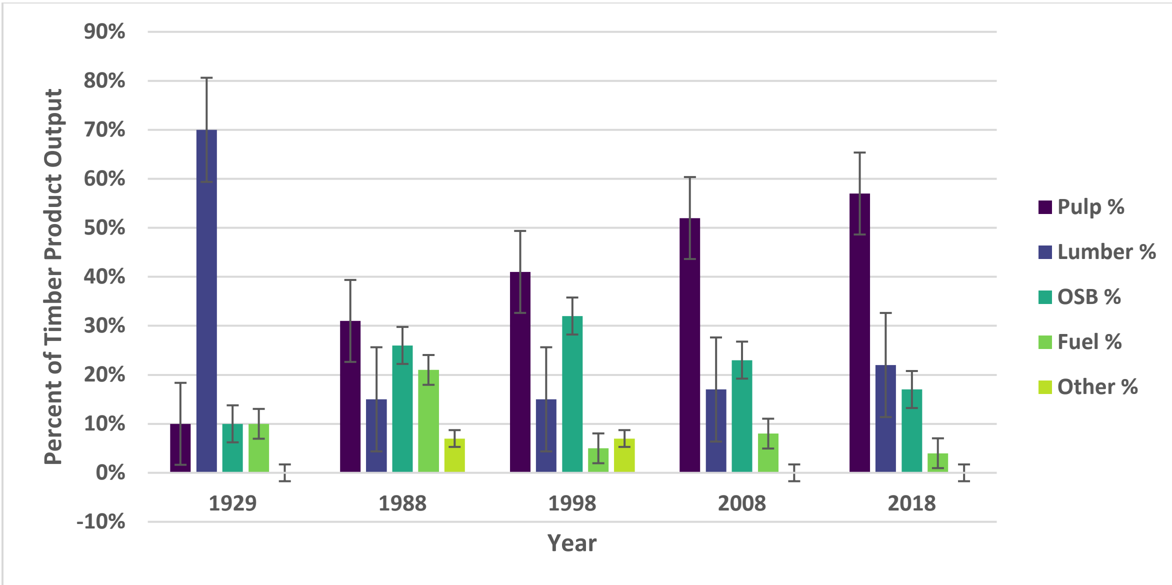

Figure 1.3. Timber product output distribution for Minnesota: 1929-2018. Note that standard errors shown are related to variability in the average TPO proportions for each pool published in MNDNR Forest Resource Reports (1985-2020). MNDNR does not publish standard errors associated with their TPO estimates.

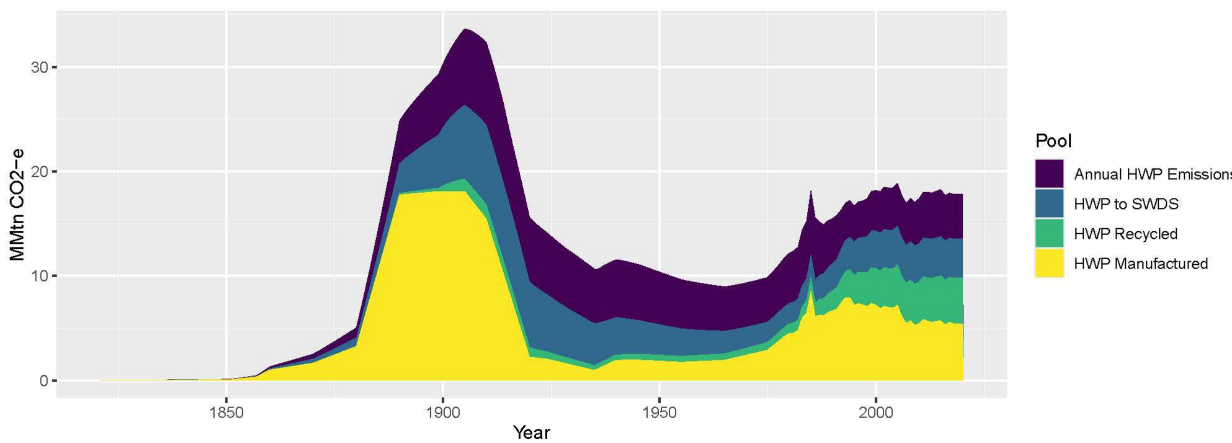

Figure 1.4. Annual harvested wood product production, emissions, and transfer to recycled and solid waste disposal site (SWDS) storage pools (1821-2020). Note: This figure does not include harvesting and manufacturing emissions.

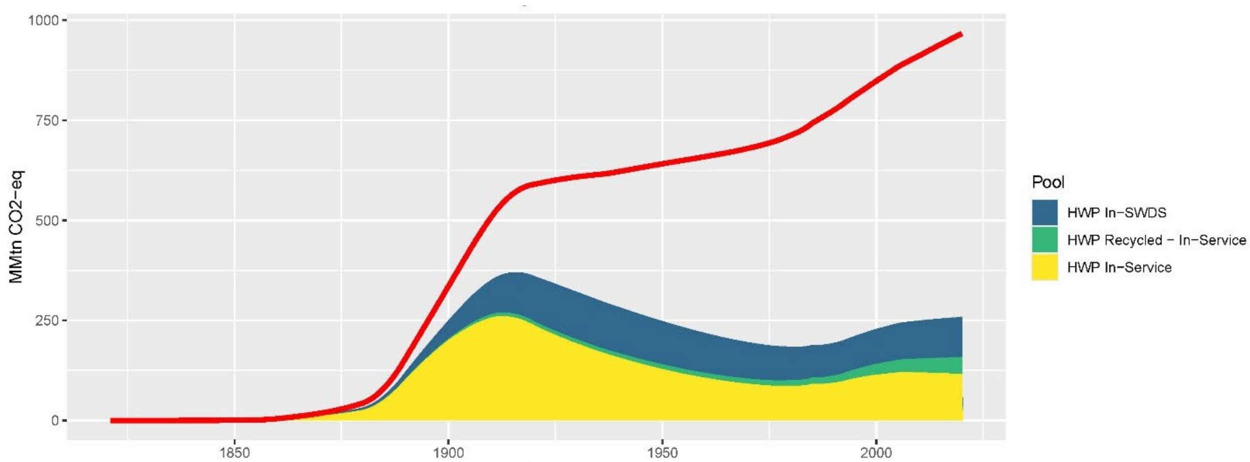

Figure 1.5. Cumulative harvested wood products produced (red line), in-service (yellow), and stored in recycled products (green) and solid waste disposal sites (blue) (1821-2020).

Estimates of harvested wood product (HWP) service lives and decay rates published by IPCC and others (IPCC 2019, Skog 2008, Alderman et al 2024) (Table 1.1) were combined with the historic TPO data (MNDNR 1985-2020, Minnesota Historical Society) to model the production and fate of stocks in different HWP carbon pools over time. Summaries of annual and cumulative stock change for carbon pools associated with historic HWP production are shown in Figures 1.4 and 1.5, respectively.

Table 1.1. Harvested wood product service and solid waste disposal site half-lives and fractions with production levels for 2020. Total HWP storage for 2020 (inflow) was 5,369,881 Mtn CO2-eq. Production, harvesting, and end of life emissions totaled 11,556,503 MT CO_2-eq with in-forest storage of 21,812,741 Mtn CO_2-eq more than balancing emissions.

Harvested Wood Product	Service half-life (years)	SWDS fraction	Recycle fraction	SWDS half-life (years)	Production 2020 (MT CO_2-eq)
Pulp and paper	2.53	0.32	0.54	14.5	3,060,831
Lumber	39	0.77	0.09	29	1,181,371
OSB and Engineered panels	25	0.32	0.54	29	871,385
Fuelwood	1	0	0	0	205,033
Other and specialty	20	0.32	0.54	29	0

1.2.4 Carbon by Region, Ownership and Products

Analysis of carbon baselines across Minnesota reveals several important differences in forest carbon attributes. For example, among the six forested regions in the state, northeast Minnesota contains 32.6% (326.0 MMT CO_2-eq) of the state's total above ground forest carbon stocks (1.0 billion MT CO_2-eq). Also, across the state, most carbon resources (45%) are associated with privately owned forestland. Collectively, public lands contain 55% of total forest carbon stocks, a percentage that is equal to the amount of public forestland in the state (9.8 out of 17.7 million acres of forestland area).

Forest management occurs at the stand level and specific silvicultural techniques depend on the forest cover type being managed. Thus, an understanding of how stand conditions influence forest stand dynamics is essential to understanding forest carbon baselines. Hoover and Smith (2021) observed average carbon stocks in aboveground live trees in the Northern Lake States to range from 43.5 to 88.6 MT CO_2-eq/ac in spruce/fir and maple/beech/birch forest types, respectively. While hardwood stands stored the most carbon, their sequestration rates were lowest, averaging 0.34 MT CO_2-eq/ac. Sequestration rates in Northern Lake States stands were highest in white/red/jack pine (1.10 MT CO_2-eq/ac) and aspen/birch forest types (0.67 MT CO_2-eq/ac) (Hoover and Smith 2021). Stand age also plays an essential role in determining the distribution of carbon across forests. In young Northern Lake States stands (0 to 20 years), average carbon storage in aboveground live trees is 17.0 MT CO_2- eq/ac compared to 89.9 MT CO_2-eq/ac in stands with ages between 81 and 120 years (Hoover and Smith 2023). Sequestration rates are highest in stands 0 to 20 years old, with an average rate of 1.68 MT CO_2-eq/ac. Sequestration rates are lowest in stands 61 to 80 years old, with an average rate of 0.21 MT CO_2-eq/ac (Hoover and Smith 2023).

1.3 Forest Types, Management Scenarios, and Models

Minnesota forests contain many different forest types that describe forest cover as either dominated by a single tree species or as groupings of several species. The forest was grouped into eight (8) forest types in this study: aspen/birch, red pine, upland spruce/fir, oak, northern hardwoods, lowland conifers, black ash, and other. The types represent the broad forest cover found in Minnesota, and many of the types undergo active forest management within the state. Black ash was included due to its important ecological niche and the peril facing the species from the invasive emerald ash borer. The "other" forest type contains all other cover types to ensure the accounting of all carbon across the landscape.

Within each broad forest type, four different forest management scenarios were modeled to provide better understanding of how potential shifts in management philosophy would impact carbon flux. Forest management scenarios and associated silvicultural prescriptions were developed and refined from discussions between project team members and comments from MFRC stakeholders. The term silviculture refers to the prescribed actions (or lack thereof) that tend the forest to meet management goals. The following provides an overview of each management scenario.

No management
No management treatments were applied in this scenario.

Business as usual (BAU)
Silvicultural prescriptions were identified for each forest type according to typical management strategies used in Minnesota. Harvests occurred at a rate identified by historical timber harvests that occurred within the forest type.

Climate-adapted
Silvicultural prescriptions were identified for each forest type that sought to promote forest resilience under an adaptive silviculture framework (e.g., Nagel et al. 2017). Characteristics included tree planting, shorter rotation ages, and managing for diverse species and stand ages.

Economic intensive
Silvicultural prescriptions were identified that sought to maximize economic return from forest management activities. Characteristics included shorter rotation ages and increased harvest intensities.

In addition, two scenarios were further refined for specific forest types to evaluate the effect of prescribed fire and the impact of emerald ash borer.

Climate-adapted + fire (*red pine and oak only*)
Identical to Climate-adapted scenarios, but with additional prescribed fires following management activities (e.g., prescribed burns following thinning).

BAU/Climate-adapted + emerald ash borer mortality (*black ash only*)
Identical to the Business as usual scenarios, but with increasing mortality rates for black ash that simulate the spread of emerald ash borer.

To simulate the forest management scenarios, FIA data for Minnesota were used in this study. The FIA program collects forest information on thousands of plots across the state and includes hundreds of variables. Plots are sampled over a five (5) year period with each cycle providing a complete snapshot of Minnesota's forestlands. This information facilitated (1) understanding of forest composition and structure across Minnesota's diverse forested landscapes, (2) determining historical harvest rates and timber products output within different forest types, (3) serving as input data to the simulation models for projecting the different management scenarios, and (4) calibrating the simulation models by individual forest type to increase accuracy and precision. All Minnesota data collected in the annual inventory design from 1999 through 2021 were used at some point during the analysis. Up to five measurements on the same FIA plots were available over the 22-year period. While FIA provides a detailed forest type classification for their inventory, FIA plots used in this study were placed into one of the eight different broad forest type groups defined herein.

All FIA data were used to estimate historical harvest rates across Minnesota and within each forest type. The annual harvest rate informed by FIA data was 0.92% of timberland acres, and within forest types, annual harvest/treatment rates ranged from 0.43% in lowland conifers to 2.51% in red pine forests. It is important to note that intermediate thinning (common in red pine) is included in the calculation of the 2.51% annual treatment rate.

The model used in the project was the Lake States variant of the Forest Vegetation Simulator (FVS). This model is informed by a detailed array of FIA tree growth data and grows individual trees provided to it across a user defined time horizon. In this study, tree data from the FIA plots previously described were used to define stands. The development of these stands was then projected over time with the addition of defined management actions (silviculture) corresponding to different broad approaches to managing the forest. Mortality, regeneration, harvesting, and carbon attributes were tracked, among many others. Critically, FVS was first intensively calibrated to local conditions using FIA data and Minnesota Department of Natural Resources harvest reports, then used to simulate the different forest management scenarios. FIA measurements collected between 2017 and 2021 were used as input data into FVS. Biomass and carbon calculations were provided from the Fire and Fuels Extension of FVS using the Jenkins et al. 2003 equations. Carbon storage and stock change rates were computed across the simulation period, including storage in various pools (e.g., aboveground biomass, belowground biomass, standing dead wood, downed dead wood, and forest floor). Simulations in FVS were run for 100 years. Mortality rates were calibrated to rates reported in the FIA database for Minnesota (20-year average).

1.4 Forest Vegetation Simulator Results

Across all forest types, average carbon stocks increased for all management scenarios throughout the 100-year simulation. Forests in the No management scenario had the greatest carbon storage. By year 100, however, Climate-adapted scenarios reached comparable levels of total carbon storage (127 tonnes CO_2-eq/ac) followed by BAU (119 tonnes CO_2-eq/ac), No management, and Economic intensive scenarios (107.5 tonnes CO2-eq/ac).

Carbon stock change rates generally decreased throughout the simulation across all management scenarios. Averaged across the 100-year simulation, stock change was highest in the Climate-adapted treatment (0.78 tonnes CO_2-eq/ac/yr), followed by BAU, Economic intensive, and No management (0.64 tonnes CO_2-eq/ac/yr).

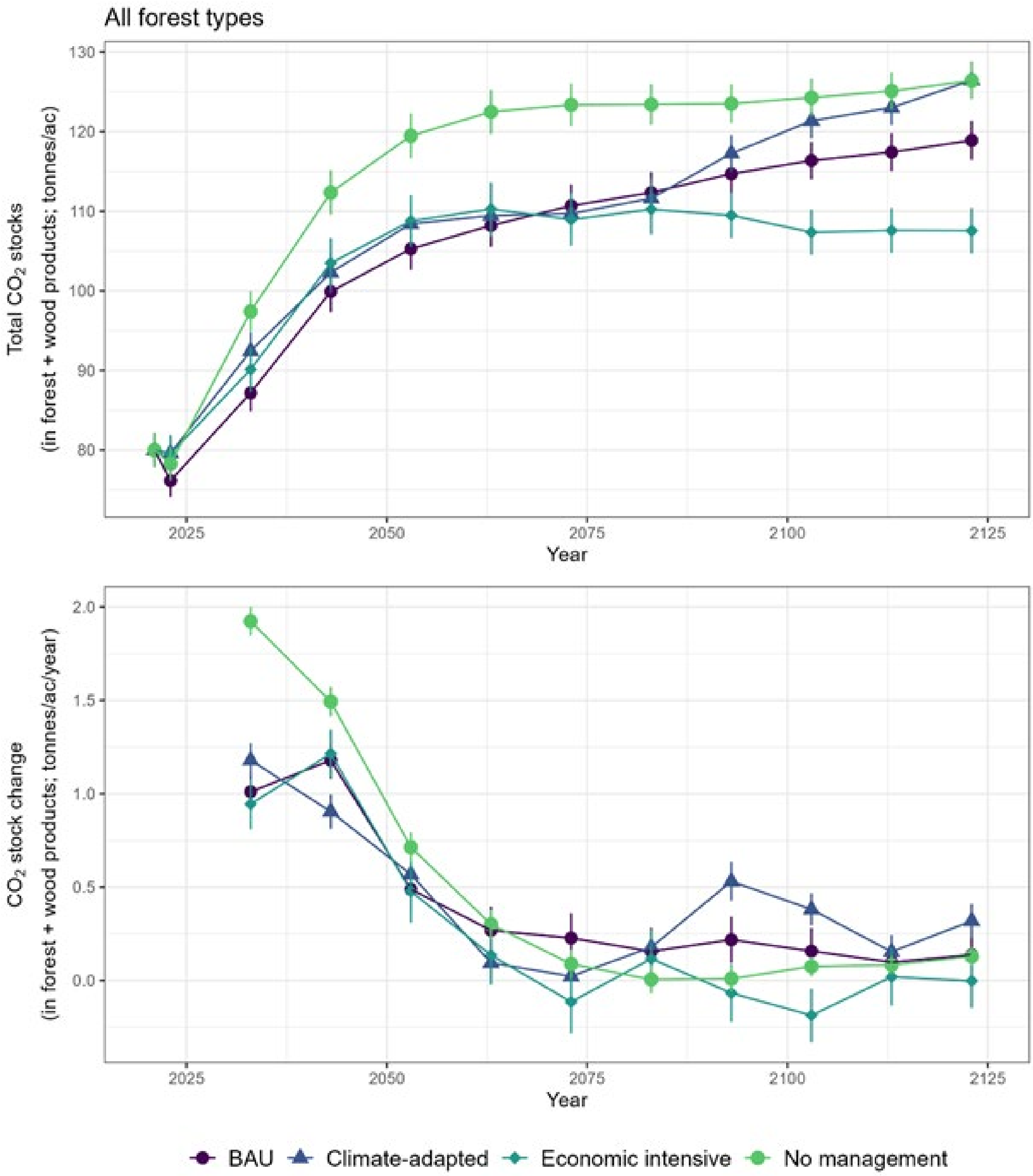

Figure 1.6. Mean forest carbon stocks and carbon stock change rates (in forest and in harvested wood products) for all forest types across each of the four scenarios. Error bars show ± 2 standard errors.

1.5 LIFE CYCLE ASSESSMENT

Life-cycle assessment (LCA) has evolved as an internationally accepted method to analyze complex impacts and outputs of a product or process and the corresponding effects they might have on the environment, including carbon emissions and storage. LCA is an objective method to evaluate a product's life cycle by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials uses and releases on the environment; and to evaluate and implement opportunities to effect environmental improvements. LCA studies can evaluate full product life cycles, often referred to as "cradle-to-grave" or incorporate only a portion of the product life cycle, referred to as "cradle-to-gate" or "gate-to-grave." Information in LCAs associated with this project include cradle-to-gate analysis and end-of-life stages to complete gate-to-grave analyses.

For each forest type by management scenario combination, detailed data on silvicultural inputs (planting, pre-commercial thinning, prescribed fire) and harvest alternatives (thinning, shelterwood, seed tree, clearcut) were developed to create a life cycle inventory (LCI) for a 'representative metric tonne' based on input data from the simulated scenarios. Data from Blinn and Nolle (2023) were mined to generate estimates for personnel transport distance, roundwood haul distance, opening size, and equipment utilization. These data were incorporated into the LCI models, along with the harvest volumes from the simulation data, to create a larger picture of the impacts of silviculture, harvesting, and hauling operations. Harvesting equipment was allocated to specific treatment/entry types based on a combination of recovered volume, green tree retention requirements noted in the prescription, and common system configurations.

After the product is removed from service, there are several possible outcomes for its fate. The product can be disposed via landfill, incinerated, or reused/recycled (which may or may not require reprocessing). The results presented include a 100% landfill scenario, a 100% incineration scenario, and an average of the two based on disposal rates from the EPA (EPA 2019) (82 % landfill and 18% incineration). Included in these end-of-life models is the collection of materials, transportation of waste material, and disposal of waste.

Allocated values for the BAU, Climate-adapted, and Economic intensive scenarios show some variability around an average value of 30.9 kg CO_2-eq/metric tonne of logs produced. The outlier in this scenario analysis is the Climate-adapted plus fire scenario, which shows substantially higher emissions due to repeated under burns in the red pine and oak forest types. Because the fire scenarios generated relatively little volume and had multiple burns over the 100-year scenario, the emissions per metric tonne of green logs are very high.

Among the various forest management scenarios, the contribution of forest resources varied from <1-34% of the total embodied carbon impacts of paper and textiles. The highest impact of forestry was the Climate-adapted plus fire management scenario, due to burning of red pine which still only represented about <2% of the pulpwood input. Oriented strandboard (OSB) had the highest embodied carbon over all the wood products (except pulp). On the other hand, OSB stores more carbon because it is a denser wood product and can utilize roundwood not suitable for lumber.

Every product and use has a different carbon impact. Wood growth, harvest, and manufacturing generates less carbon emissions than most other non-biobased materials which usually emit substantially more fossil fuel emissions during production. These differences for functionally equivalent materials (e.g., steel stud vs. wood stud) are what translate into climate benefits measured in carbon equivalents.

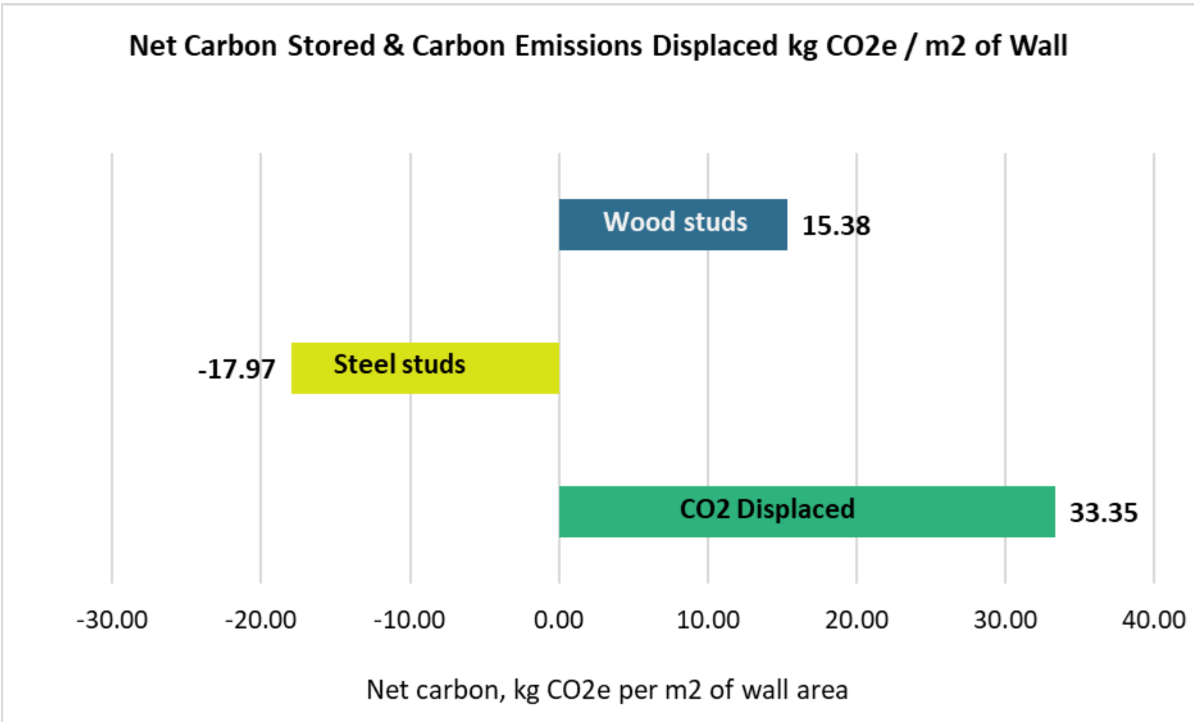

Figure 1.7. Comparison of the net carbon stored, emissions and carbon displaced for a wood stud versus a steel stud in one square meter of wall area.

1.6 Synthesis of Results

This study investigated the effect of four silvicultural scenarios (No management, Business as usual (BAU), Climate-adapted, Economic intensive) for all Minnesota forest types on forest sector carbon storage, sequestration, and emissions. Additional scenarios evaluated included prescribed burning for red pine and oak (Climate-adapted plus fire) and increased mortality due to emerald ash borer for black ash (BAU/Climate-adapted plus EAB). Simulations of forest stand development spanned 100 years, while life cycle assessments (LCAs) of harvested wood products covered up to 200 years. Considering the breadth of results from this study, we summarize the key findings and implications below.

Simulation results over 100 years show divergent trends when investigating carbon storage and carbon stock change across forest types and management scenarios across Minnesota. When interpreting modeling results from simulation experiments such as conducted here, it is essential to discuss carbon storage and sequestration as separate entities. It is the interplay between carbon sequestration and different storage pools existing at a landscape level that determines standing stocks and rates of change.

The statewide carbon storage estimates were expanded from average per acre carbon stores included in the above ground portions of live trees and in harvested wood products (HWP) (in-service or in a SWDS) (Figure 1.8). Average per acre carbon is calculated as the mean of the per acre values for live and removed trees simulated on FIA plots in FVS. This includes all forest types and conditions found on whole condition plots in the FIA database. Per acre carbon storage values projected over time were expanded to the full 15,799,295 acres of productive timberland in Minnesota to allow comparison of different broad management choices to the Business as usual scenario. This statewide expansion assumes the exclusion of non-productive and reserved forested acres. Initial FIA inventory estimates of in-forest carbon stores on timberland were adjusted with the addition of cumulative carbon stored in HWPs over time (Figure 1.8 black line), along with a decay factor assuming a 25-year average half-life for HWPs in-service or stored in SWDS. After the staggered initial projection period (2017-2023), the 100-year projections to 2123 were evaluated for key differences.

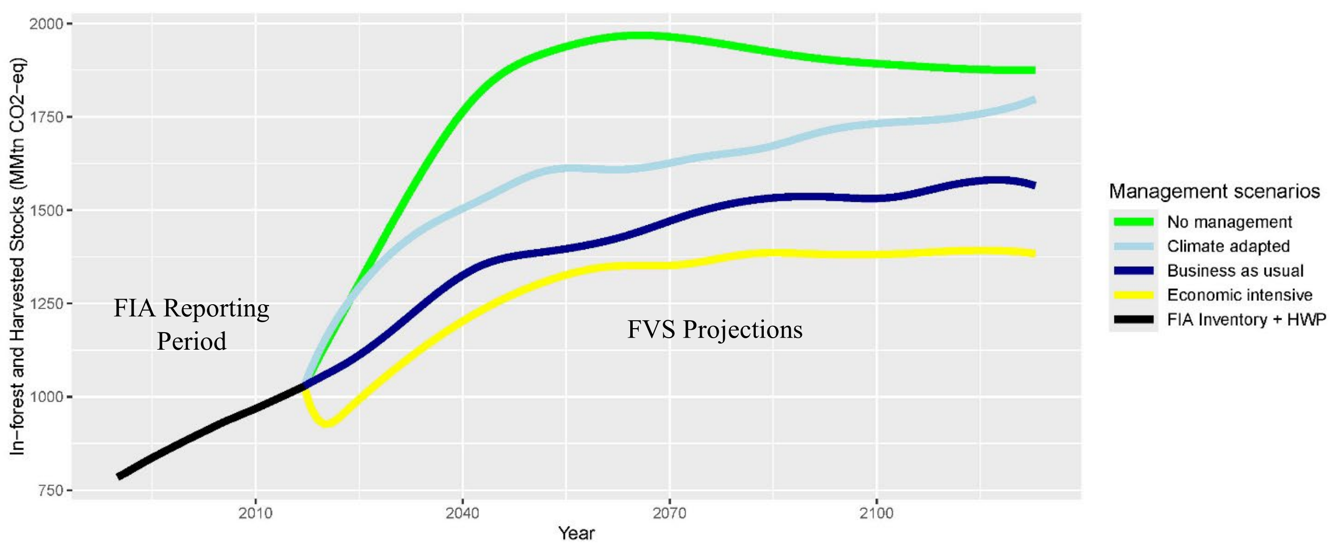

Figure 1.8. FIA inventory and cumulative harvested wood products (HWPs; 1990-2017) are depicted by the black line. FVS projected (2017-2021 to 2123) HWPs and in-forest above ground carbon stocks (MMT CO2-eq) under the four management scenarios illustrate the effect of management on carbon storage. The highest carbon storage is found under the No management scenario (green). The Business as usual scenario (dark blue) maintains its rate of stock growth (in-forest + stored HWP) over time, but removals lower in-forest stocks while recycling and SWDS storage tend to hold stocks for a longer period. The Climate-adapted (light blue) scenario resulted in increased in-forest stocks over time. Economic intensive (yellow) resulted in the lowest in-forest stocks over time due to increased removals. Note: This figure does include carbon stored in in-service HWPs and SWDS.

For all scenarios, in-forest and HWP carbon storage increases across the projection period, although at different rates due to differences in management paradigms (Figure 1.8). This increase in storage results at least in part from current harvest rates being approximately half of the maximum sustainable level (MN DNR 2024, GEIS 1994), resulting in continued carbon accumulation regardless of scenario. Other factors may include the lack of simulated large-scale disturbances and increased mortality due to changing climate conditions. The Business as usual scenario (dark blue line in Figure 1.8) depicts the result of average current management prescriptions and harvest levels simulated through time. This line serves as an important reference when comparing the carbon outcomes of alternative scenarios. The concept of additionality is always used with reference to the change nothing, or BAU, scenario.

The Economic intensive scenario (yellow line in Figure 1.8), defined broadly by a shortening of the rotation interval while managing the same total acres over time, shows lower total carbon storage than the other management scenarios, a trend that appears early in the simulation and continues until its end in 2123. This likely results from less carbon being stored in the forest due to removals and the effect of embodied carbon during production of HWP, although overall carbon storage increased across the projection period.

The light blue Climate-adapted scenario depicted in Figure 1.8 shows expanded average per acre carbon stores included in the above ground portions of live trees and in HWP (in-service or in a SWDS) over time. Assumptions underlying this scenario include using a series of partial harvest entries at 20-year intervals (for most forest types) with supplemental planting to increase resilience to changing climatic conditions. Although this scenario results in higher overall treatment rates, the many individual entries have smaller volume removals and thus store more carbon in live trees and in timber products than either the BAU or Economic intensive scenarios. However, in the absence of markets for forestry residual biomass, the multiple entries may present additional challenges to landowners and loggers trying to balance the cost of management with revenues generated by the sale of timber.

The No management scenario (green line) in Figure 1.8 depicts the average above ground live carbon stored in trees between 2023 and 2123. This No management line can be considered an average trendline for expected growth of carbon stocks on un-managed stands in Minnesota, barring large changes in mortality or reproduction due to climate driven disturbance. Carbon quickly accumulates on the landscape in the absence of harvest through 2060, then begins to decline due to naturally increased mortality. While evaluating landscape scale risks associated with retaining large stocks of fuel in the forest is beyond the scope of this study, the risks of wildfire should be considered in a full evaluation of likely climate outcomes associated with forest management (or lack thereof). Here, we do explore the likely carbon outcomes of making the choice to reduce or eliminate management from Minnesota's forests by considering carbon outcomes related to choosing more carbon intensive alternatives than wood (e.g., steel or concrete) and the likelihood of harvest simply being shifted to another region to meet timber demand. These phenomena are known as substitution and leakage, respectively, and are explored further below.

Substitution impacts are expected to reduce net CO2 storage from the No management scenario. An example of this can be found in Figure 1.9 in which the green No management line has been adjusted according to the product substitution equation for steel vs. lumber (Equation 1.1). This substitution assumes that all lumber (11.45% of total HWP production) that would have been used in construction is replaced by steel beams.

Equation 1.1: Relative kg/kg substitution effect for embodied and stored carbon in lumber vs. steel construction materials in terms of the substitution impact of using steel in place of 1 MT CO_2-eq contained in the harvested wood product.

$$-1\ Mtn\ CO2eq. -1.17\ Mtn\ CO2eq = -2.17\ Mtn\ CO2eq\ per\ Mtn\ material\ substituted$$

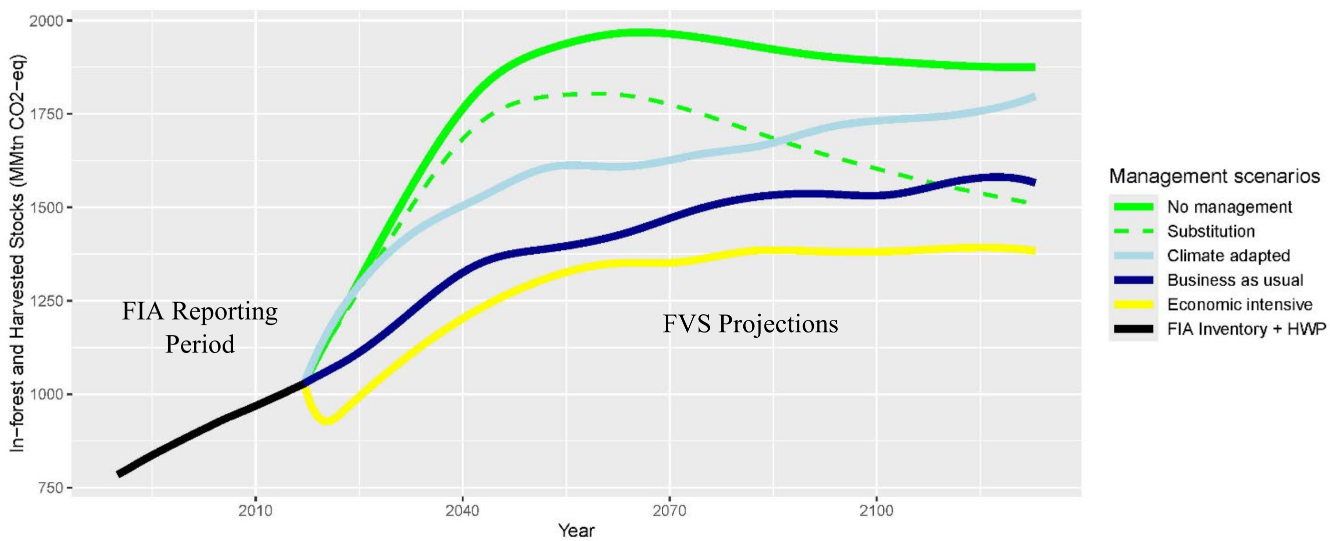

Figure 1.9. FVS projected (2017-2021 to 2123) harvested wood products (HWPs) and in-forest above ground carbon stocks (MMT CO2-eq) under the four management scenarios illustrate the effect of management on carbon storage. In this figure, the No management scenario (green) has been adjusted to account for the relative substitution effect (dashed line) of using steel instead of lumber as produced by the BAU scenario. Note: This figure does include carbon stored in in-service HWPs and SWDS.

Timber harvest leakage can be assumed to reduce the expected benefits of avoided HWP production in the No management scenario over time. Leakage occurs when a reduction in timber harvesting in one region causes an increase in timber harvesting elsewhere to meet timber demand. True leakage rates for the Northeastern United States are often in excess of 80% of expected emissions reductions (Gan & McCarl 2007, Wear & Murray 2004, Nepal et al. 2013). However, harvest leakage and carbon leakage are not always comparable (Daigneault et al., 2023), as some harvest may shift to more productive forested acres in another region, thereby improving the efficiency of harvest and resulting in increased growth on highly productive acres outside of Minnesota. Assumptions related to leakage depend on forest type, rotation length (and nature of changes), assumed implementation rates (for No management), permanency of harvest reductions, and market response via product substitution and other factors. Nevertheless, it is likely that harvest leakage from a No management scenario in Minnesota would be in the 50-80+% range (Figure 1.10). The reduction in carbon storage is even more pronounced when combined with the substitution effect (Figure 1.11).

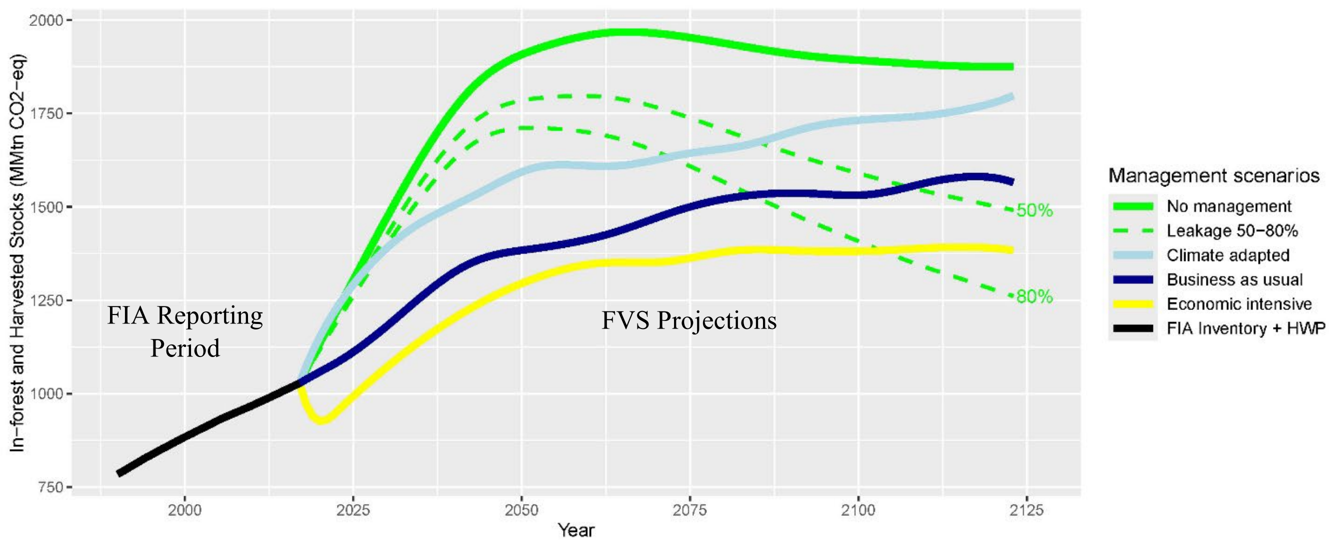

Figure 1.10. FVS projected (2017-2021 to 2123) harvested wood products (HWPs) and in-forest above ground carbon stocks (MMT CO2-eq) under the four management scenarios illustrate the effect of management on carbon storage. In this figure, the No management scenario (green) has been adjusted to account for the effects of leakage (dashed lines). Leakage of overall BAU harvest is assumed to vary between 50% (upper dashed line) and 80% (lower dashed line). Note: This figure does include carbon stored in in-service HWPs and SWDS.

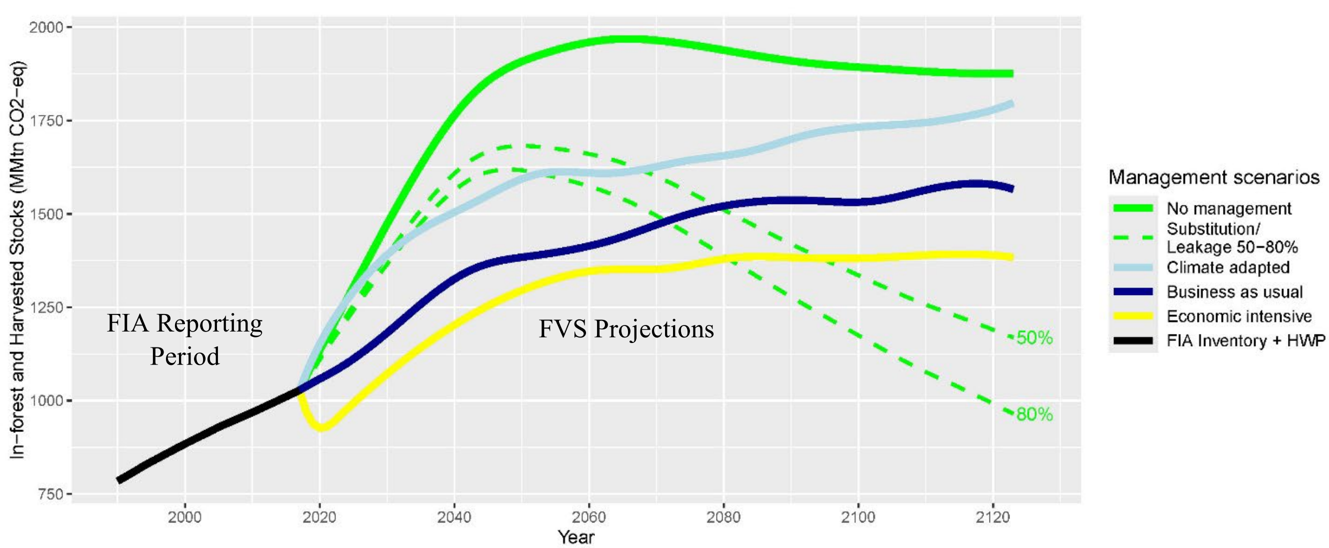

Figure 1.11. FVS projected (2017-2021 to 2123) harvested wood products (HWPs) and in-forest above ground carbon stocks (MMT CO2-eq) under the four management scenarios illustrate the effect of management on carbon storage. In this figure, the No management scenario (green) has been adjusted to account for the effects of substitution and leakage (dashed lines). Leakage of overall BAU harvest is assumed to vary between 50% (upper dashed line) and 80% (lower dashed line), while steel use is substituted for lumber. Note: This figure does include carbon stored in in-service HWPs and SWDS.

To further illustrate how HWPs store and release carbon over time, the Business as usual FVS estimates of harvested wood were used to forecast (via thousands of individual stand growth and harvest simulations) likely storage and emissions for HWPs produced between 2023 and 2123 (Figure 1.12). These estimates were fused with the historic estimates described above to create a carbon timeline for HWPs from Minnesota's forests spanning 300 years.

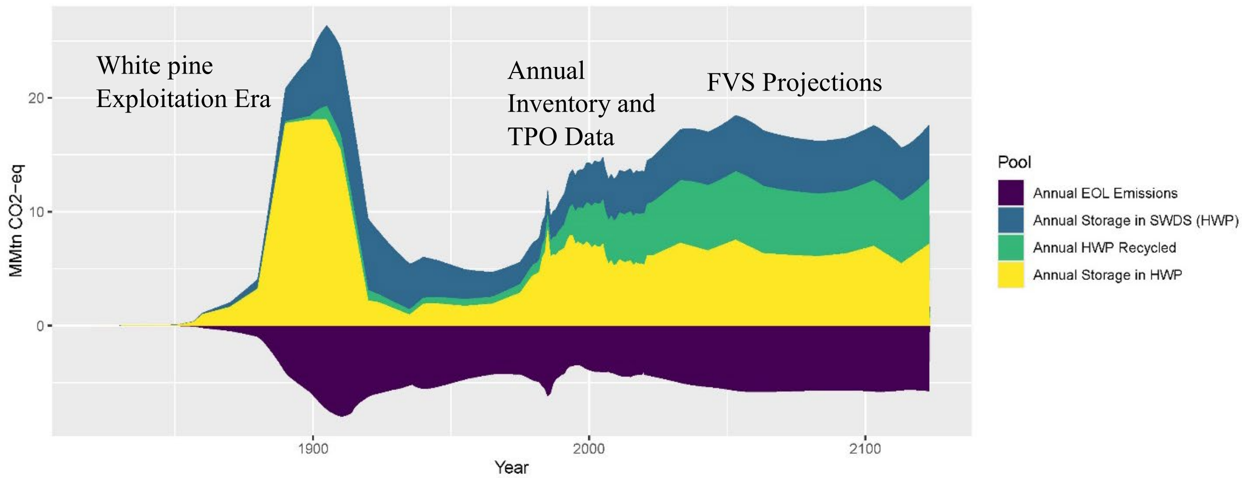

Figure 1.12. Historic harvested wood product production and carbon flow for Minnesota with projections for 2021-2123. Note: This figure does not include harvesting, transportation and manufacturing emissions as determined by the LCA component of this study.

Cumulative storage and emissions related to HWPs produced from Minnesota's forests are shown in Figure 1.13. Because current HWP production is nearly balanced by HWP end-of-life emissions and decay from service, the BAU scenario projects relatively level continued HWP storage in in-service products (~6 MMT CO_2-eq annually). The in-service HWP and recycled HWP storage pools continue to grow at a modest rate (~10 MMT CO_2-eq annually combined). Carbon storage in the secondary recycled HWP and SWDS pool is expected to continue increasing as a proportion of total storage.

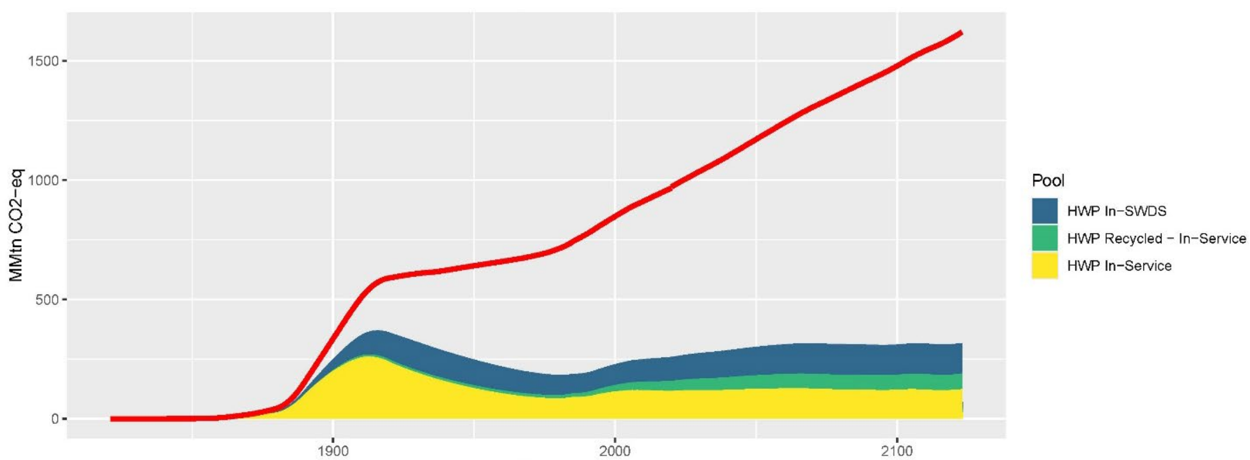

Figure 1.13. Estimated harvested wood product (red line, cumulative) storage in in-service (yellow), recycled (blue green), and SWDS (blue) storage pools with projections for 2021-2123 (BAU). Note: This figure does not include harvesting and manufacturing emissions.

Because calibrated FVS projections were run under different management scenarios and paired with a full life-cycle-assessment, we can now integrate the historic and projected HWP information with our understanding of in-forest carbon flux and processing and manufacturing emissions under different broad management projections (Figure 1.14).

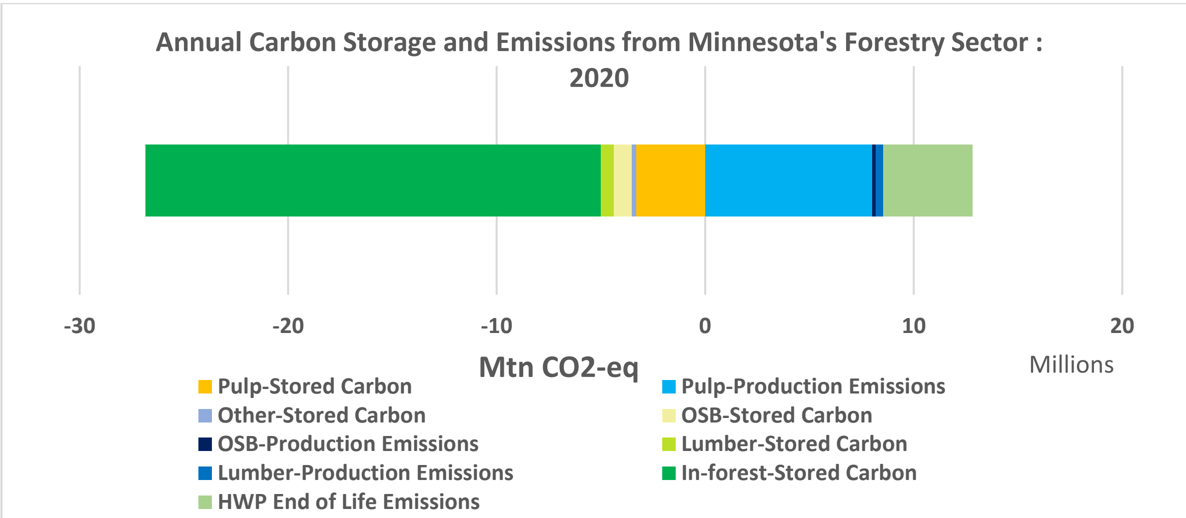

Figure 1.14. Annual life cycle assessment emissions, end of life emissions, and harvested wood product and in-forest carbon storage for Minnesota (2020).

When compiled with EPA and USDA-FIA reporting on Minnesota's in-forest carbon flux for the 1990-2022 period, an estimate of the trend in total forestry sector carbon flux can be generated (Figure 1.15). When balanced by emissions related to forestry and HWP manufacturing and end of life, the net annual storage in Minnesota's forests is approximately 10.7 MMT CO_2-eq in 2022 (26.96 MMT CO_2-eq storage – 16.24 MMT CO_2-eq emissions = 10.7 MMT CO_2-eq net storage). HWP harvesting, transport, and manufacturing emissions, on average, exceed storage of carbon in those products. This outcome is largely related to the substantial energy and industrial chemical footprint associated with pulp production for kraft pulp and viscose fiber-based industries. However, it is important to acknowledge that current management levels (including harvest) support the overall sustainability of forests in Minnesota as it continues to strengthen as a carbon sink.

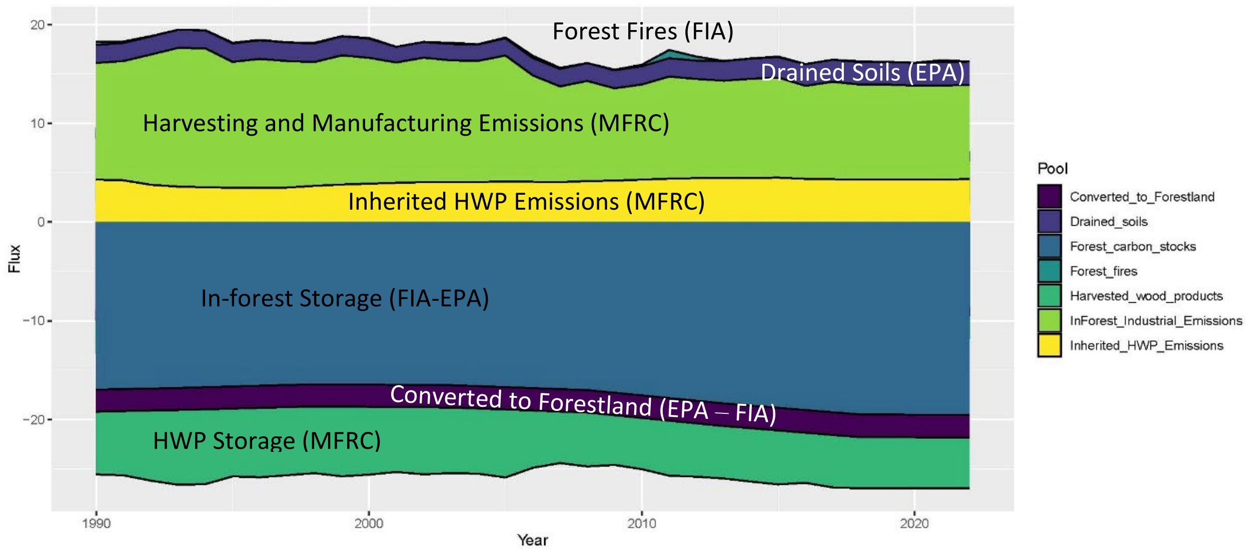

Figure 1.15. From 1990 to 2022, increasing in-forest carbon storage more than offset end of life and manufacturing emissions for Minnesota's harvested wood products. HWP storage and conversion to forested land use add to this effect.

As more wood fiber enters the pool of in-service HWPs each year, the annual end-of-life (EOL) calculation is based on an ever-growing quantity of carbon. This tends to increase annual EOL emissions to the extent that HWP production exceeds the rate of decay for in-service HWPs. Secondary storage of carbon in recycled and SWDS pools tends to further delay the eventual emission of carbon stored in those pools, especially for paper and other short-lived HWPs. This slow release of stored carbon can be seen in the graph of HWP emissions associated with the No management scenario (Figure 1.16). Cumulative total emissions continue to grow (height of the purple area in Figure 1.16), even if the harvesting and manufacturing of HWPs ceases.

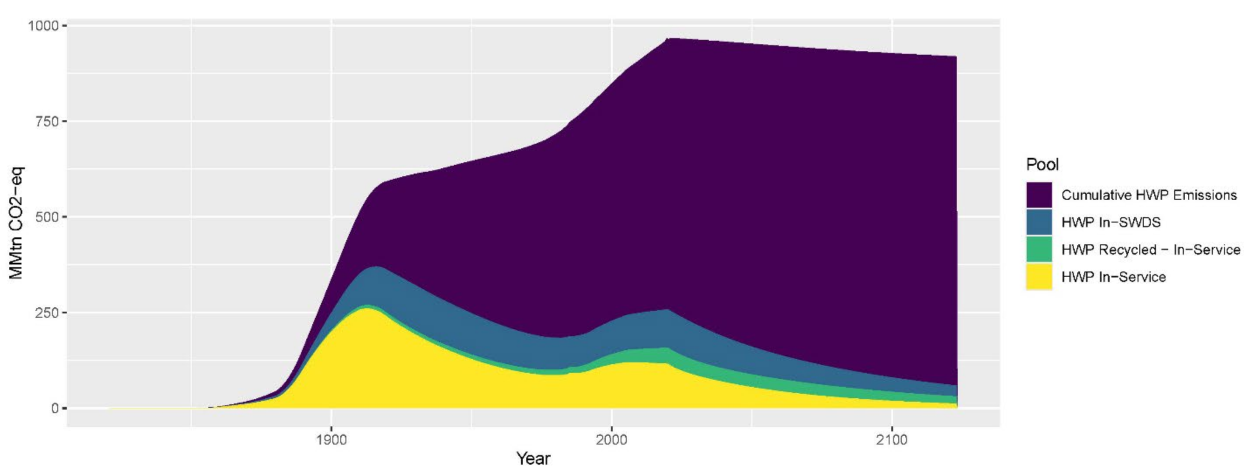

Figure 1.16. Historic cumulative harvested wood products in-service (yellow), recycled (blue-green), in a SWDS (blue), and emitted (dark purple) with projections for 2021-2123 (No management). For this non-managed forest scenario, HWP production drops to zero in 2023. Remaining stocks of in-service HWP

slowly reach their end-of-life and are emitted through combustion or transitioned through the recycled and SWDS carbon storage pools prior to emission. Note the continued growth in the size of the purple cumulative emissions and that this figure does not include harvesting and manufacturing emissions.

Important differences in total emissions and in the rates of carbon storage in HWP, recycled HWP, and SWDS pools can be seen by comparing the cumulative outcomes of HWP production in the FVS management scenarios for Economic intensive and Climate-adapted projections with the BAU and No management scenarios. Importantly, both the Economic intensive and Climate-adapted management scenarios resulted in increased HWP production, although through different harvesting regimes. Economic intensive management used clearcut with reserves combined with a shortened rotation length to increase the intensity of harvest on managed acres. Climate-adapted management used a larger number of more frequent entries with scattered removals to guide development of the forest towards greater resilience to changing climate conditions, resulting in relatively increased carbon storage over time.

1.7 KEY TAKEAWAYS

In summary, these results indicate that forest management activities within Minnesota's diverse forest types contribute to long-term carbon storage both within forests and in harvested wood products. By combining forest dynamics in response to different forest management scenarios (i.e., forest simulations) with an assessment of the environmental impacts associated with them (i.e., the LCA analysis), this study reveals that regardless of forest management scenario, forest carbon stocks will continue to increase with few differences from a life cycle perspective. The quantification of the substitution benefit of harvested wood reveals an important consideration of the benefits of managed forests. This report quantifies several nuances of forest carbon outcomes that can be weighed with other management approaches seeking to balance ecological, wildlife, economic, and many other benefits Minnesota forests provide.

In closing, several key takeaways from this study include the following:

1. Minnesota's forests are a carbon sink (i.e., they absorb more carbon dioxide from the atmosphere than they release) that offsets 15±3% of total statewide greenhouse gas emissions each year.
2. The amount of CO_2 sequestration and carbon storage that is occurring in MN forests and harvested wood products (Total Storage = 26.96 MMtn CO_2-eq per year) is very significant and exceed rates previously assumed for purposes of the Minnesota's Climate Action Framework.
3. Detailed calibration of the FVS model was needed to get accurate results.
4. Forest management activities within Minnesota's diverse forest types contribute to long-term carbon storage both within forests and in harvested wood products.
5. Differences in average growth rates resulting under various management scenarios contribute substantially differences in annual net carbon flux.

6. Regardless of forest management scenario, forest carbon stocks will continue to increase through 2050 with few emissions differences from a life cycle perspective.
7. Harvested wood and wood products emissions are more than offset by in-forest and HWP carbon storage (Net annual stock change = 10.7 MMtn CO_2-eq per year).
8. All forest management scenarios result in increased CO_2 sequestration and carbon storage over baseline conditions up to 2050 (+35% to 45% for AGB).
9. Long-term storage of sequestered carbon in harvested wood offsets carbon emissions associated with logging, hauling, and manufacturing of forest products and supports management for continued health and vigor (growth) of the forest.
10. Changes in net annual flux in above ground biomass pools account for most differences among scenarios.
11. In addition to maintaining health and vigor of the forest, management helps to reduce the risk of carbon stock loss to natural, and increasingly climate-driven, disturbances causing damage and mortality to trees, although this benefit was not modeled here.
12. Substitution of more carbon intensive materials for wood (i.e., steel beams instead of lumber used in structures) and leakage of deferred harvests to another region will dramatically reduce the perceived carbon benefits of the No management scenario over time. Beyond 2070, the managed scenarios including harvested wood products exceed the greenhouse gas benefits expected for No management.
13. After 2100, annual carbon sequestration and storage by Minnesota's forests slows (managed scenarios) or declines (unmanaged). Increasing total acreage of active forest management is needed to further increase carbon sequestration and storage beyond this period.
14. The quantification of the carbon storage and substitution benefit of harvested wood reveals that managed forests store slightly less carbon (due to removals) but accumulate carbon at a faster rate (increased growth).
15. Beyond 2050, annual CO_2 sequestration and carbon storage rates of the different management scenarios slow, stabilize or start to decrease. Lesser management resulted in a sharper decrease in storage rates over time.
16. The nuances of the forest carbon cycle can be evaluated in the context of the many and varied management approaches that seek to balance the climate, ecological, wildlife, social, and economic benefits forests provide; carbon is only one consideration.
17. The implications of large-scale disturbance and changing growth and mortality due to changing climate conditions should be considered when interpreting results, as these may significantly influence future forest conditions and trajectories.
18. The models and methodology developed for this project can be used or expanded to assess CO_2 storage and emission consequences of other forestry sector scenarios. Examples include:

a. Increasing or reducing harvest intensity or acres managed.
b. Expanding forest acreage by tree planting or reducing forest acreage through land conversion.
c. Utilization of different carbon pools (e.g., harvesting logging slash).
d. Producing different forest products (e.g., biofuel) that directly offset fossil carbon emissions.
e. Assessing the risk of increased forest disturbance or increased wildfire risk conditions resulting from climate change.
f. Comparing results associated with different types of land ownership (e.g., public vs. private).
g. Comparing results associated with different forest regions (e.g., Northeast MN vs. Southeast MN).

2 INTRODUCTION

2.1 BACKGROUND

Minnesota forests and forest products play an essential role in sequestering and storing atmospheric carbon. Sequestration is the photosynthetic process of removing carbon dioxide from the atmosphere, releasing oxygen back into the air, and storing the carbon in the biomass of live trees and other plants in the forest. Carbon also is stored in forest soils, as well as in dead trees and woody debris until the wood decays or burns whereby carbon is released back into the atmosphere as carbon dioxide. When trees and woody biomass are harvested, some of the carbon remains stored in forest products such as lumber or paper, and some ends up stored in solid waste disposal sites. Eventually, forest products and solid waste disposal sites decay and the stored carbon is released back into the atmosphere.

Carbon sequestration and storage also depend on the age of the forest. Generally, younger, faster growing forests sequester more carbon from the atmosphere, but their trees store less carbon in the forest. Older, slower growing forests sequester less carbon but retain much higher stocks in the trees. These tradeoffs directly influence management considerations for carbon, including sequestration, storage in the forest, and storage in harvested wood products.

The concept of using management of Minnesota's 17.7 million acres of forest to assist with both adaptation of the ecosystem to changing conditions and mitigation of the climate change driven increase in disturbance patterns (Wilson et al. 2019, Edgar and Westfall 2022) has gained substantial attention in recent years. While forestry represents the only economic sector with net negative emissions in Minnesota (Figure 2.1), the risks associated with climate change are potentially problematic. While forests represent a massive carbon sink (potentially removing substantial amounts of carbon from our atmosphere), changes in precipitation, temperature, evapotranspiration, insect and disease lifecycles, and more hold the potential to curtail future sequestration of carbon by the forest.

One line of reasoning is that by introducing additional tree species diversity and holding more of our forest at a slightly earlier developmental stage, we can improve adaptation of our forest to changing conditions. Balancing the goals of increased biodiversity and in-forest carbon storage over time yields a prescription which entails managing for larger trees overall, but with more numerous and smaller entries focused on maintaining a specified diameter distribution while introducing additional "future climate adapted" tree species and spurring greater regeneration of more mid to shade tolerant tree species.

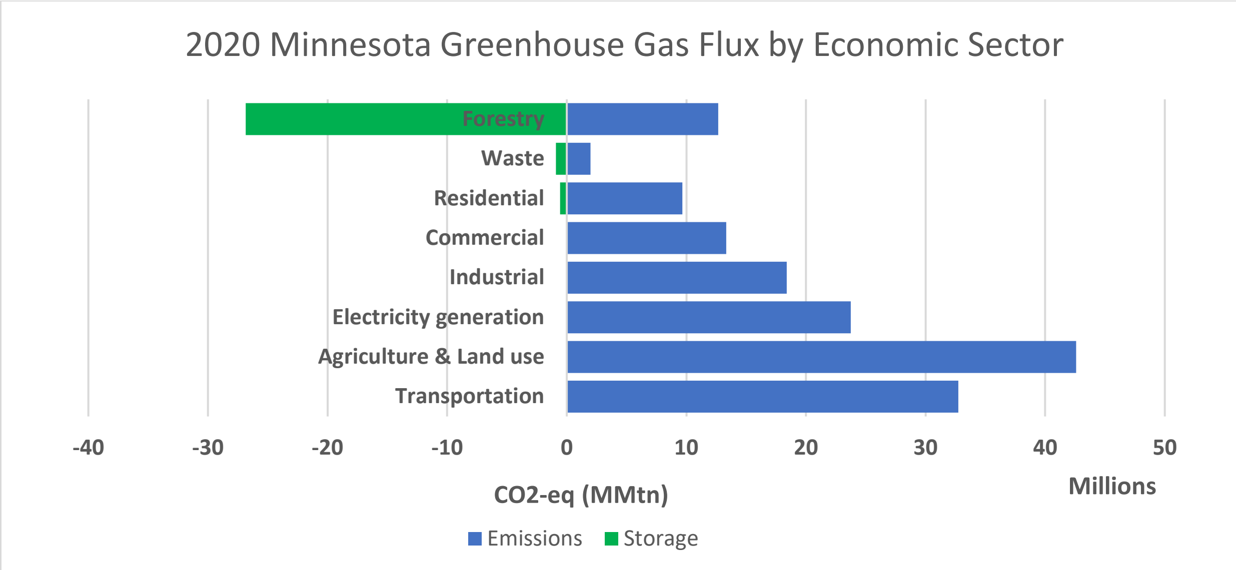

Figure 2.1. Forestry is the only economic sector that has "net negative" emissions in Minnesota. Graph generated from following data sources: 1. Minnesota Pollution Control Agency. "Greenhouse Gas Emissions (CO2-e Tons) by Sector, Activity, Source, GHG and Year." Greenhouse Gas Emissions Data, Tableau.com, 23 August. 2024, GHG emissions data | Tableau Public. Accessed 23 Aug. 2024, 2. Minnesota Department of Natural Resources Forest Resources Reports (1985-2020), 3. USDA-FIA, and current MFRC research.

Another line of reasoning is that by maintaining the forest at a younger overall age through economically intensive management, we can increase the average rate of carbon sequestration while simultaneously storing more carbon in harvested wood products. This management strategy would keep the forest at a younger, more adaptable developmental stage and hedge against increased forest disturbance by capturing the carbon from more trees that would otherwise have been lost to disease or wind or fire. However, this strategy would also favor faster growing tree species over long-lived species potentially able to store more carbon in the forest.

Others have proposed that reducing or eliminating harvest of trees would allow for greater in-forest carbon storage and produce maximum climate mitigation benefits over time. The literature related to pro-forestation details the reasoning behind this approach. Essentially, this approach maximizes in-forest carbon storage projected by growth models while assuming that substitution and leakage effects related to the decision to avoid using wood fiber for construction, textiles, energy, and other needs will be less than the total carbon stored.

Alternatively, a combination of approaches focused on sustainable management of our forests at something less than the maximum sustainable harvest level could achieve some of the objectives outlined in each of the strategies above. In fact, 20 years of timber management in Minnesota largely resembles this approach. Minnesota Department of Natural Resources (MN DNR) - Forestry provides an array of silvicultural prescriptions used to manage different forest types according to accepted forest regulation techniques (harvest scheduling and optimization are a part of the planning process for state forest lands). The management planning process balances timber management objectives with an array of other priorities and values related to the forest (biological, social, economic). The result is that most public lands are managed on something like an economic rotation, but with numerous exceptions related to alternative priorities. Conversely, most family forest lands in Minnesota are not actively managed on an economic rotation. Instead, many landowners are opting to postpone harvest, leading to older (and bigger), but less vigorous forests more prone to change through increasing climate related disturbance.

The potential trade-offs among these competing management strategies are unclear. Therefore, in order to understand the short and long-term carbon consequences of different forest management scenarios, the Minnesota Forest Resources Council (MFRC)[1] has commissioned a forest carbon baseline and life-cycle assessment (LCA) study for Minnesota's forests, including harvested wood products. A full LCA is needed to account for embodied emissions (embodied emissions result from energy and chemical inputs related to harvesting, transport, and manufacturing of timber and finished wood products) associated with different harvested wood products, as well as substitution and leakage effects related to trade-offs inherent to the different management scenarios and decisions.

As background, the MFRC previously commissioned a synthesis of the current status of carbon in Minnesota's forests by researchers at the University of Minnesota, Department of Forest Resources (Russell et al. 2022). This report presented nine key information needs related to carbon in Minnesota's forests and forest products. The MFRC identified two information needs from this report to be further explored in the current research effort. Results of this effort will inform future prioritization of research, development of policy positions, strategic decision making by land managers, and forest product industries focused on utilizing the Minnesota forestry sector to reduce emissions and improve carbon sequestration and storage associated with both forests and forest products.

2.2 Information Needs

This project seeks to address two information needs related to carbon in Minnesota's forests and forest products.

> ***Information Need #1****: Understanding Minnesota's current forestry sector carbon storage and emissions baselines, including products; and developing, improving, and reporting this*

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1 The Minnesota Forest Resources Council (MFRC) was established under the authority of Minnesota's Sustainable Forest Resources Act MN Stat. 89A for the purpose of developing recommendations to the governor and to federal, state, county, and local governments with respect to forest resource policies and practices that result in the sustainable management, use, and protection of the state's forest resources. MFRC consists of 17 forest stakeholder members appointed by the Governor to broadly represent the environmental, economic, and social values of Minnesota forest resources.

information for both forests and forest products in a form that is accessible, understandable, and useful to broad audiences.

The first information need addressed by this research is understanding Minnesota's current forestry sector carbon storage and emissions baselines, including products; and developing, improving, and reporting this information for both forests and forest products in a form that is accessible, understandable, and useful to broad audiences. This need includes the analytical development of carbon storage, sequestration rates, and emission baselines resulting from various forest management scenarios and harvest levels, including business as usual as tracked by statewide inventory data, harvest rates, and timber product utilization levels published by MN DNR. This research will support discussion of proposed carbon storage, sequestration and emission management scenarios including net carbon flux associated with past, current, and future forest management. This discussion will support establishment and potential expansion of Minnesota's contribution to climate mitigation efforts. Enhanced understanding of Minnesota's forest carbon baseline will help to guide future efforts to enhance total carbon sequestered and stored by the forest, and as an index to annually monitor future storage, sequestration rates and emissions.

Information Need #2*: Conduct life cycle assessments (LCA) of forest management intensities and strategies and harvested timber for products, with focus on carbon storage and emission reductions to better understand adaptation strategies, substitution effects, opportunities, and tradeoffs.*

The second information need addressed here is a life-cycle assessments (LCA) of forest management intensities and strategies and harvested timber for products, with focus on carbon storage and emission reductions to better understand adaptation strategies, substitution effects, opportunities, and tradeoffs. This research aims to account for carbon sequestered and stored in Minnesota forests under different management intensities and scenarios and forest products generated from Minnesota's forests over a 100-200 year timeframe. Preferred carbon pools to be evaluated include above and below ground biomass, soils (organic and mineral), products, decay emissions, emissions from fire (prescribed), insects and disease, harvest emissions, and manufacturing and transportation emissions. Reductions in emissions should include substitution effects (the use of wood vs. another carbon-intensive material). The LCA aims to compare the carbon outcomes of alternative forest management scenarios that are applicable to Minnesota forests (cradle-to-gate) and of HWPs resulting from these forest management scenarios (gate-to-grave).

2.3 Desired Outcomes

The results of this research are intended to explain the relative short and long-term outcomes of different forest management strategies in light of their carbon consequences. It is anticipated that the extensive foundation of science and knowledge around forest growth and yield, forest regulation, harvest scheduling, and yield optimization will be valuable in both the development of needed methodology and the interpretation of results.

Two measures of success will include: 1) Can results be explained using accepted forest science, and 2) Does the Business as usual scenario perpetuate a reasonably continuous flow of fiber to markets while maintaining reasonable growth expectation, based on levels from recent statewide inventories and MN DNR Forest Resources Reports?

This research will enable the MFRC, stakeholders, policy makers, scientists, land managers, forest product industries, and the public to better understand the long-term carbon impacts that are associated with different forest management strategies, as well as the potential for development of new bio-based products derived from Minnesota's forests. The results of this research will contribute to the Minnesota Climate Action Framework (n.d.) and dovetail with international, national, and regional efforts to address climate change through improved understanding of carbon cycles and trends associated with forests and forest products.

2.4 Caveats/Limitations

For several reasons discussed below, careful consideration should be given when interpreting results from this study. The forest projections could not directly model all the influences on carbon storage and flux within the forest. Therefore, several assumptions had to be made regarding these unmodeled natural processes, activities, and other factors that affect forest carbon. In addition, the study focused on a specific range of management goals and resulting actions. The following explores the implications of these assumptions and scope on interpretation and application of the results.

2.4.1 Management goals

This project narrowly focuses on one possible management goal: carbon storage and sequestration. However, in practice, forest practitioners and landowners consider many other objectives. These include promoting and/or maintaining wildlife habitat, recreational space, valuable timber, carbon credits, cultural resources, and clean water, among many others. The results and discussion surrounding each management scenario evaluated in this study emphasize the implications for the forest carbon life cycle only. Other management goals may be positively or negatively affected by the same management strategies. Typical forest management seeks to balance diverse landowner goals, and interpretation and application of project results must acknowledge the other factors influencing forest management decisions.

2.4.2 Envelope of management scenarios

The four main management scenarios modeled in the study were selected to provide a range of silvicultural approaches and management goals. Business as usual represents the "average" management paradigm currently in use in Minnesota, and the other scenarios provide alternatives across the spectrum of approaches. In reality, on-the-ground management across the state includes all four approaches to varying degrees. However, in order to provide an envelope of possible outcomes across the state, management scenarios were applied to all acres within all forest types. The results illustrate what could happen if select silvicultural prescriptions were applied uniformly statewide. Interpretation of results should include the understanding that scenarios reflect "what-if" situations, rather than expected future management.

2.4.3 Catastrophic Disturbances

The effects of frequent prescribed fire and spread of emerald ash borer were modeled directly. In addition, the Forest Inventory and Analysis (FIA) data used to calibrate the model includes information from all stand histories, and thus the models will reflect the effects of low to moderate disturbances. However, simulating stand-replacing disturbances such as insect outbreaks, drought, windthrow, and wildfire were beyond the scope of this project and assumed absent aside from disturbance related mortality rates informed by FIA monitoring. The lack of large-scale increases in modeled disturbances prevents some of the treatments (e.g., Climate-adapted, economically intensive) from demonstrating their potential to limit impacts. This limits comparisons between the managed scenarios and the No management scenario, with the latter carrying higher risk of loss and substantial carbon emissions under large disturbances. When assessing results across scenarios, interpretations should consider the risk and potential effects of large disturbances on the carbon stored in-forest and in harvested wood products (Figure 2.2).

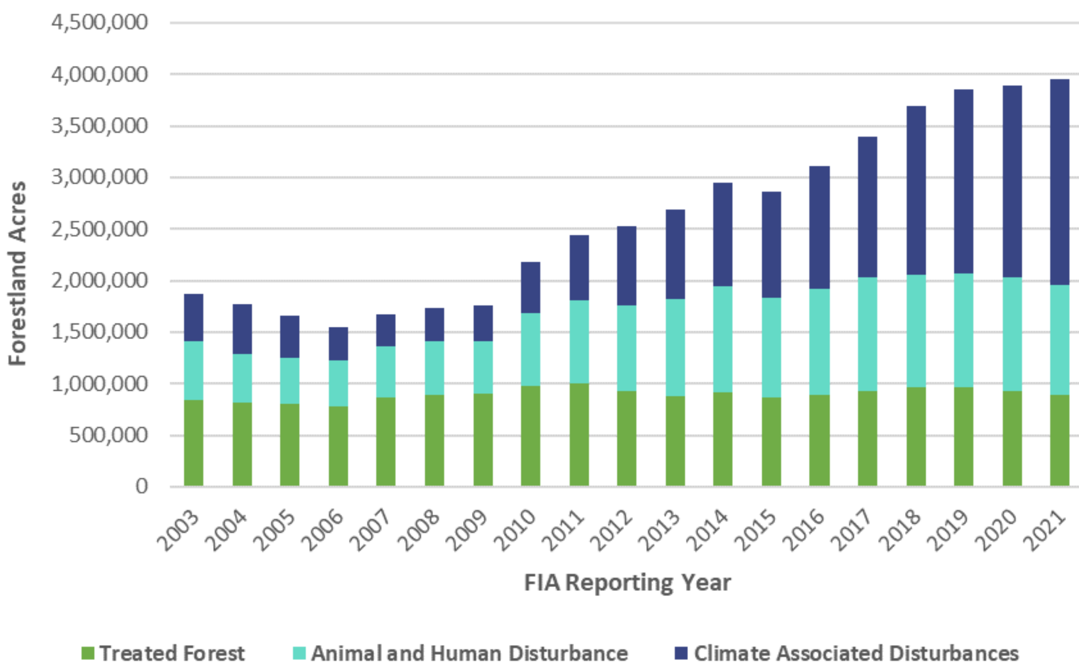


Figure 2.2. Forest disturbance trends in Minnesota (2003 – 2021) associated with climate change (insects, disease, wind, fire, drought, flooding, and extreme weather), animal and human disturbance, and intentional treatment or management of the forest. USDA-FIA 2021 (EVALIDator 2.1.0 (usda.gov))

2.4.4 Changing climate conditions

Similar to large disturbances, simulating the effects of changing climate conditions on carbon pools was beyond the scope of this project. Climate variables such as temperature and precipitation have been forecasted by others to change over the projection period (Lee et al. 2021), potentially leading to different forest type responses to management paradigms. In particular, the Climate-adapted approach was developed to minimize the effect of these climate shifts. Without directly including climate effects in the model, some management scenario comparisons will be less pronounced. Interpretations of results should understand that climate conditions were assumed constant and consider the implications of changing conditions when drawing conclusions.

2.4.5 Area, volume, and product control

Forest management scenarios that included harvest were controlled to project relative departures from current levels of harvest by acres and volume over time. Annual removals were held roughly constant across the projection period for BAU to allow direct comparisons between the scenarios. The mix of harvested wood products currently produced in Minnesota were also held constant through time. Additionally, it was assumed that the 2021 above ground and harvested carbon should have the same total for all scenarios. Other considerations beyond the scope of this project included raising the harvest levels to maximize sustainable fiber supply, expanding acres managed in a given year, introducing new mills or other wood processing infrastructure, adding alternative forest products (e.g., sustainable aviation fuel), and changing market conditions. Readers should consider the implications of changing harvest levels and economic factors when interpreting study results.

2.4.6 Prescribed fire

The results from the prescribed fire silviculture scenarios suggest these frequent (every 20 years) burns for red pine and oak led to substantial emission of carbon dioxide into the atmosphere, largely due to the combustion of fossil fuels in the transport of personnel and equipment to the large number prescribed burns modeled in each decade. The global warming potential as calculated in the LCAs showed 10-fold increases over management approaches without prescribed fire. Other considerations include reducing risk of catastrophic fire and resulting carbon emissions, cultural values, and forest health, among others. The prescribed fire results from this study should be evaluated in light of the many other factors surrounding using fire as a management tool, as well as assumptions used by FVS to project combustion of duff, organic soils, and coarse fuels under prescribed or cultural fire conditions. Another important consideration is that the large number of acres subjected to prescribed burning in the model is probably not achievable in real life, so overall emissions would be lower. Also, the number of personnel and acres treated is modeled after documentation from a prescribed burn on the Otter Creek unit of the Cloquet Forestry Center. This was a training burn and may not be representative of staffing or equipment levels used in other prescribed fires.

2.4.7 Black ash decline

The business as usual (BAU) and climate adaptive scenarios for black ash assumed no increased mortality from emerald ash borer. In the future, if weather remains prohibitively cold for the borer to spread north, these baseline simulations will appropriately reflect those conditions. However, under the assumption that temperature will not substantively restrict the spread of the borer, the BAU/Climate-adapted scenarios with increased mortality will better reflect those conditions. However, under the increased mortality scenario, the expected swamping effect was not modeled. If black ash are removed from a hydric ecosystem, they will no longer transpire significant amounts of water during photosynthesis, leading to several studies suggesting the water table will rise considerably (e.g., Slesak et al. 2014, Kolka et al. 2018). This increase in water levels may drown the roots of other tree species, effectively turning black ash stands into open wetlands. Readers should consider the potential swamping effect when interpreting results for black ash.

2.4.8 Landscape (Not Stand) Scale

The Forest Vegetation Simulator (FVS) projections of each silvicultural scenario represent effects across all acres of a particular forest type. The treatments were applied to every whole condition plot in the FIA database, and the resulting trendlines show the average per acre response across all sites. Application of the silvicultural prescriptions to individual stands might provide results that look very different from the figures in Chapter 4. Thus, interpretation of the FVS projections should emphasize the collective response of a forest type across Minnesota and not assume individual stands will necessarily respond the same way.

2.4.9 Substitution and leakage effects

In the LCAs, substitution effects refers to the carbon benefit of using wood (carbon sink) versus another carbon intensive product (carbon source). For example, using wood studs instead of steel studs to construct a building. Accounting for substitution becomes more critical under the No management scenario, as alternative products will be needed to replace those previously supplied by wood fiber. Alternatively, the wood supply could come from outside sources (e.g., Wisconsin) (termed "leakage"). Section 5.4.8 provides extended discussion and multiple case studies regarding the substitution benefits of using wood in the context of this project. Chapter 6 provides estimated impacts of both substitution and leakage on statewide results under the No management scenario. However, fully tracking both substitution and leakage was beyond the scope of this study. Comparisons between silvicultural scenarios with and without management should recognize the broader implications of substitution and leakage effects when interpreting results.

3 FOREST CARBON BASELINE INFORMATION

3.1 MINNESOTA'S FOREST CARBON PROFILE

3.1.1 All Forest Types

The state of Minnesota and its forests play an essential role in the carbon cycle. Throughout this project, carbon will be referred to as **storage** when discussing the amount of carbon in a tree or forest. Carbon will be referred to as **sequestration** when it refers to the process by which trees and other plants use carbon dioxide and photosynthesis to store carbon as plant biomass. Hence, carbon storage reflects a physical amount that is the result of sequestration. Carbon will be referred to as **stock change** when it refers to carbon accumulation rates as a difference between points in time (Hoover and Smith 2023). Over the last 32 years, in forests that have remained forests total forest ecosystem carbon stocks in Minnesota have increased from 4,150 million metric tonnes of CO_2-equivalent (MMT CO_2-eq) in 1990 to 4,506 MMT CO_2-eq in 2022, an increase of 8.6% (Figure 3.1). Across all component pools, the largest increase has occurred in the aboveground biomass pool, where carbon stocks have increased from 741 MMT CO_2-eq in 1990 to 974 MMT CO_2-eq in 2022, an increase of 31.5%. In relative terms, the largest percent increase in carbon stocks has been in dead wood pools (+37.0%). Carbon stocks have also increased in belowground biomass (+32.5%), litter (+2.6%), and mineral soil (+0.62%) with a slight decrease in organic soil (-0.02%). In 2022, carbon stocks in belowground biomass represented 19.6% of the aboveground component. Carbon stocks in mineral and organic soil represented 63.6% of total forest ecosystem carbon in 2022 (Walters et al. 2023).

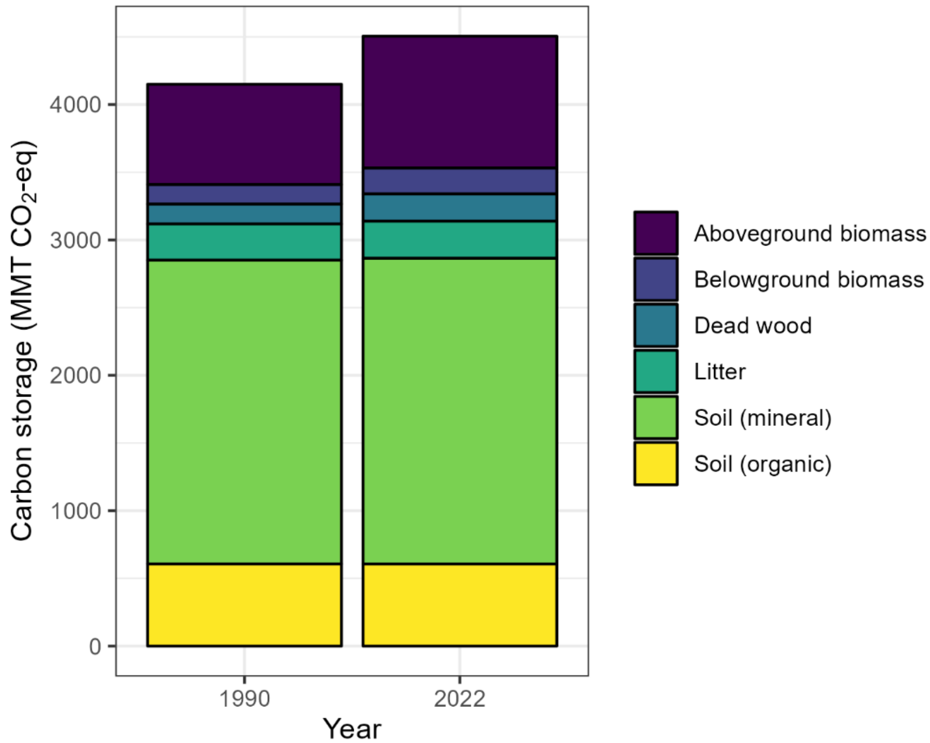


Figure 3.1. Carbon stocks in forests remaining forests in Minnesota in 1990 and 2022 (Walters et al. 2023).

Analysis of geographic trends across Minnesota reveals important differences in forest carbon attributes. Most of Minnesota's forest carbon resources are found in northeast Minnesota (FIA's Aspen-Birch survey unit), followed by the Northern Pine, Central Hardwood, and Prairie survey units (Figure 3.2; Table 3.1). Across the state, public lands contain 55% of total forest carbon stocks, a percentage that is equal to the amount of public forestland in the state (9.8 out of 17.7 million acres of forestland area). On a per acre basis, forest carbon stocks are highest on public lands in the Prairie (86.3 MT CO_2-eq/ac) and lowest on private lands in Northern Pine and public lands in the Central Hardwood units (76.0 MT CO_2-eq/ac).

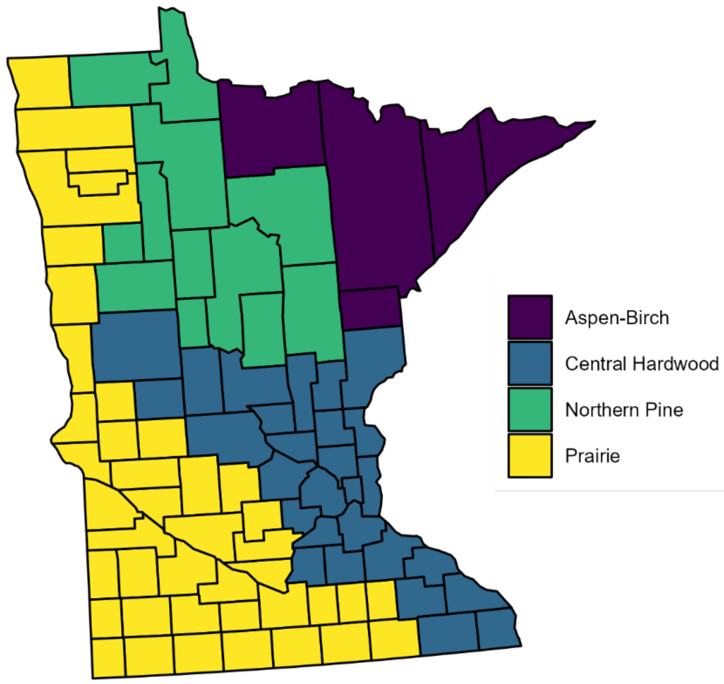


Figure 3.2. Location of four survey units identified in the Forest Inventory and Analysis program in Minnesota.

Table 3.1. Distribution of forest carbon across Minnesota's four survey units identified in the Forest Inventory and Analysis program in Minnesota, 2017-2021.[1]

FIA survey unit	Ownership	Forested acres	Forest carbon (MMT CO_2-eq)[1]	Forest carbon per acre (MT CO_2-eq/ac)[2]
Aspen-Birch	Public	5,382,309	1,574.3	78.9
	Private	2,102,906	586.0	78.8
Northern Pine	Public	3,626,235	1,010.0	79.8
	Private	2,946,897	822.5	76.0
Central Hardwood	Public	600,164	189.9	76.0
	Private	2,213,444	661.5	76.1
Prairie	Public	144,210	45.7	86.3
	Private	649,646	216.5	81.5
All Survey Units	Public	9,752,917	2,819.8	78.9
	Private	7,912,893	2,286.0	78.8
TOTAL		17,665,810	5,106.3	78.8

[1] FIA EVALIDator estimates, https://apps.fs.usda.gov/fiadb-api/evalidator
[2] Forest carbon pools include live aboveground, live belowground, dead wood, litter, and organic soil.

Forest management and silvicultural techniques occur at the stand level, hence, an understanding of how stand conditions influence forest stand dynamics is essential to understanding forest carbon baselines. Hoover and Smith (2021) observed average carbon stocks in aboveground live trees in the Northern Lake States to range from 43.5 to 88.6 MT CO_2-eq/ac in spruce/fir and maple/beech/birch forest types, respectively. While hardwood stands stored the most carbon, their sequestration rates were lowest, averaging 0.34 MT CO_2-eq/ac. Sequestration rates in Northern Lake States stands were highest in white/red/jack pine (1.10 MT CO_2-eq/ac) and aspen/birch forest types (0.67 MT CO_2-eq/ac) (Hoover and Smith 2021). Stand age also plays an essential role in determining the distribution of carbon across forests. In young Northern Lake States stands (0 to 20 years), average carbon storage in aboveground live trees is 17.0 MT CO_2-eq/ac compared to 89.9 MT CO_2-eq/ac in stands with ages between 81 and 120 years (Hoover and Smith 2023). Sequestration rates are highest in stands 0 to 20 years old, with an average rate of 1.68 MT CO_2-eq/ac.). Sequestration rates are lowest in stands 61 to 80 years old, with an average rate of 0.21 MT CO_2-eq/ac (Hoover and Smith 2023).

3.1.2 Forest Carbon Baselines by Forest Type

The distribution of forest carbon storage is generally correlated with the amount of forestland area in each forest type. The greatest amount of forest carbon is stored in the aspen/birch forest type (478 MMT CO_2-eq) followed by the lowland conifer (288 MMT CO_2-eq) and other forest types (171 MMT CO_2-eq; Figure 3.3). From the five forest carbon pools considered, red pine forest types contain the largest percentage of carbon stored in aboveground biomass (32%), oak forest types contain the largest percentage of carbon stored in dead wood (7.6%), and lowland conifers contain the largest percentage of carbon stored in soil (73%).

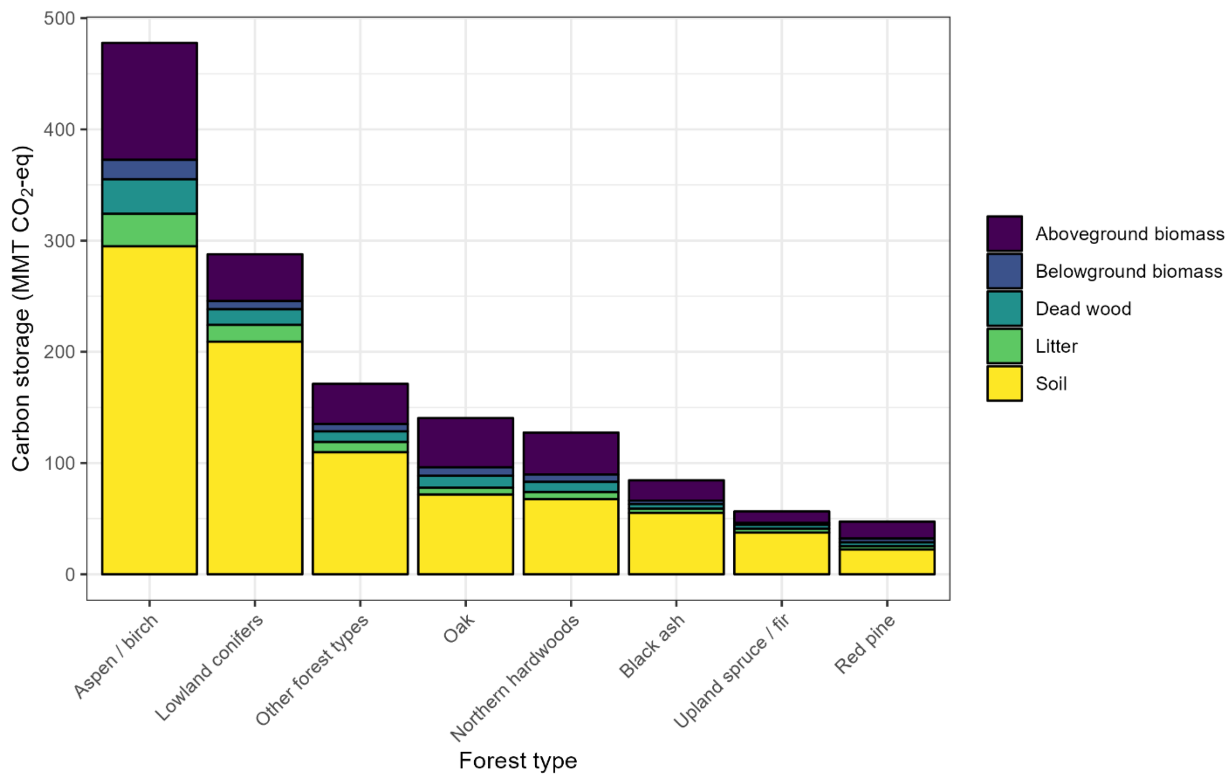


Figure 3.3. Distribution of forest carbon across eight forest types identified in the Forest Inventory and Analysis program in Minnesota, 2017-2021.

The amount of forest carbon stored in the aboveground biomass pool varies across stand ages within each forest type (Figure 3.4). Based on FIA information from 2017 through 2021, the amount of aboveground carbon is greatest in stands 21 to 30 years old in the aspen/birch forest type. The greatest amount of aboveground carbon occurs at later years for all other forest types (e.g., 71 to 80 years in lowland conifers and 81 to 90 years in black ash forest types). Information on carbon sequestration in these forest types is less understood, but Hoover and Smith (2023) estimate carbon sequestration in the aboveground carbon pool in the Northern Lake States to range from 0.33 to 1.80 MT CO_2-eq/ac/yr in conifer-dominated stands that are 81 to 120 and 0 to 20 years old, respectively. For hardwood-dominated stands, Hoover and Smith (2023) estimate carbon sequestration in the aboveground carbon pool to range from 0.15 to 1.65 MT CO_2-eq/ac/yr in that are 61 to 80 and 0 to 20 years old, respectively.

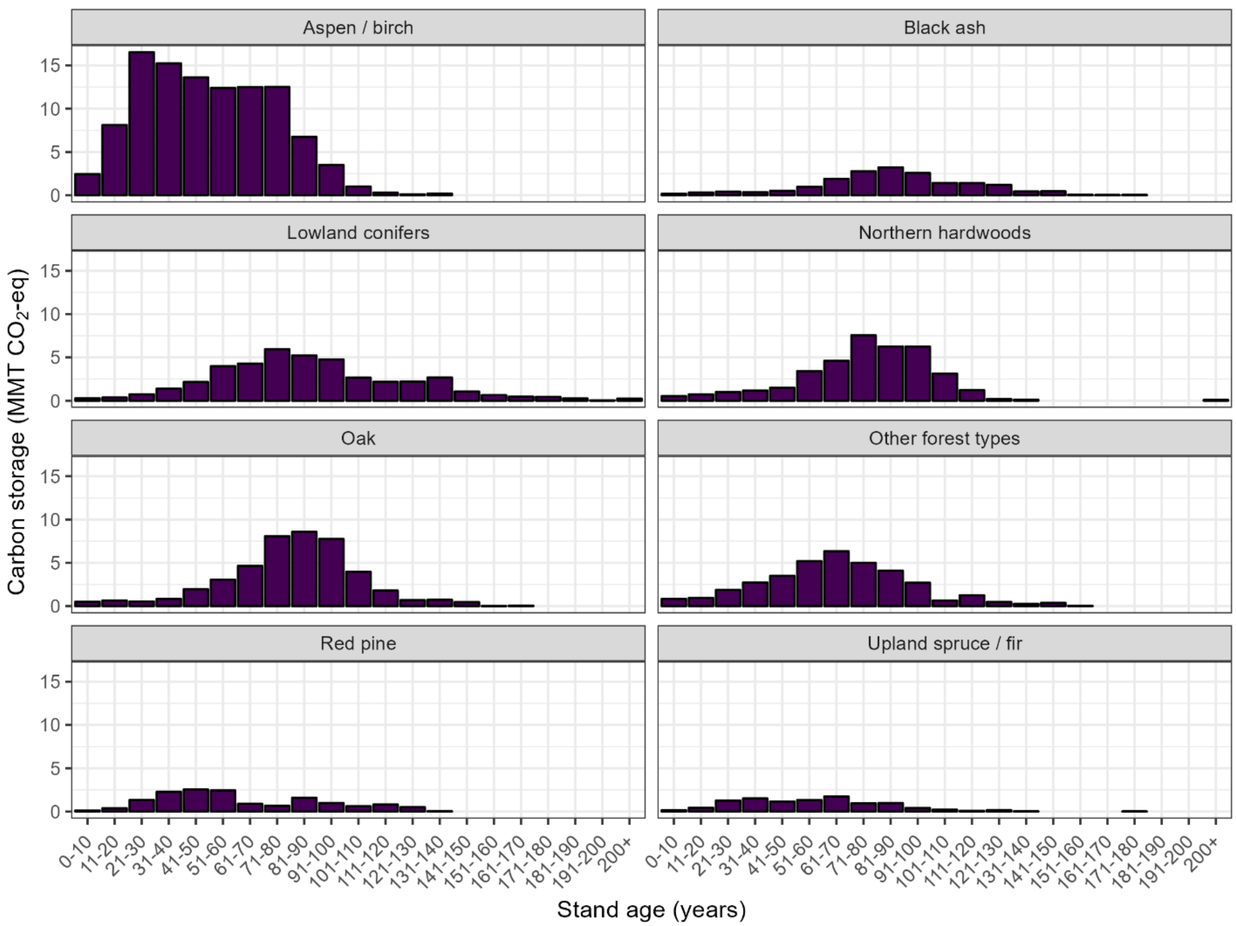


Figure 3.4. Distribution of aboveground forest carbon by age class and forest type identified in the Forest Inventory and Analysis program in Minnesota, 2017-2021.

3.2 HARVESTED WOOD PRODUCTS

Harvested wood products represent an important pool of baseline carbon storage and emissions. Historic harvest information paired with historic product allocation trends show how carbon has been stored in wood products in the past and inform baseline levels of storage and emission from the harvested wood products pool. Current allocation of harvested forest species into different product categories informs LCA efforts and carbon accounting. The full LCA explores how carbon embodied in tree species harvested from various forest types is stored or emitted from different product classes over time. While USDA-FIA provides much of the data necessary to understand recent timber utilization and carbon emissions from Minnesota's forests, additional methods are needed to summarize and assess the carbon currently embodied in harvested wood products from past production. This stored carbon is emitted over time and will form an important data point more fully informing the current baseline carbon profile associated with Minnesota's forestry sector.

3.2.1 Minnesota's Timber and Forest Product Carbon Emissions History: 1821-2020

A brief history of timber utilization in Minnesota (Figure 3.5) is helpful to understanding conditions today[2]. The first sawmill was constructed at St. Anthony Falls to supply Fort Snelling's construction in 1821. More mills were steadily added as land treaties were signed, and investors purchased rights to the standing timber. By the 1880's, the timber industry had grown to become a powerful force in Minnesota. Peak harvest occurred in 1899 (2.3 billion board feet produced or 9.2 million cords used). In 1918, Minnesota's cut was 91% white pine, including red and lower grades of northern pines. By 1920, Minnesota's forests had been culled of all the best materials (e.g., old growth white and red pine). Harvest efficiency was low, with many harvested boles (46%) left in the woods or discarded at the mills. Pooled output of Minnesota mills in 1920 was 600,000,000 board feet or 2.4 million cords used.

[2] The historical narrative from Section 3.2.1 can be collectively attributed to multiple sources including Bromley (1905), Larson (2007), Minnesota Historical Society (n.d.), Oilman, and USDA Forest Service 1920.

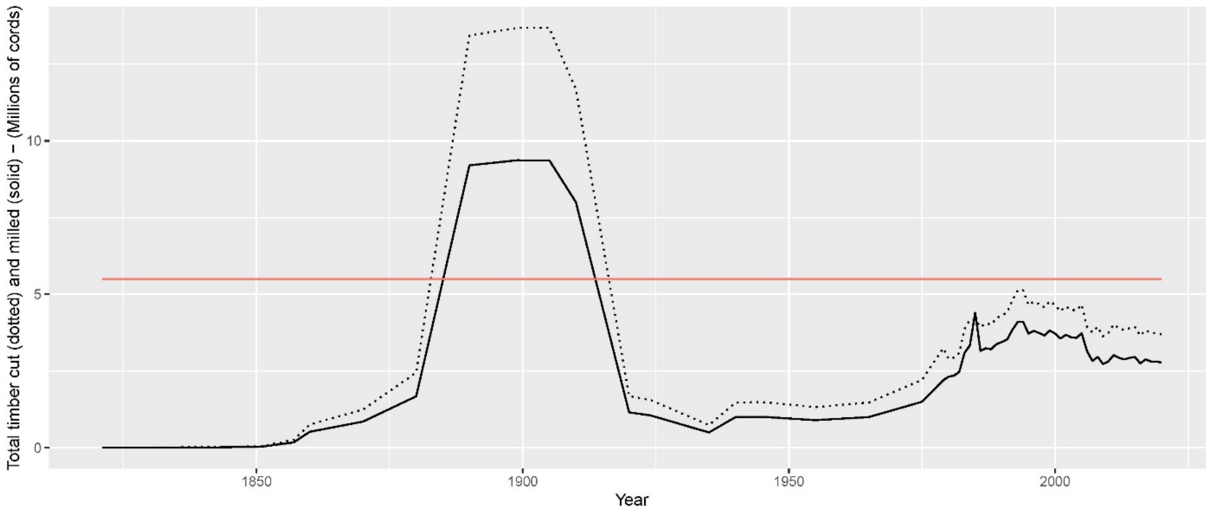


Figure 3.5. Total cords of timber cut (dotted line) and milled (solid line) in Minnesota: 1822-2020. The red line represents the sustainable harvest level identified in the 1993 General Environmental Impact Statement on Timber Harvesting in Minnesota.

The last large log sawmill in Minnesota closed in 1929. By the 1930's, timber production had moved to the Pacific Northwest. This left forests to recover for several decades until a new crop of mature timber became available. By 1980, the timber industry in Minnesota had largely rebounded, but with the focus substantially on pulpwood species. Modern harvest levels are much more balanced, since a large proportion of pulpwood is taken from fast growing aspen forests, which largely replaced the white pine taken during peak harvest years. Around the time of the agricultural collapse in northern Minnesota (roughly the 1950's-1960's), aspen began giving way to multi-aged maturing mixed hardwood, oak, or northern white-cedar stands, depending on soils, physiography, and exact disturbance leading to demographic change. This has left approximately 2.6 million acres of forested tax forfeit land under the administration of County Land Departments with the mission to manage it for timber and ecological purposes. While aspen composes a large proportion of state and county timberland (37%), harvest levels are substantially below the maximum sustainable harvest level (GEIS 1994) leaving many stands unmanaged. Remaining old-aged aspen is, of course, at much greater risk for rot, disease, blowdown, and other disturbances than younger stands. As the aspen ages out, a transition to oak, ash, maple, and other northern hardwoods is occurring.

Timber product output has changed over the years as well. Production has shifted from a mix of lumber and fuelwood to composite panels, lumber, and pulp for paper, textiles, and other products. Here, we use data from the Minnesota DNR Forest Resources Reports published from 1985-2020 (Minnesota DNR 1985-2020) to reconstruct a recent history of this product distribution (Figure 3.6). Historical reports on mill establishment and product innovations were also used to reconstruct historic distributions (pre-1985).

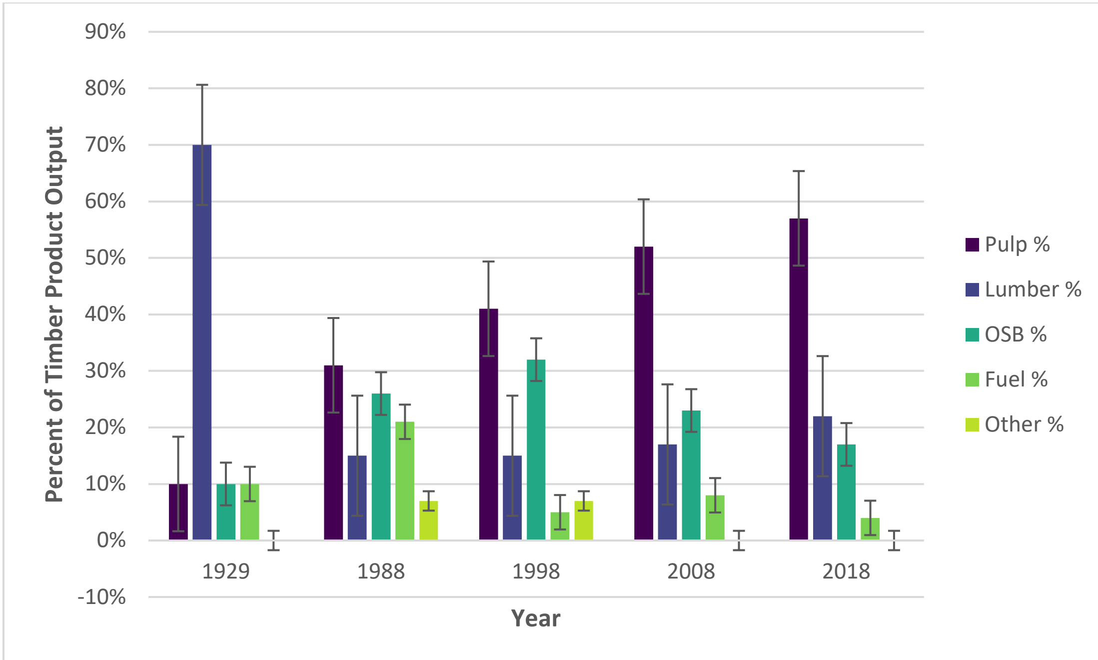


Figure 3.6. Timber product output distribution for Minnesota: 1929-2018. Note that standard errors shown are related to variability in the average TPO proportions for each pool published in MNDNR Forest Resource Reports (1985-2020). MNDNR does not publish standard errors associated with their TPO estimates.

Using the timber product distributions summarized above, we developed an annualized estimate of wood volume used to create those products as well as carbon contained in the manufactured wood products. This information was then combined with information about the service lives, solid waste disposal site (SWDS) half-lives, and recycling rates for the different products to develop a carbon storage and emissions profile for Minnesota's harvested wood products (Figure 3.7) spanning the years 1822-2020. We used the stock change method (Skog 2008; IPCC 2019) to summarize contributions to and emissions from each harvested wood product pool (Equations 3.1-3.3).

Equation 3.1: $\Delta CO_{2\,Total}(i) = -\frac{44}{12}\sum_{l=0}^{n} \Delta C_l(i)$

Where:

i = year

$\Delta CO_{2\,Total}(i)$ = total CO2 emissions and removals from net changes of the carbon stock in HWP in use during the year *i*, in Mt CO_2

C_l = carbon stock in HWP, in Mt C

$\Delta C_l(i)$ = changes of the carbon stock *C* in the HWP commodity class *l* during the year *i*, in Mt C yr^{-1}

l = index number of the semi-finished HWP commodity class

n = number of selected HWP commodity classes of the semi-finished HWP commodities of sawn wood, wood-based panels, paper, and paperboard.

Carbon stock change was estimated as:

Equation 3.2: $C_l = e^{-k} \bullet\ C_l\ (i) +\ \left[\frac{(1-\ e^{-k})}{k}\right] \bullet Inflow(i)$, and

Equation 3.3: $\Delta C_l(i) =\ C_l(i+1) -\ C_l(i)$

Where:

i = year
$C_l(i)$ = the carbon stock in the particular HWP commodity class l at the beginning of the year i, in Mt C,
k = decay constant of FOD for each HWP commodity class l given in units yr^{-1} (= ln(2)/HL, where HL is the half-life of the HWP commodity in the HWP pool in years,
Inflow(i) = the carbon inflow to the HWP commodity class l during the year i, Mt C yr^{-1},
$\Delta C_l(i)$ = changes of the carbon stock C in the HWP commodity class l during the year i, in Mt C yr^{-1}.

Because of the long time-series available for Minnesota's timber harvest and wood production history, we were able to assume that prior to 1821, there was essentially no carbon stored in harvested wood products. Carbon began to be added to this pool with the construction of Fort Snelling in 1821. Carbon flux (additions and emissions) associated with the harvested wood products pools were tracked (additions of harvested wood) and estimated (emissions) using Equations 3.1, 3.2 and 3.3 in combination with product pool specific half-lives and decay factors (Table 3.2). Results are shown in Table 3.3 and Figure 3.7.

Table 3.2. Harvested wood product service life, recycling fraction, solid waste disposal site (SWDS) fraction, and SWDS half-lives by product class. Half-lives are expressed in years and are converted to decay factors using the equation k = ln(2)/half-life.

Harvested Wood Product	***Service Half-life***	***SWDS fraction***	***Recycle fraction***	***SWDS Half-life***	***Production (2020 Mtn CO2-eq)*LCA***
Pulp and paper	2.53	0.32	0.54	14.5	3,321,753
Lumber[1]	39	0.77	0.09	29	637,760
OSB and Engineered Panels	25	0.32	0.54	29	849,250
Fuelwood	1	0	0	0	453,682
Other and Specialty	20	0.32	0.54	29	214,522

1 The service half-life for lumber was calculated as the weighted average of half-lives for different end uses (Alderman and Brandeis 2023). End uses considered include new housing, repairs and remodels, commercial construction, manufacturing, and packaging and shipping.

Table 3.3. Harvested wood product (HWP) carbon produced in total, produced annually, emitted, and stored in solid waste disposal (SWDS) sites, or recycled in thousands of metric tons of carbon. Multiply by 44/12 to convert to CO_2 equivalent.

Year	Annual C to HWP	Cumulative C to HWP	Current C in HWP	Annual C to Recycling	Current C in Recycled HWP	Annual C to SWDS	Current C in SWDS	Total Annual Emissions from HWP	Cumulative HWP Carbon Emitted
1821	1.3	1.3	1.3	-	0.0	-	-	-	-
1830	1.3	12.6	8.2	0.0	0.1	0.4	1.9	0.4	2.7
1840	8.3	67.5	43.0	0.1	0.3	1.9	9.0	2.3	16.6
1850	17.6	187.9	109.0	0.2	1.2	4.4	27.1	5.3	53.3
1860	273.9	1,219.3	876.7	1.3	5.7	30.5	120.2	49.4	253.8
1870	448.8	4,920.7	3,174.6	5.0	32.0	104.9	620.8	125.2	1,167.1
1880	883.5	11,799.8	7,089.1	11.2	92.1	216.3	1,634.2	262.5	3,129.6
1890	4,846.6	42,431.8	28,125.4	43.8	292.8	777.3	4,825.3	1,110.2	9,946.6
1900	4,934.3	91,425.0	54,730.2	147.3	875.5	1,518.8	12,557.0	1,659.8	24,134.3
1910	4,214.4	138,608.3	70,124.6	374.3	2,263.6	2,075.7	23,405.9	2,166.8	44,036.5
1920	606.9	160,911.0	64,933.5	248.0	2,691.4	1,712.7	30,782.3	1,697.3	63,480.5
1930	396.5	165,990.5	52,492.7	149.9	2,790.1	1,252.6	32,365.0	1,521.5	79,382.0
1940	526.8	169,681.0	42,741.7	140.2	2,970.0	975.5	31,334.5	1,510.1	94,066.4
1950	502.9	174,901.1	35,006.9	160.6	3,225.9	794.0	29,441.9	1,374.1	108,556.2
1960	500.5	179,778.8	29,061.6	162.8	3,375.1	646.0	27,127.8	1,216.8	121,362.0
1970	658.5	185,389.3	25,020.0	181.2	3,530.2	552.2	24,785.0	1,153.8	133,044.1
1980	1,220.7	194,380.3	23,559.3	254.7	3,866.0	536.4	22,854.5	1,313.4	145,089.3
1990	1,816.7	211,279.4	25,673.6	528.0	4,934.1	709.3	22,187.1	1,170.3	159,094.0
2000	1,959.7	231,328.7	31,173.4	965.3	7,356.6	981.3	23,820.9	1,057.5	169,133.6
2010	1,481.4	248,519.4	32,655.8	1,092.0	9,501.2	1,003.9	25,846.0	1,169.2	180,277.1
2020	1,464.5	263,665.6	31,784.3	1,213.1	11,384.1	1,020.8	27,405.6	1,168.7	192,210.6

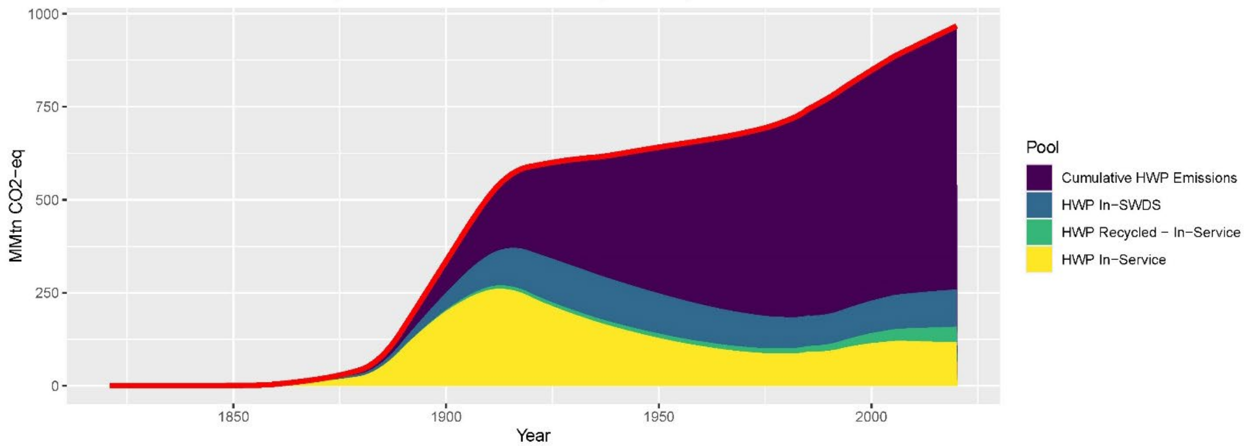


Figure 3.7. Estimated harvested wood product (HWP) carbon storage and emission from Minnesota's forests: 1821−2020. The red line is the cumulative amount of CO2-eq found in all harvested wood products produced since 1821. Assumes product half-lives from IPCC Guidelines (2019).

Results indicate that Minnesota is, as of 2020, carrying approximately 43 million metric tons (MMT) of carbon (158 MMT CO_2-eq) stored in currently used harvested wood products (including recycled products) forward, with additions and emissions each year. An additional 27.4 MMT of carbon (100.5 MMT CO_2 equivalent) is stored in discarded wood products in a SWDS. Total annual emissions from harvested wood products amount to just over 4.29 million metric tons of CO_2-eq, with 5.37 MMT CO_2-eq stored in HWP each year (Figure 3.8).

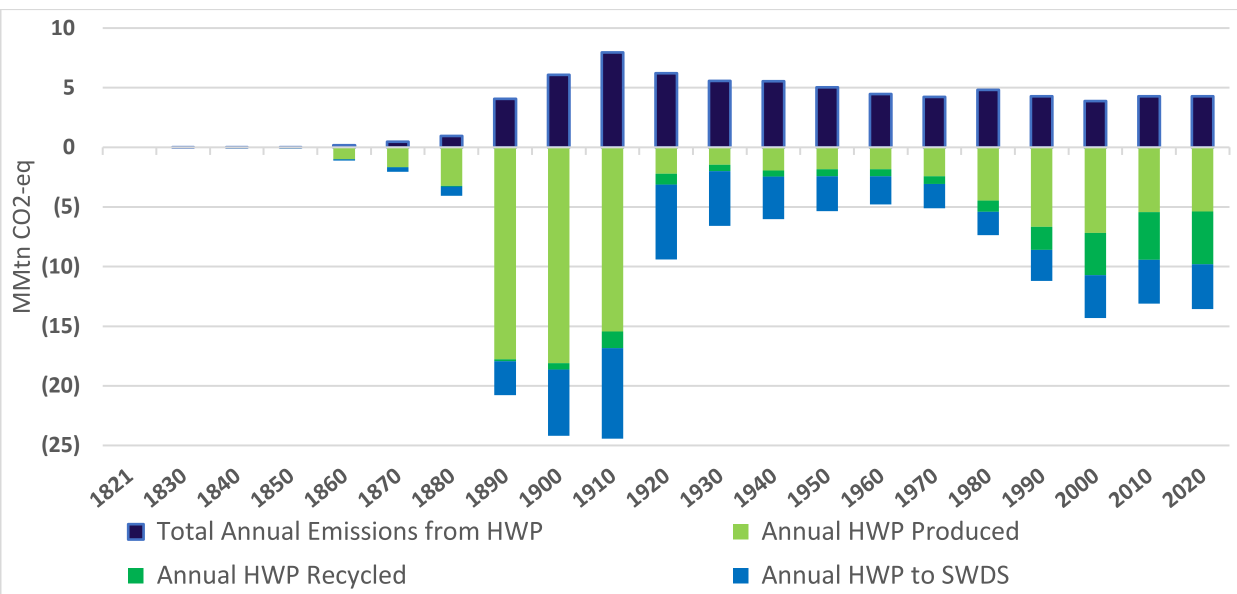


Figure 3.8. Net annual flux of CO_2-eq for Minnesota's harvested wood products: 1821-2020. HWP = harvested wood product; SWDS = solid waste disposal sites.

These results can be used to inform baseline emissions for future management scenario development related to the forestry sector in Minnesota. This baseline of emissions from harvested wood products will inform the overall level of emissions related to HWP production, service lives and end-of-life disposition. These results will supplement the harvested wood product life cycle assessment (LCA) presented later in this report for different future forest management scenarios. In combination, these research products will inform the overall level of emissions we can expect from harvested wood products going forward. While we are currently adding (sequestering) more carbon to the HWP pool than is emitted each year, both forest management decisions and HWP utilization over time are relevant to the net flux associated with the forestry sector.

3.2.2 Current Product Allocation

Timber Products Output (TPO) data from the USDA Forest Service were used to understand current baseline information on harvested forest species allocation to wood product categories. The TPO data collection is housed within the broader FIA program. Historically, TPO data were periodically collected from all active mills until 2019 (corresponding to the 2018 survey year), when the survey design transitioned to annual mill samples (Markowski-Lindsay et al. 2023). In Minnesota, TPO surveys have been carried out every 2 to 7 years dating back to 1988. The most recent publicly available TPO data for Minnesota is from the 2018 survey. Even older TPO surveys in the state were conducted prior to the 1988 survey. TPO data provides information on primary wood processing mills including industrial roundwood receipts, tree species used, and mill residues among other variables.

Table 3.2 provides percentages of harvested species allocated to one of eight product categories as well as the proportion of all harvests a species represents. As the 2018 survey represents the most recent vetted survey, 2018 TPO data were downloaded in October 2023 from the USDA Forest Service Timber Products Output Interactive Reporting Tool (USDA Forest Service 2024). Other potential sources of data were explored including Minnesota Department of Natural Resources Forest Resources Reports (FRRs) and other TPO survey years. While FRRs provide important information on the annual state of forestry in Minnesota, harvested wood product allocation within FRRs did not provide the same species or product category resolution as TPO. The inclusion of older TPO reports to provide a measure of variability in product allocation was considered. After accounting for significant shifts in trends due to historical time periods (e.g., post-Great Recession), the minimal sample size showed small variation in product allocation and the capacity to build that uncertainty into other analyses was beyond the scope of this project. Ultimately, 2018 TPO data was chosen for its well-established methodology, level of detail, and recency.

Table 3.2. Overview of the percentage of harvested wood products by detailed species group for Minnesota using 2018 Timber Products Output data. Table values represent the percent of total harvest within a species utilized for a particular product (i.e., rows sum to 100%). Also included is the percentage of all harvests represented by each product category and by each species group (i.e., the last row and column sum to 100%).

Detailed Species Group	**Harvested Wood Product**								**% of Total Harvest**
	Bioenergy/ Fuelwood	*Composite panel*	*House logs*	*Veneer logs*	*Poles, Posts, Pilings*	*Pulpwood*	*Saw logs*	*Miscellaneous*	
Cedars	5.16%	0.00%	3.22%	0.00%	0.00%	0.00%	56.28%	35.34%	0.39%
True firs	3.71%	0.00%	0.00%	0.00%	0.00%	82.44%	13.24%	0.61%	3.64%
Jack pine	7.34%	1.25%	0.00%	0.00%	0.00%	35.32%	54.07%	2.02%	2.37%
Red pine	7.56%	7.34%	0.19%	0.00%	1.08%	6.82%	65.11%	11.90%	12.01%
White pine	36.87%	0.26%	0.57%	0.00%	0.00%	17.87%	38.11%	6.39%	0.81%
Other pines	0.00%	0.00%	0.00%	0.00%	0.00%	1.22%	98.78%	0.00%	0.03%
Spruce	0.90%	0.00%	0.00%	0.00%	0.00%	86.89%	11.96%	0.25%	9.42%
Larch	25.41%	22.35%	0.00%	0.00%	0.00%	47.51%	4.54%	0.19%	1.97%
Ash	28.68%	0.00%	0.00%	0.06%	0.02%	44.77%	24.29%	2.18%	3.34%
Aspen	3.07%	26.69%	0.00%	0.00%	0.00%	63.00%	4.90%	2.34%	49.44%
Basswood	4.17%	7.69%	0.00%	0.46%	0.00%	26.82%	38.01%	22.84%	2.17%
Other birch	10.63%	22.50%	0.00%	0.27%	0.00%	50.87%	14.07%	1.67%	4.58%

Table 3.2 continued

Yellow birch	0.00%	0.00%	0.00%	1.62%	0.00%	78.38%	20.00%	0.00%	0.08%
Black cherry	46.85%	0.00%	0.00%	0.00%	0.00%	0.00%	50.45%	2.70%	0.05%
Black walnut	0.35%	0.00%	0.00%	0.70%	1.06%	0.00%	98.24%	0.00%	0.12%
Cottonwood	2.36%	0.00%	0.00%	0.09%	0.00%	0.00%	97.41%	0.18%	0.92%
Elm	64.50%	0.00%	0.00%	0.00%	0.59%	0.00%	27.22%	7.69%	0.07%
Hickory	42.31%	0.00%	0.00%	0.00%	0.00%	0.00%	55.38%	2.31%	0.05%
Hard maple	13.34%	1.86%	0.00%	1.71%	0.00%	64.34%	18.33%	0.37%	1.12%
Soft maple	6.81%	0.00%	0.00%	0.00%	0.00%	86.64%	5.49%	1.06%	2.68%
Select red oaks	8.53%	0.00%	0.00%	0.30%	0.01%	0.42%	87.06%	3.67%	3.19%
Select white oaks	14.28%	0.00%	0.00%	0.11%	0.06%	0.14%	83.30%	2.11%	1.48%
Other hardwoods	57.45%	0.00%	0.00%	0.00%	0.00%	0.00%	42.55%	0.00%	0.02%
Sycamore	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
Hemlock	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.05%
% of Total Harvest	6.16%	15.77%	0.04%	0.06%	0.13%	52.60%	21.54%	3.71%	100.00 %

4 FORECASTING FOREST CONDITIONS UNDER MANAGEMENT SCENARIOS

4.1 METHODS

4.1.1 Forest Inventory and Analysis data

Forest Inventory and Analysis (FIA) data were used in this project to (1) understand forest composition and structure across Minnesota's diverse forested landscapes, (2) determine historical harvest rates and timber products output within different forest types, (3) serve as input data to the Forest Vegetation Simulator, and (4) calibrate simulation models by individual forest type. The FIA program uses a nationally consistent sampling protocol with a systematic design collected in a three-phase inventory (Westfall et al. 2022). Phase 1 stratifies plots into forested and non-forested conditions, Phase 2 collects a base sample of ground plots, and Phase 3 collects more detailed forest health measurements on a subset of Phase 2 plots. The national sample intensity is one plot per ~6,000 acres, however, Minnesota intensifies the number of FIA plots measured compared to other states. In 2018, information was gathered from 6,307 forested plots in Minnesota representing approximately one FIA plot for every 2,791 acres (Hillard et al. 2022).

FIA inventory plots in the Phase 2 design consist of four, 24-ft fixed-radius subplots spaced 120 ft apart in a triangular arrangement with one subplot in the center. All live and standing dead trees with a diameter at breast height (DBH) of at least 5.0 in are measured on these subplots. Within each sub-plot, a 6.8-ft microplot offset 12 ft from subplot center is established where live trees with a DBH between 1.0 and 5.0 in and seedlings are measured.

All FIA data were acquired using the rFIA package and R software (Stanke et al. 2020). The primary data used originated from the tree, plot, and condition tables. Plots with a single condition were used in this analysis. All Minnesota data collected in the annual inventory design from 1999 through 2021 were used. With a remeasurement interval of approximately every five years, up to five measurements on the same FIA plots were available over the 22-year period. FIA plots were placed into one of eight different broad forest type groups based on the FIA-designated forest type (Table 4.1).

Table 4.1. Forest type groupings and attributes used in this analysis based on Forest Inventory and Analysis (FIA) forest type codes.

Forest type	FIA forest types (code)	Number of FIA plots[1]	Forestland area (acres)[2]	Timberland area (acres)[2]	Rotation age (years)	Annual harvest rate (%)
Aspen/birch	Aspen (901), Balsam poplar (904), Paper birch (902)	1,033	6,450,137	5,855,639	50	1.27
Red pine	Red pine (102)	135[3]	544,148	524,286	75	2.51
Upland spruce/fir	Balsam fir (121), White spruce (122)	89	726,754	509,976	60	1.40
Oak	Northern red oak (505), White oak (504), White oak / red oak / hickory (503), Bur oak (509)	227	1,160,879	1,096,519	90	0.65
Northern hardwoods	Hard maple / basswood (805), Mixed upland hardwoods (520), Sugar maple / beech / yellow birch (801)	261	1,502,530	1,403,510	85	0.68
Lowland conifers	Black spruce (125), Northern white-cedar (127), Tamarack (126)	771	3,599,865	3,162,574	75	0.43
Black ash	Black ash / American elm / red maple (701)	144	1,055,023	962,243	120	0.56
Other forest types	All other forest types	239	2,671,475	2,284,548	80	0.93
All forest types	All forest types	2,899	17,665,810	15,799,295	-	0.92

[1] Number of single condition plots used throughout modeling scenarios.
[2] Forestland and timberland area estimates summarized from FIA EVALIDator, 2017-2021 data.
[3] Additional plots were included if a red pine forest type comprised more than 75% of a plot.

4.1.2 Harvest rates

All FIA data were used to determine historical timber harvest rates across Minnesota and within each forest type. A timber harvest was defined as occurring if (1) basal area reduction was greater than 25% from subsequent measurements of an FIA plot or (2) cutting was observed on the FIA plot at some point in the last five years (i.e., TRTCD = 10). In both cases, no disturbances should have been recorded on the FIA plot between measurements (as identified through the DSTRBCD variable) to separate natural disturbances from timber harvests. The annual harvest rate informed by FIA data was 0.92%. This statewide estimate is the same as reported in Minnesota's 2017 silviculture report, which indicated 145,000 acres were harvested from a total of 15.8 million acres of timberland, resulting in the 0.92% annual harvest rate.

(Windmuller-Campione et al. 2019; their Table 2). This harvest rate estimate is also similar to the USDA Forest Service's estimate of 160,146 acres of forest land treated by cutting (e.g., harvest, thinning, etc.) annually, equivalent to a 1.01% harvest rate (USDA Forest Service 2021). Within forest types, annual harvest rates ranged from 0.43% in lowland conifers to 2.51% in red pine forests (Table 4.1).

4.1.3 Forest management scenarios

Within each broad forest type, up to five different forest management scenarios were identified (Table 4.2). Forest management scenarios were developed and refined from discussions between project team members and comments from MFRC members and stakeholders. The following provides an overview of each management scenario.

<u>No management</u>

No management treatments were applied in this scenario.

<u>Business as usual (BAU)</u>

Silvicultural prescriptions were identified for each forest type according to typical management strategies used in Minnesota. Harvests occurred at a rate identified by historical timber harvests that occurred within the forest type (Table 4.1).

<u>Economic intensive</u>

Silvicultural prescriptions were identified that sought to maximize economic return from forest management activities. Characteristics included shorter rotation ages and increased harvest intensities.

<u>Climate-adapted</u>

Silvicultural prescriptions were identified for each forest type that sought to promote forest resilience under an adaptive silviculture framework (e.g., Nagel et al. 2017). Characteristics included tree planting, longer rotation ages, and managing for diverse species and stand ages.

Climate-adapted plus fire (red pine and oak, only)

Similar to Climate-adapted scenarios, but includes prescribed fires following management activities (e.g., prescribed burns following thinning).

BAU/Climate-adapted plus emerald ash borer mortality (black ash, only)

Similar to Climate-adapted scenarios, but includes a simulation of tree mortality of all ash trees greater than 1-inch in diameter spread out over the first 50 years of the simulation. This simulated an emerald ash borer (EAB) outbreak in the black ash forest type.

Table 4.2. Overview of management definitions by forest type for four silviculture scenarios simulated using the Forest Vegetation Simulator. The simulation spans 100 years and produces estimates of carbon attributes[1].

Forest Type	**Silviculture Scenario**			
	No management	*Business as usual*[2]	*Climate-adapted*[3]	*Economic intensive*[4]
Aspen/birch	No management	Harvest aspen at year 50; simulate two cycles. Leave conifer residuals as leave trees.	Plant mixed-woods systems and encourage conifer with aspen (40%), white spruce (40%), eastern white pine (10%), and northern red oak (10%). Harvest 50% of aspen at year 40 and let conifers grow; second harvest at year 75[5].	Clearcut with no residuals every 40 years.
Red pine	No management	Thin from below to 90 sq ft/ac every 20 years. Leave white pine as leave trees. Rotation at 90 years.	Plant red pine and native future-adapted species in half of stand, including eastern white pine, northern red oak, bur oak, and red maple. Thin from below; thinning to 120 sq ft/ac every 20 years. Extended rotation of 150 years[6]. Run additional fire option[7].	Thin from above to 90 sq ft/ac at year 30; second thin from above when 130 sq ft/ac; Third thin from above ten years following second thin; remove overwood at year 70[8,9].
Upland spruce/fir	No management	Thin from throughout diameter range 50% of basal area at year 40-50 (low SI [<50 ft]) or year 20-30 (high SI [>50 ft]). Rotation age: 65-75 years (high SI) or 90-100 years (low SI)	Manage for mixed-wood systems – plant upland spruce crop trees while encouraging aspen growth[11]. Clearcut at age 100.	Thin from throughout diameter range at year 35 to 90 sq ft/ac, clearcut at year 55; promote natural regeneration of aspen.
Oak	No management	Two-stage shelterwood cut; first cut at year 80, removal of overwood at 90.	Plant native future-adapted species in half of stand, including basswood, black cherry, and bur oak. Three-stage shelterwood cut; first cut at year 70, second prep cut at 95 with planting, final removal cut at 110[12]. Additional fire option[7].	Thin at year 50 (remove 40% of basal area from throughout the diameter range); two-stage shelterwood cut; first cut at year 70, removal of overwood at 80.
Northern hardwoods	No management	Thinning every 20 years beginning at year 50; thin to 90 sq ft/ac.	Selection harvests, with cuts every 20 years beginning at year 50 to promote uneven-aged stands. Shift to variable density harvests with both patches and thinning the matrix[13].	Thin year 50 and 70 to 90 sq ft/ac; shelterwood with reserve at year 80, reserves compose 30 sq ft BA, promoting red oak, basswood, yellow birch.

Lowland conifers	No management	Clearcut between year 80 and 120 - no residuals. Rotation age for high site index (> 35 ft) is 80-90 years and for low site index (< 35 ft) is 110-120 years.	Shelterwood with reserves at year 100, with the likelihood that the reserve trees will fall over creating down dead wood. Regeneration of black spruce, eastern larch, northern white cedar, aspen, eastern white pine, and paper birch[14].	* Same as BAU scenario.
Black ash	No management	On more mesic hardwood sites, clearcut with aspen, balsam poplar, and ash resprouts[15]. On more wet sites, group selection with underplanting. Group selection cuts of 25% of the stand of the stand happening every 20 years. Underplanting of swamp white oak, balsam poplar, sycamore, and river birch[15,16]. Includes a scenario that simulates EAB mortality. Increased disturbance and spread out mortality on all stands across first 50 years of simulation. Specified a 100% mortality rate to all black ash >= 1.0 inches DBH.		Heavy shelterwood with reserves. Harvest at year 90 to a basal area of 40 sq ft.
Other[18]	No management	Thinning every 20 years beginning at year 30; thin to 90 sq ft/ac. Clearcut at year 70.	Aggregated shelterwood with reserves with the goal of increasing species diversity.	Thin at year 35; clearcut at year 50.

1 – Currently aboveground and belowground carbon. **2 –** Unless otherwise noted, Business as usual derived primarily from regional forest management guides, MN DNR forest cover type guidelines, and extensive expertise. **3 –** Unless otherwise noted, Climate-adapted primarily derived and modified from ASCC experiments and extensive expertise. **4 –** Unless otherwise noted, Economic intensive derived from regional forest management guides, MN DNR forest cover type guidelines, personal communication, observation, and extensive expertise. **5 –** Follows the strategy to promote long-lived conifers in many areas such as the North Shore. Also TNC and the "conifer stronghold" approach: https://silvlib.cfans.umn.edu/conifer-strongholds-changing-northwoods-landscape-crooked-lake-usfs and e.g., what John Almendinger has done: https://silvlib.cfans.umn.edu/aspen-birch-long-lived-conifers-mn-private. **6 –** Generally follows the resilience treatment at the ASCC experiment at the Cutfoot EF: https://www.adaptivesilviculture.org/node/956. **7 –** Run a second Climate-adapted simulation using the same parameters as the first, but with the addition of prescribed burning. For red pine, this included the "Thin-burn-burn-rest-repeat" approach, where prescribed burns occurred two and five years following thinnings. This is similar to the Cloquet Forestry Center's Otter Creek management strategy: https://silvlib.cfans.umn.edu/mid-rotation-site-preparation-and-community-wellness-support-through-prescribed-fire-otter-creek. For oaks, this included prescribed fires occurring every 10 years, similar to management of oak forests at Cedar Creek: https://cbs.umn.edu/cedarcreek/about-cedar-creek/land-management. **8 –** Magruder et al. 2013. **9 –** Berguson and Buchman 2017. **10 –** Russell et al. 2015. **11 –** Leveraging current management strategies used by UPM Blandin. See: https://silvlib.cfans.umn.edu/patch-clearcuts-and-enrichment-plantings-blandin and https://silvlib.cfans.umn.edu/iic-white-spruce-release-hart-lake-upm-blandin. **12 –** Similar shelterwood approach is being used in the resistance treatment at an ASCC site in southern New England: https://www.adaptivesilviculture.org/node/1071. Shelterwoods are being used at St. John's oak forests: https://silvlib.cfans.umn.edu/pottery-clay-piles-shelterwood-deer-browse-control-st-johns. **13 –** Selection harvests are the go-to resilience treatment in northern hardwoods in New England: https://www.adaptivesilviculture.org/node/996. **14 –** Based on an ongoing experiment on the Big Falls Experimental Forest: Anderson et al. 2020. **15 –** Windmuller-Campione et al. 2021. **16 –** The D'Amato/Slesak/Palik papers; in particular, D'Amato et al. 2018. **18 –** Includes all other forest types besides the seven specifically listed. The most abundant of the other types include jack pine and bur oak, comprising 32% of the other forest types.

4.1.4 Forest Vegetation Simulator modeling

The Lake States variant of the Forest Vegetation Simulator was used to simulate the different forest management scenarios (FVS Staff 2023; version 20240101). The most recent FIA measurement collected between 2017 and 2021 were used as input data into FVS and were prepared in an FVS-ready format using R software. Productivity differences across plots were localized by using stand conditions (e.g., stand age, elevation, site index) and the National Forest code for the Superior (909) or Chippewa National Forests (code 903).

Biomass and carbon calculations were provided from the Fire and Fuels Extension of FVS using the Jenkins et al. (2003) equations. Simulation output for the project was analyzed using the following tables from FVS:

Summary statistics table: To examine trends in stand composition and structure (e.g., basal area, volume) throughout the simulation period.

Carbon table: To quantify carbon storage and sequestration rates throughout the simulation period. Carbon was expressed in metric tonnes (MT) as carbon dioxide equivalents on a per acre basis (i.e., MT CO_2-eq/ac) and was stored in multiple pools (Table 4.3).

Stand stocking table: To quantify volume/basal area by species to examine stand composition and structure.

Harvested wood products table: To quantify trends in wood products if harvesting occurred during the simulation. The carbon stored in products in use and in solid waste disposal sites was added to carbon stored within forests to determine total storage and sequestration rates if harvests occurred.

Table 4.3. Forest carbon pools summarized from Forest Vegetation Simulator output.

Pool	Definition
Aboveground biomass	Live trees (including stems, branches, and foliage), herbs, and shrubs.
Belowground biomass	Roots of live trees.
Standing dead wood	Dead trees; including stems and any branches and foliage still present, and roots of dead and cut trees.
Downed dead wood	All woody surface fuel.
Forest floor	Litter and duff.
Harvested wood products (stored)	Carbon stored in wood products in use and in landfills.

Simulations in FVS were run for 100 years. The stands that were first selected to be harvested were ones with the greatest basal area. Management activities occurred when stands reached the appropriate stand age that would trigger management activities, according to the appropriate prescription as noted in the table of proposed scenarios (Table 4.2). The forest-type-specific harvest rate was applied across stands for the BAU scenario. Generally, Economic intensive scenarios resulted in shorter rotation ages which resulted in more harvests occurring compared to the BAU scenario. The NOTRIPLE keyword was specified to reduce the amount of replications that FVS makes with the tree input list and simplify its prediction errors.

4.1.4.1 Additional FVS calibrations

4.1.4.1.1 Mortality

Preliminary FVS model runs with Minnesota data indicated an overestimation of volume and carbon and a lack of ability for FVS to incorporate mortality, particular in stands with older stand ages and those that have seen disturbances. This analysis performed a calibration exercise to overcome this challenge by determining the appropriate mortality parameters to employ for each forest type. The calibration exercise involved (1) comparing initial measurements on FIA plots collected from 1999 through 2003 with their most recent measurements collected from 2017 through 2021 (providing up to 18 years of calibration data), (2) running the initial FIA data through FVS and comparing predicted values with observed values up to 18 years later, (3) iteratively running FVS for each forest type at different levels of mortality applied to stands older than the rotation age (Table 4.1), and (4) identifying which set of mortality parameters most closely match the most recent FIA observations.

The calibration exercise modified the FIXMORT parameter within FVS. The calibration ran FVS for each forest type by changing the proportion of the tree record that will be killed (at levels of 0.05, 0.10, 0.20, 0.30, 0.40, and 0.50) and the smallest DBH to which the mortality rate will be applied (at levels of 0, 5, 10, and 15 inches). The mortality parameters that were ultimately selected for use in the analysis were ones that resulted in the lowest root mean square error and mean absolute bias of stand basal area when comparing FVS predictions to FIA observations collected from 2017 through 2021. The selected mortality parameters for each forest type are shown in Appendix 9.3.

4.1.4.1.2 Regeneration

The Lakes States variant of FVS does not employ a regeneration model, so will grow only the trees provided in the input list. Recognizing the long-term simulations in this project (100 years) and the importance of regeneration in Minnesota diverse forest types, regeneration was added for each forest type. Regeneration (either natural or planted) was added differently according to two scenarios: (1) regeneration following management activities and (2) background regeneration. The species and number of trees to regenerate differed by forest type and scenario (Appendix 9.4). The regeneration inputs were added with the NATURAL or PLANTED keywords in FVS.

For regeneration following management activities, the species and number of trees to regenerate as seedlings were developed and refined from discussions between project team members and comments from MFRC stakeholders. These were also informed through case studies archived on the Great Lakes Silviculture Library (SFEC 2024; https://silvlib.cfans.umn.edu/).

For background regeneration, i.e., regeneration that occurs and is not related to management activities, FIA data were used to identify the number of ingrowth trees at least 1 inch in DBH (RECONCILECD = 1). These ingrowth trees were recorded on the FIA microplot. This project determined the most abundant ingrowth species and number of regenerating trees within each forest type. This background regeneration was quantified as the average ingrowth over a 10-year time period and was added to each 10-year cycle within FVS. To account for different regenerating trees throughout stand development, these differed by stands in the (1) first half of the stand's rotation age, (2) second half of a stand's rotation age, and (3) beyond a stand's rotation age.

4.1.4.1.3 Growth

In addition to adding variables to the FVS input files that provided productivity differences to each FIA plot (e.g., stand age, elevation, site index, and National Forest codes), this project also included the tree's recent diameter and height increment, if the tree was measured in the previous measurement on the FIA plot. This was accomplished using the CALBSTAT and GROWTH keywords within FVS.

To further calibrate the growth of FVS output, estimated removals from harvests that occurred under the BAU scenario were compared with expected volume removals for the state. Expected volume removals were acquired for each forest type from the MN DNR's estimates of wood harvested in 2020 (MN DNR 2024, their Table 2-1). Along with calculated harvest rates, the expected average volume removed per acre was determined for each forest type (Appendix Table 9.9). For example, estimated annual timberland harvests in aspen/birch forests totaled 74,367 acres with 1.54 million cords harvested in 2020, resulting in an average volume harvested of 20.7 cords per acre. This was assumed to represent the BAU harvest scenario and FVS growth estimates were calibrated to match these removals for each forest type. FVS simulations were run iteratively for the BAU scenario in each forest type to arrive at volume removals that were approximate to the average volume harvested informed by the MN DNR data (Appendix Figure 9.3). In FVS, the FixDG and FixHTG keywords were modified to calibrate the diameter and height growth of individual trees, respectively.

Note that the MN DNR reports total harvest by species, rather than by forest type, which may contain a mix of species. When calibrating FVS, the necessary assumption was made that the harvest volumes from a forest type approximately equal the harvest volumes of the associated target species across all forest types.

4.2 RESULTS

4.2.1 All forest types

Across all forest types, average carbon stocks increased for all management scenarios throughout the 100-year simulation. Forests that saw No management had the greatest carbon storage throughout the simulation. By year 100, Climate-adapted and No management scenarios contained the largest amount of carbon storage (126.4 tonnes CO_2-eq/ac) followed by BAU and Economic intensive scenarios (107.6 tonnes CO_2-eq/ac; Figure 4.1).

Carbon stock change generally decreased throughout the simulation across all management scenarios. Averaged across the 100-year simulation, average carbon stock change was highest in the Climate-adapted and No management scenarios (0.47 and 0.48 tonnes CO_2-eq/ac/yr, respectively) followed by BAU and Economic intensive scenarios (0.28 tonnes CO_2-eq/ac/yr; Figures 4.1-4.2).

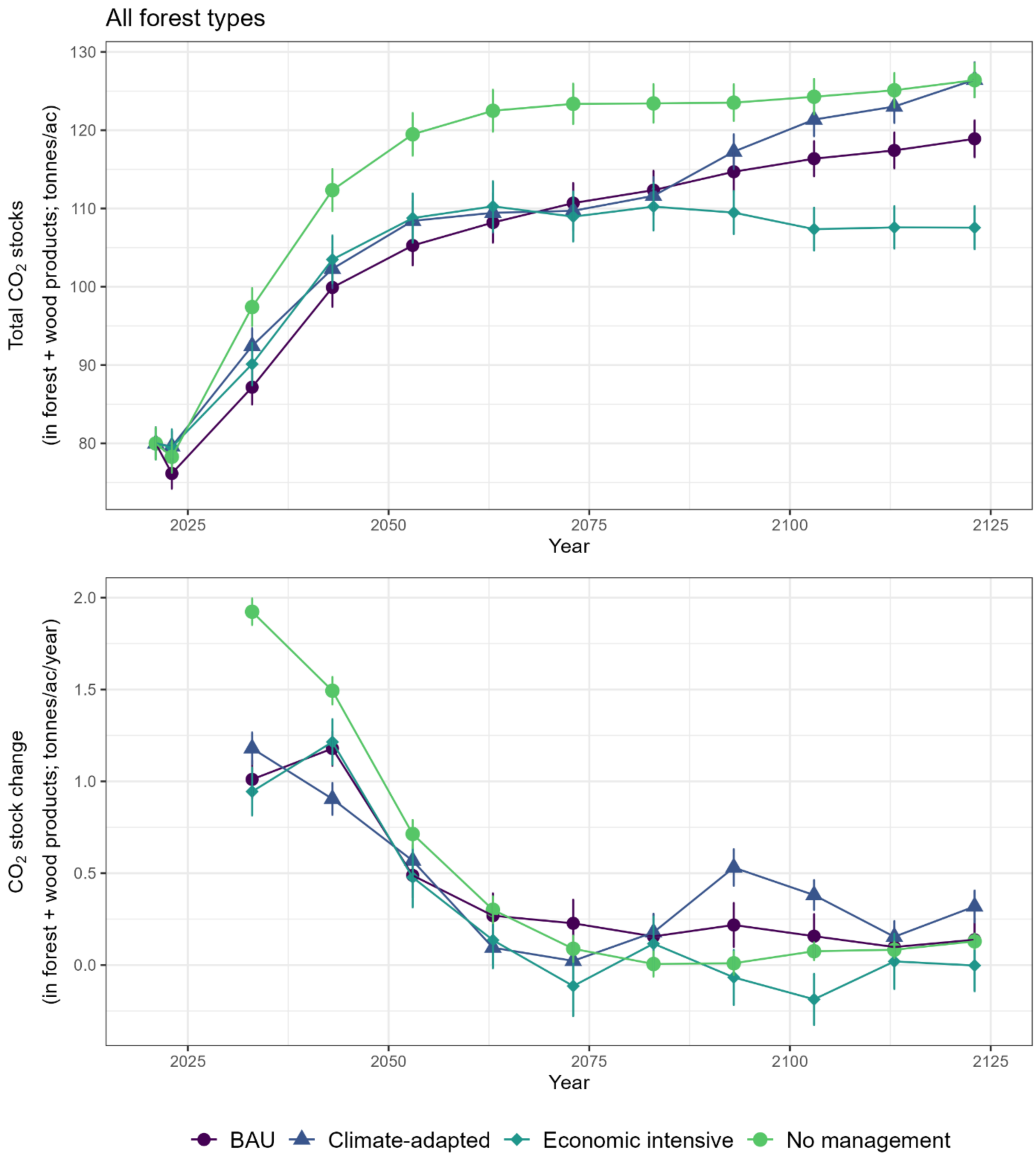


Figure 4.1. Mean forest carbon stocks and stock change (in forest and in harvested wood products) for all forest types across each of the four scenarios. Error bars show ± 2 standard errors.

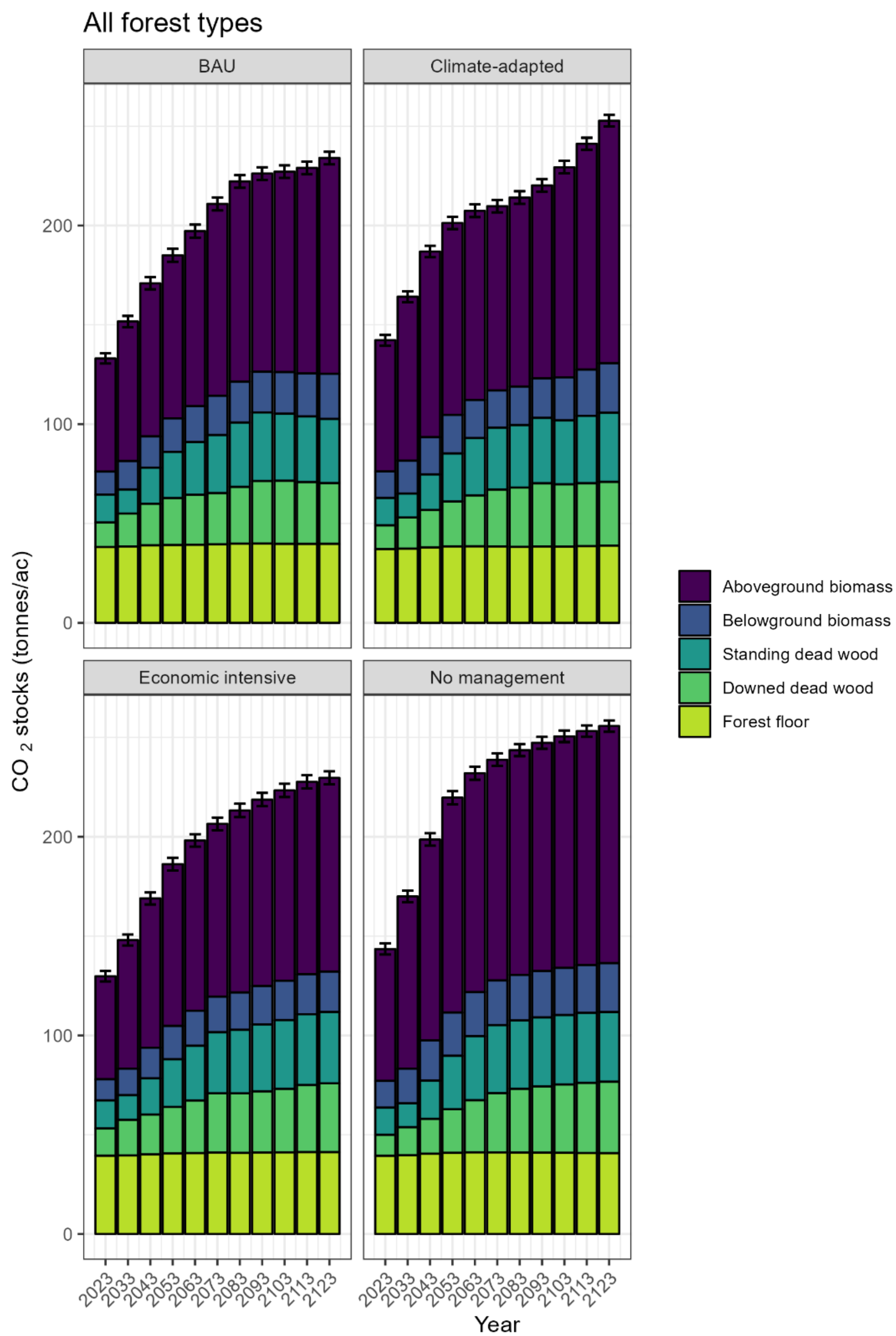


Figure 4.2. Mean carbon stored in various pools for all forest types. Error bars show ± 2 standard errors of the total carbon in all five pools.

4.2.2 Aspen / birch

Within the aspen/birch forest type, average carbon stocks increased for all management scenarios throughout the 100-year simulation. Forests that saw No management had the greatest carbon storage for the first 40 years of the simulation. By year 50, BAU scenarios contained the largest amount of carbon storage and by year 100, Climate-adapted scenarios contained the largest amount of carbon storage (106.1 tonnes CO_2-eq/ac; Figure 4.3; Table 4.4). The majority of carbon in this forest type resided in the aboveground biomass pool (Figure 4.4). Aspen species were generally resilient within the BAU and Economic intensive scenarios, while Climate-adapted and No management scenarios introduced a greater number of species throughout the simulations. No management scenarios resulted in an increase in non-aspen species (e.g., shade tolerant hardwoods and balsam fir) as the simulation lengthened (Figure 4-5).

Carbon stock change generally decreased in the aspen/birch forest type, with slight increases in the BAU and Climate-adapted scenarios. Averaged across the 100-year simulation, average carbon stock change was highest in the Climate-adapted treatment (0.44 tonnes CO_2-eq/ac/yr) followed by BAU, Economic intensive, and No management (0.23 tonnes CO_2-eq/ac/yr; Figure 4.3; Table 4.4).

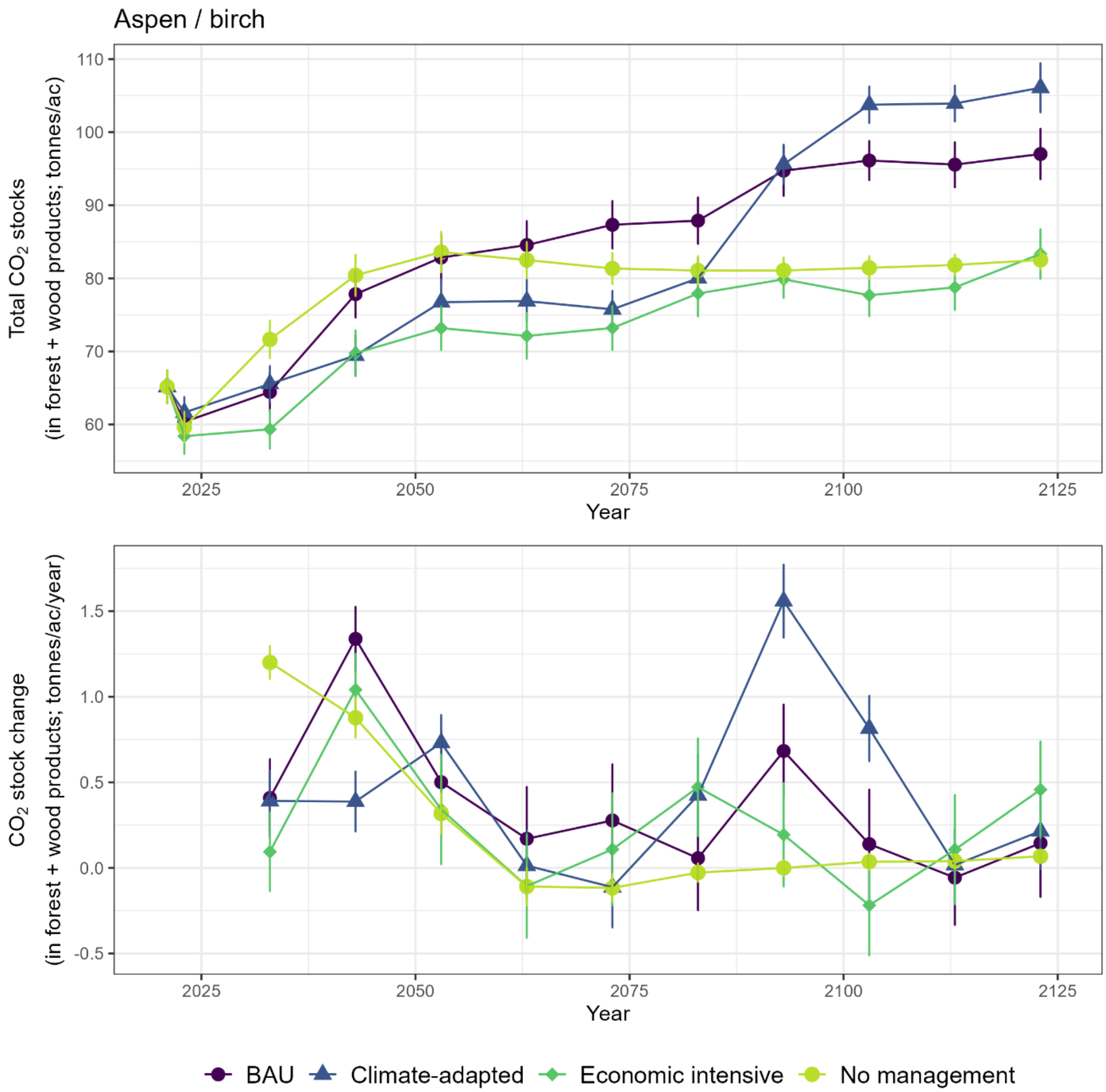


Figure 4.3. Mean carbon stocks and stock change (in forest and in harvested wood products) for the aspen/birch forest type. Error bars show ± 2 standard errors.

Table 4.4. Forest carbon stocks and stock change for the aspen/birch forest type (n = 1,033).

	Carbon stocks (tonnes/ac)				Carbon stock change over 100 years (tonnes/ac/yr)	
	Year 50		Year 100			
	Mean	SD	Mean	SD	Mean	SD
BAU	87.3	52.0	97.0	55.0	0.37	0.46
Climate-adapted	75.8	40.3	106.1	53.6	0.44	0.61
Economic intensive	73.2	48.0	83.3	54.1	0.25	0.63
No management	81.3	34.1	82.5	20.5	0.23	0.40

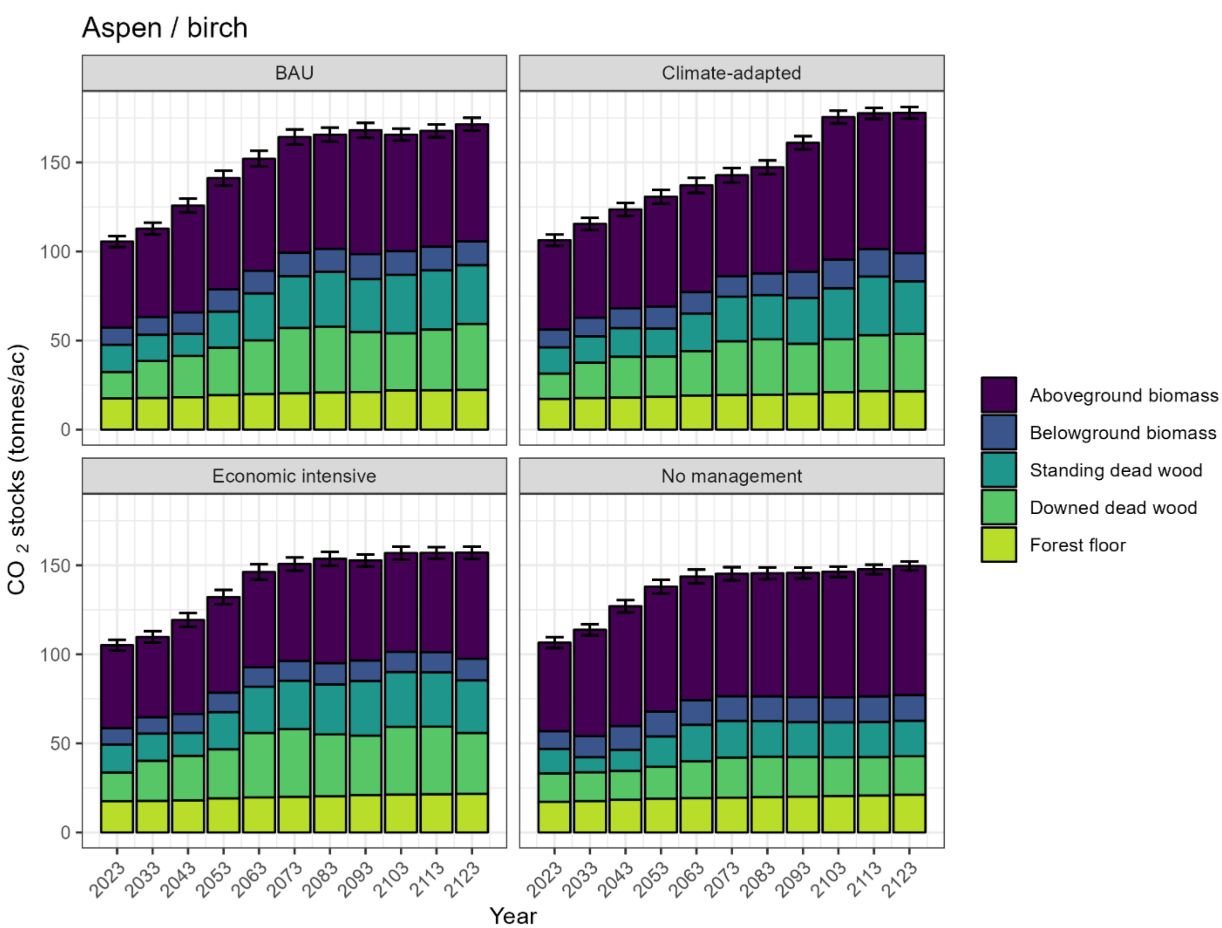


Figure 4.4. Mean carbon stored in various pools for the aspen/birch forest type. Error bars show ± 2 standard errors of the total carbon in all five pools.

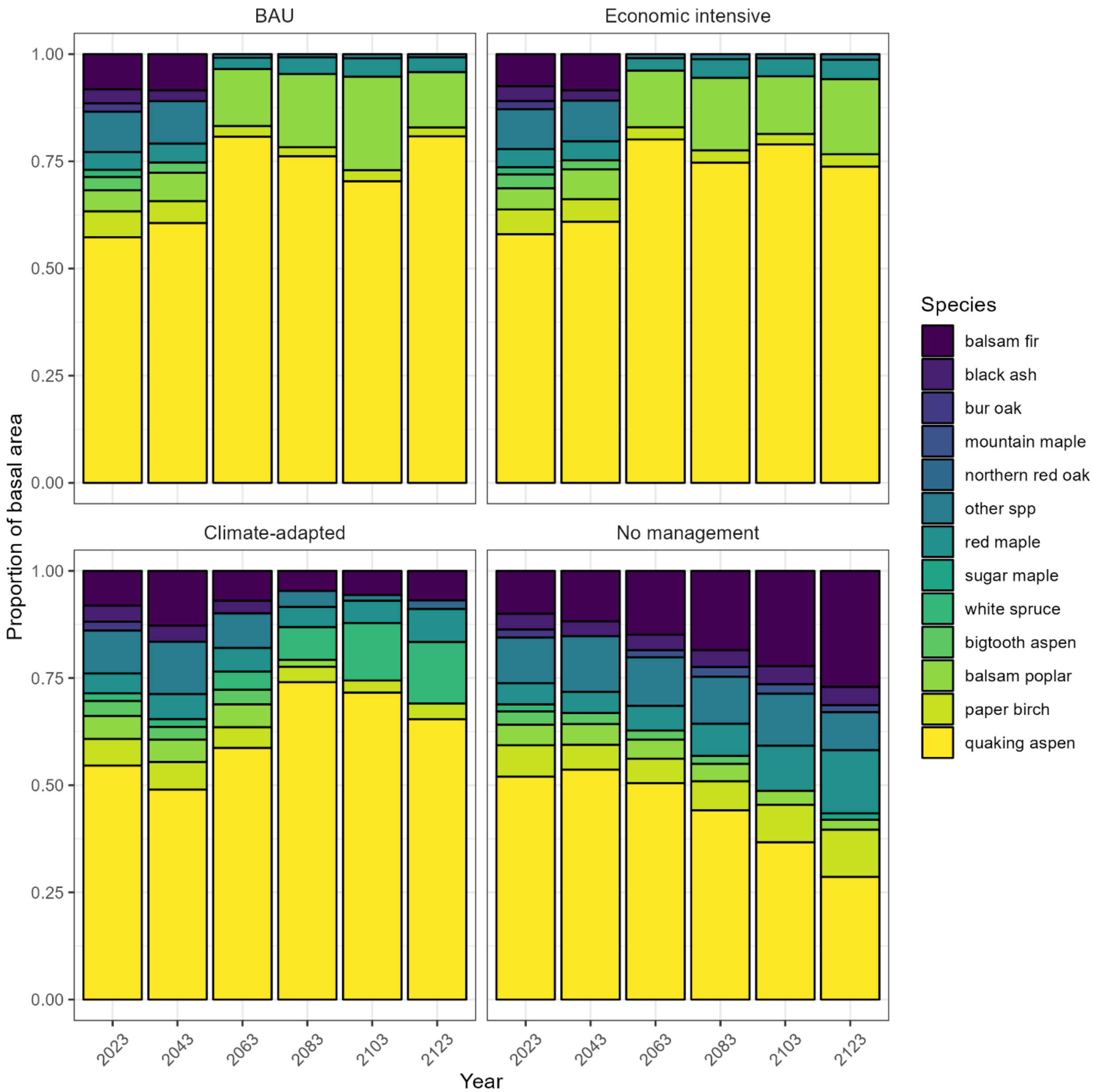


Figure 4.5. Changes in species composition for live trees in the aspen/birch forest type under four management scenarios.

4.2.3 Red pine

Average carbon stocks in red pine forests increased for all management scenarios throughout the 100-year simulation. Forests that saw No management had the greatest carbon storage throughout the 100-year simulation. At the end of the 100-year simulation, No management stands stored the most carbon (249.7 tonnes CO_2-eq/ac), followed by BAU, Economic intensive, Climate-adapted and Climate-adapted plus fire treatments (Figures 4.6-4.7; Table 4.5). Red pine remains the dominant species in all scenarios throughout the simulation (Figure 4.8).

Carbon stock change decreased in the red pine forest type. Averaged across the 100-year simulation, average carbon stock change was highest in the No management treatment (1.25 tonnes CO_2-eq/ac/yr) followed by BAU, Economic intensive, and the two Climate-adapted treatments (Figure 4.6; Table 4.5).

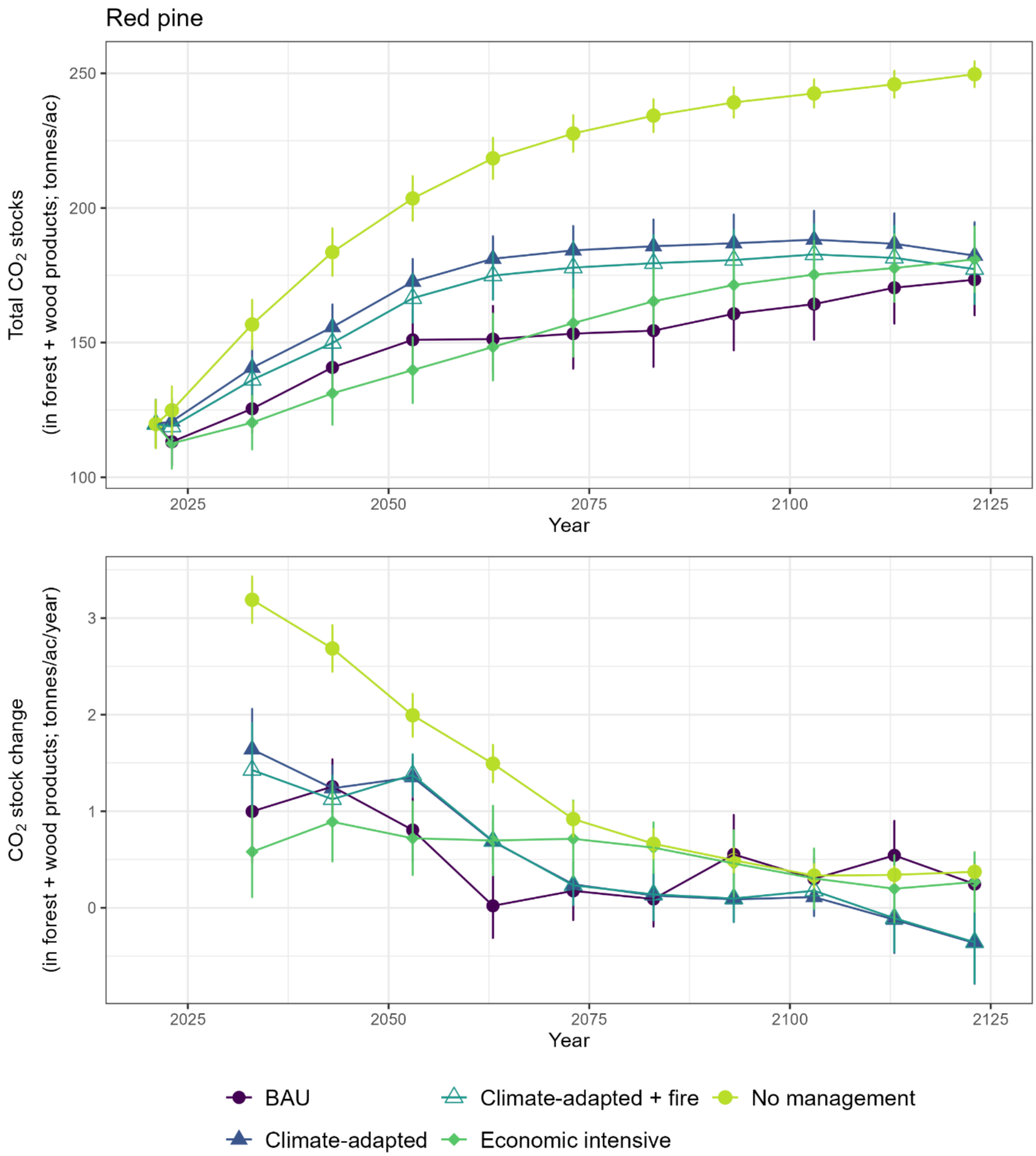


Figure 4.6. Mean carbon stocks and stock change (in forest and in harvested wood products) for the red pine forest type. Error bars show ± 2 standard errors.

Table 4.5. Forest carbon stocks and stock change for the red pine forest type (n = 71).

	Carbon stocks (tonnes/ac)				Carbon stock change over 100 years (tonnes/ac/yr)	
	Year 50		Year 100			
	Mean	SD	Mean	SD	Mean	SD
BAU	153.3	75.3	173.4	77.0	0.60	0.73
Climate-adapted	184.3	52.4	182.3	72.0	0.62	0.82
Climate-adapted + fire	177.3	75.4	177.3	75.4	0.59	0.83
Economic intensive	157.3	72.2	180.9	70.6	0.68	0.71
No management	227.7	39.4	249.7	27.6	1.25	0.46

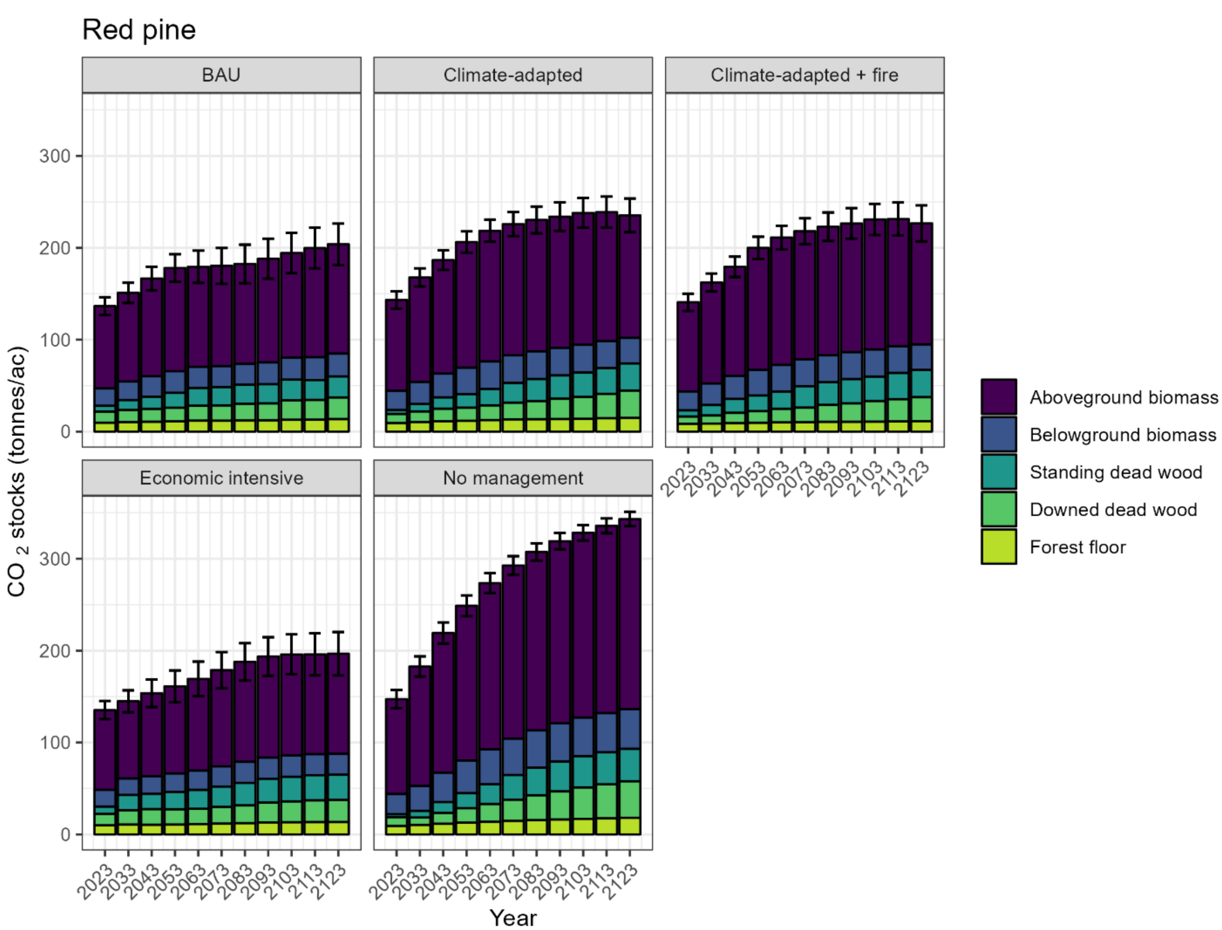


Figure 4.7. Mean carbon stored in various pools for the red pine forest type. Error bars show ± 2 standard errors of the total carbon in all five pools.

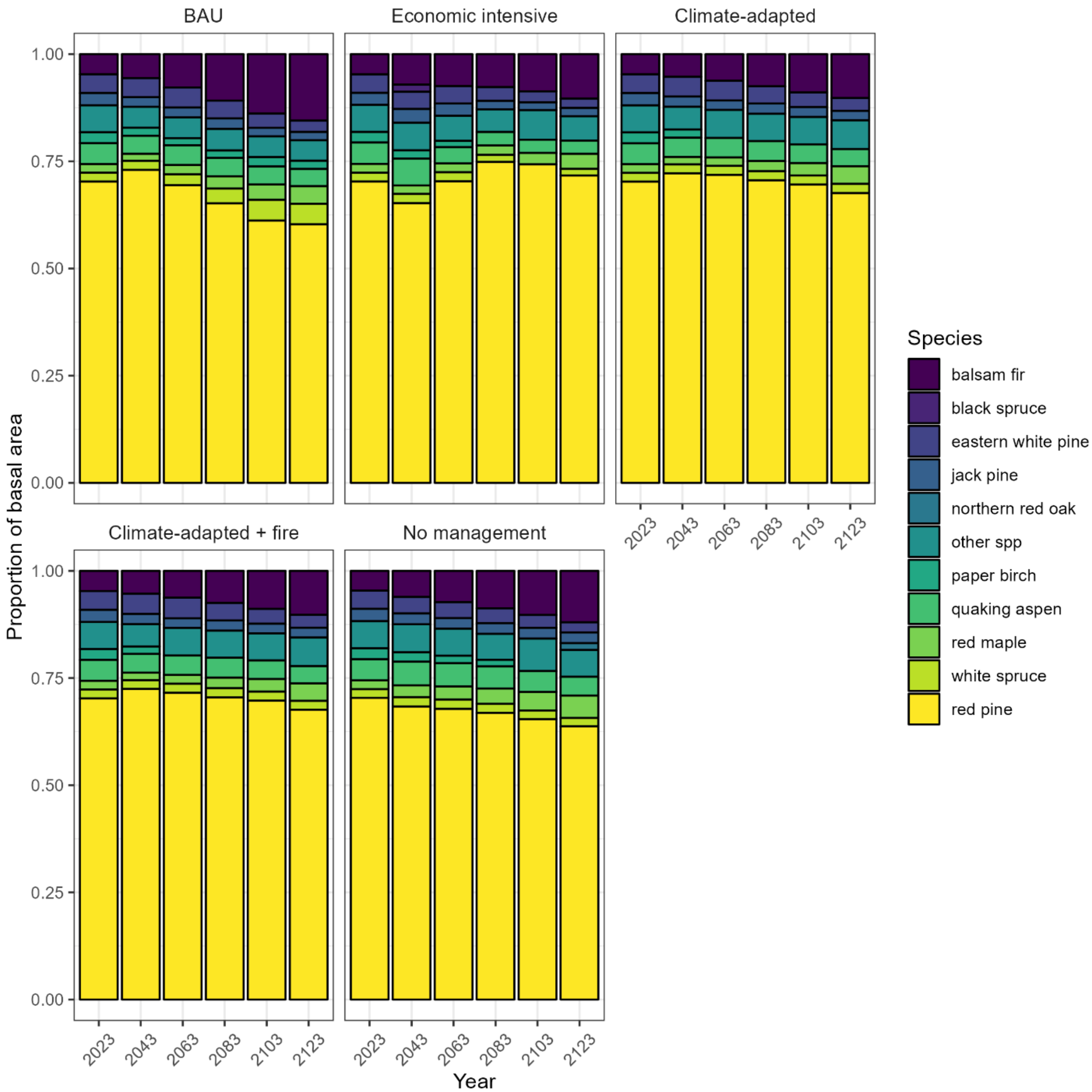


Figure 4.8. Changes in species composition for live trees in the red pine forest type under four management scenarios.

4.2.4 Upland spruce / fir

Average carbon stocks in upland spruce/fir forests increased for all management scenarios up until approximately 2043, then declined throughout the remainder of the 100-year simulation. Spruce/fir forests under a BAU management scenario and those that saw no management had the greatest carbon storage at the end of the 100-year simulation (average storage of 87.6 tonnes CO_2-eq/ac). The greatest carbon storage at the end of the 100-year simulation was followed by Economic intensive and Climate-adapted treatments (Figure 4.9; Table 4.6). Notably, spruce/fir forests stored a large proportion of carbon in the forest floor pool relative to other forest types (Figure 4.10). Balsam fir and white spruce were maintained across all management scenarios, with a greater amount of balsam fir relative to other species in the No management scenario after 100 years (Figure 4.11)

Across the 100-year simulation, average carbon stock change was similar across all scenarios, ranging from -0.04 to 0.21 tonnes CO_2-eq/ac/yr in the Climate-adapted and No management scenarios, respectively (Figure 4.9; Table 4.6).

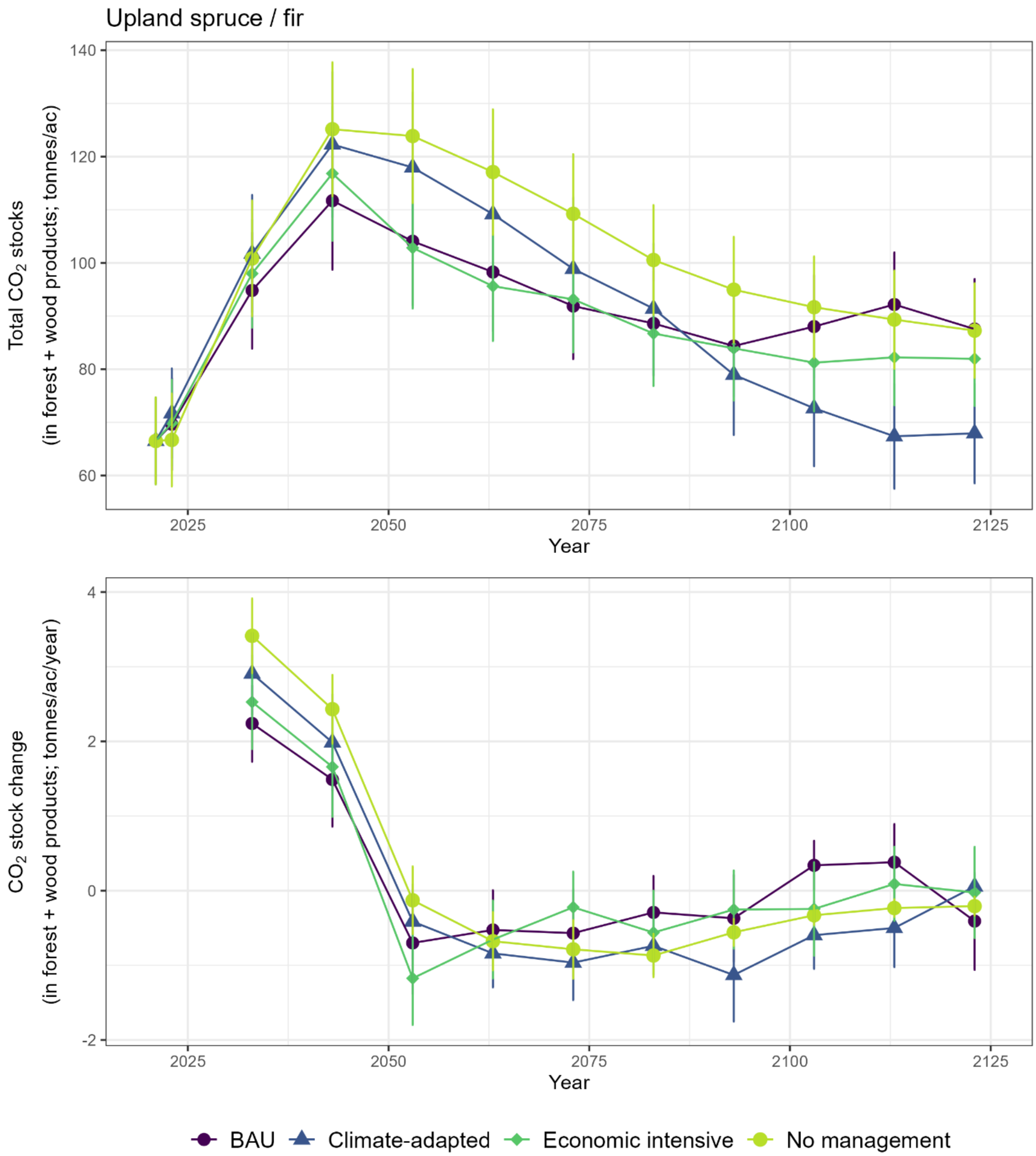


Figure 4.9. Mean carbon stocks and stock change (in forest and in harvested wood products) for the upland spruce/fir forest type. Error bars show ± 2 standard errors.

Table 4.6. Forest carbon stocks and stock change for the upland spruce/fir forest type (n = 71).

	Carbon stocks (tonnes/ac)				Carbon stock change over 100 years (tonnes/ac/yr)	
	Year 50		Year 100			
	Mean	SD	Mean	SD	Mean	SD
BAU	91.9	46.9	87.6	44.4	0.18	0.56
Climate-adapted	98.9	63.1	67.9	44.3	-0.04	0.55
Economic intensive	93.1	47.0	82.0	41.7	0.12	0.50
No management	109.2	53.0	87.3	41.9	0.21	0.54

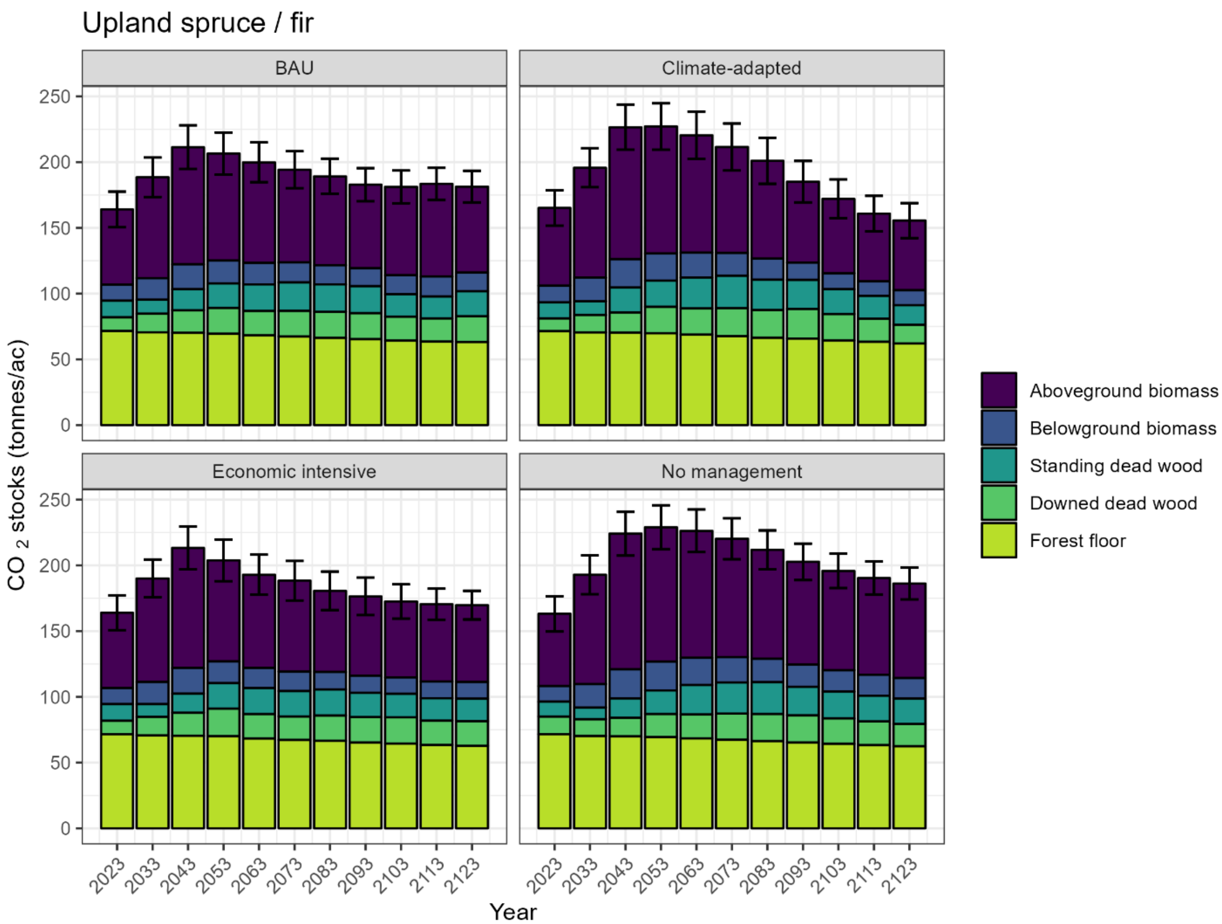


Figure 4.10. Mean carbon stored in various pools for the upland spruce/fir forest type. Error bars show ± 2 standard errors of the total carbon in all five pools.

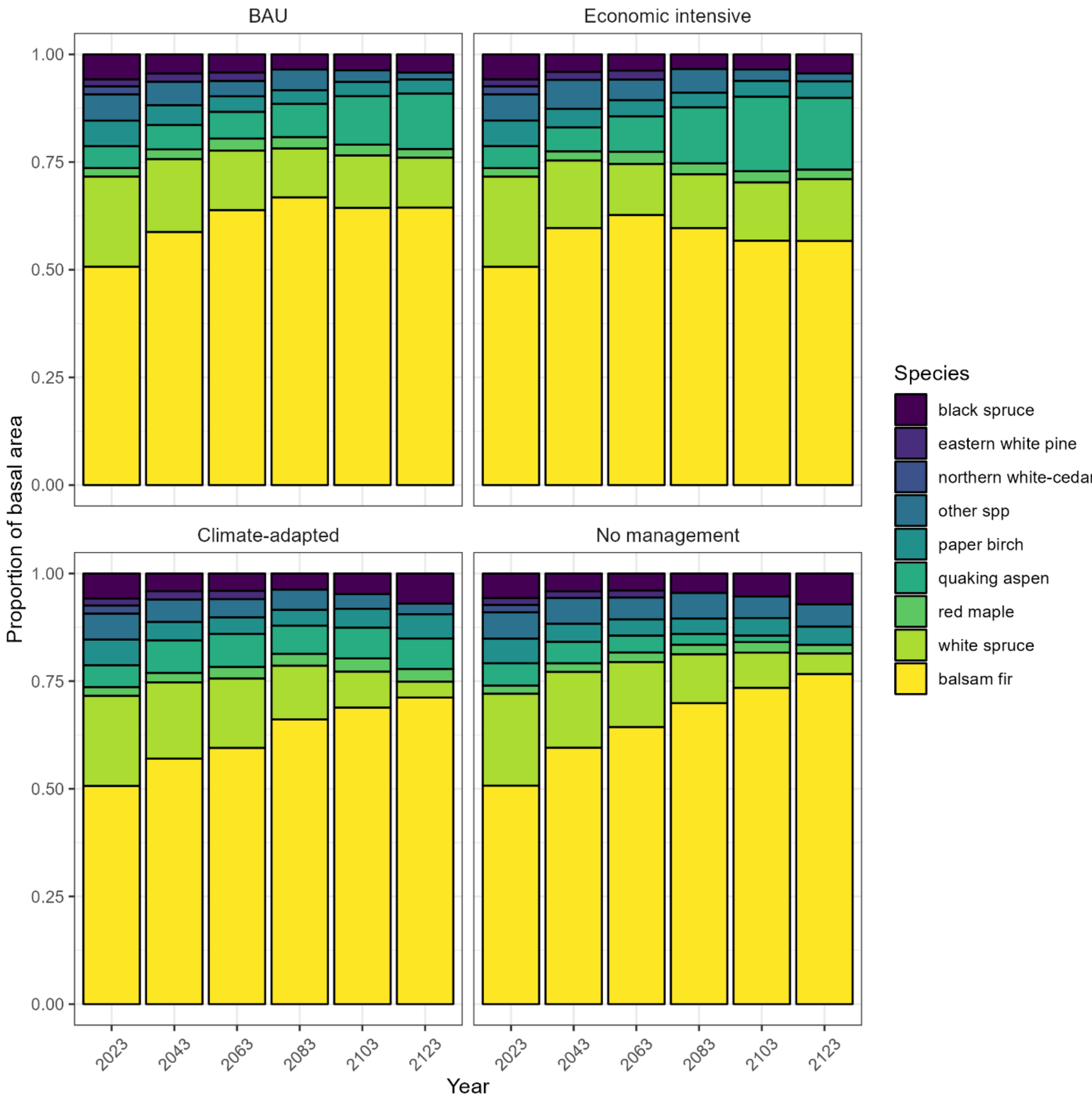


Figure 4.11. Changes in species composition for live trees in the upland spruce/fir forest type under four management scenarios.

4.2.5 Oak

Average carbon stocks in oak forests generally increased until around 2043, then decreased slightly throughout the 100-year simulation. Oak forests with no management stored the greatest carbon at the end of the 100-year simulation (average storage of 164.7 tonnes CO_2-eq/ac). The Climate-adapted plus fire scenario consistently showed the lowest carbon storage across all scenarios, averaging 101.3 tonnes CO_2-eq/ac at 100 years (Figure 4.12-4.13; Table 4.7). Species diversity in oak forests is high relative to other forest types across Minnesota (Figure 4.14).

Across the 100-year simulation, average carbon stock change ranged from -0.27 tonnes CO_2-eq/ac/yr in the Climate-adapted + fire scenarios to 0.25 tonnes CO_2-eq/ac/yr in the No management scenario (Figure 4.12; Table 4.7).

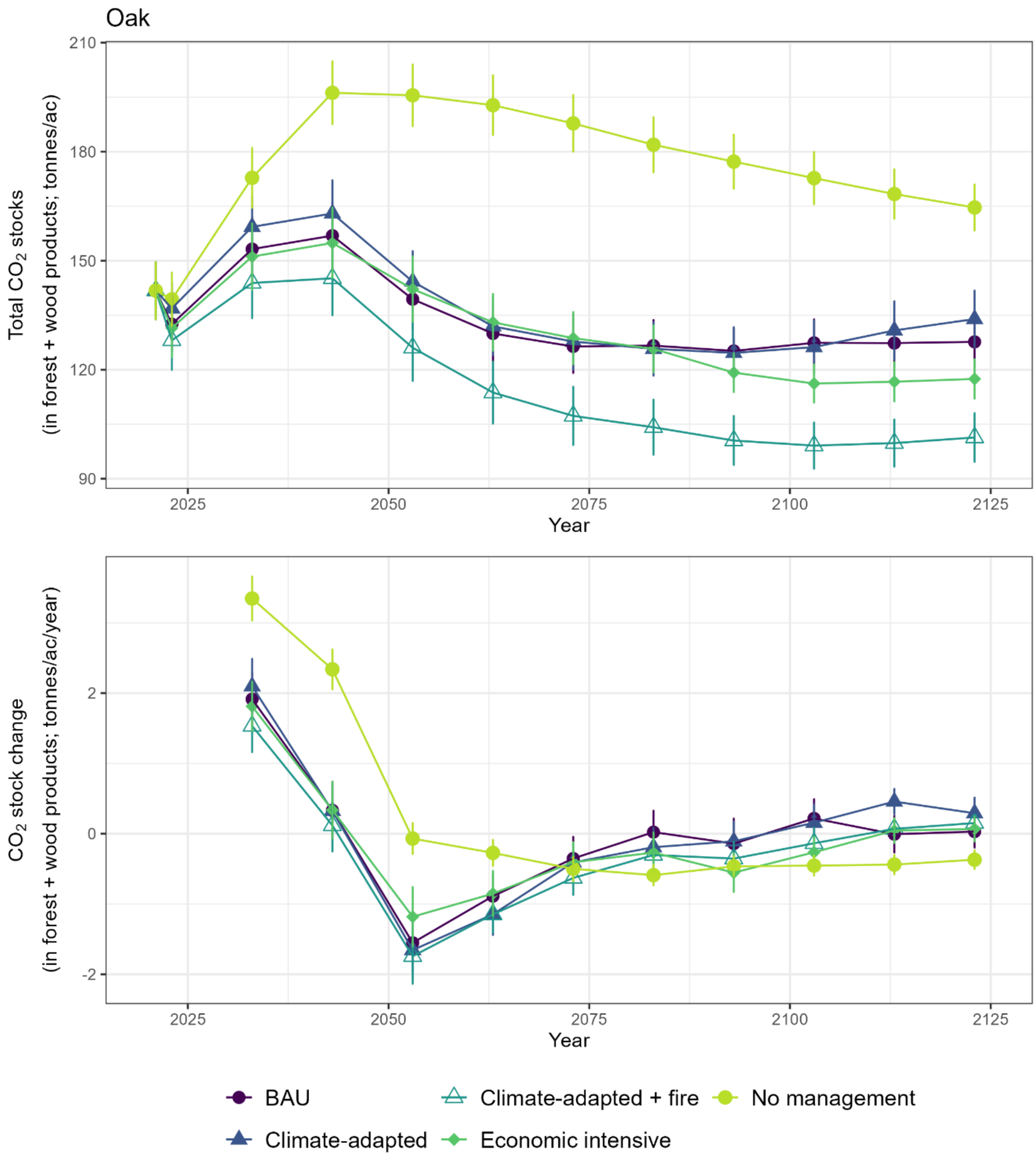


Figure 4.12. Mean carbon stocks and stock change (in forest and in harvested wood products) for the oak forest type. Error bars show ± 2 standard errors.

Table 4.7. Forest carbon stocks and stock change for the oak forest type (n = 169).

	Carbon stocks (tonnes/ac)				Carbon stock change over 100 years (tonnes/ac/yr)	
	Year 50		Year 100			
	Mean	SD	Mean	SD	Mean	SD
BAU	126.4	54.6	127.7	54.4	-0.05	0.88
Climate-adapted	127.7	58.1	133.9	58.9	-0.03	0.90
Climate-adapted + fire	107.3	60.3	101.3	50.3	-0.27	0.71
Economic intensive	128.7	53.8	117.5	40.6	-0.14	0.78
No management	187.8	58.7	164.7	47.4	0.25	0.70

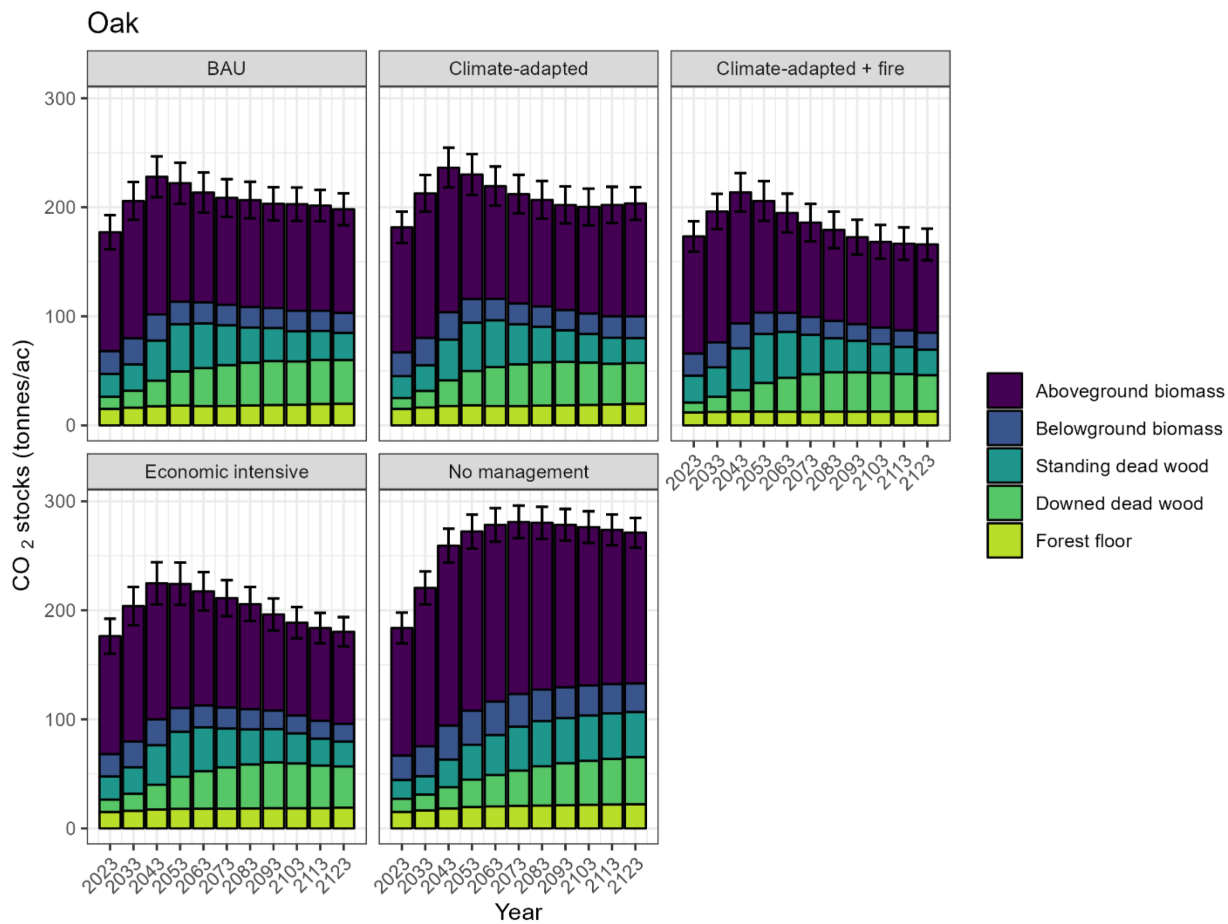


Figure 4.13. Mean carbon stored in various pools for the oak forest type. Error bars show ± 2 standard errors of the total carbon in all five pools.

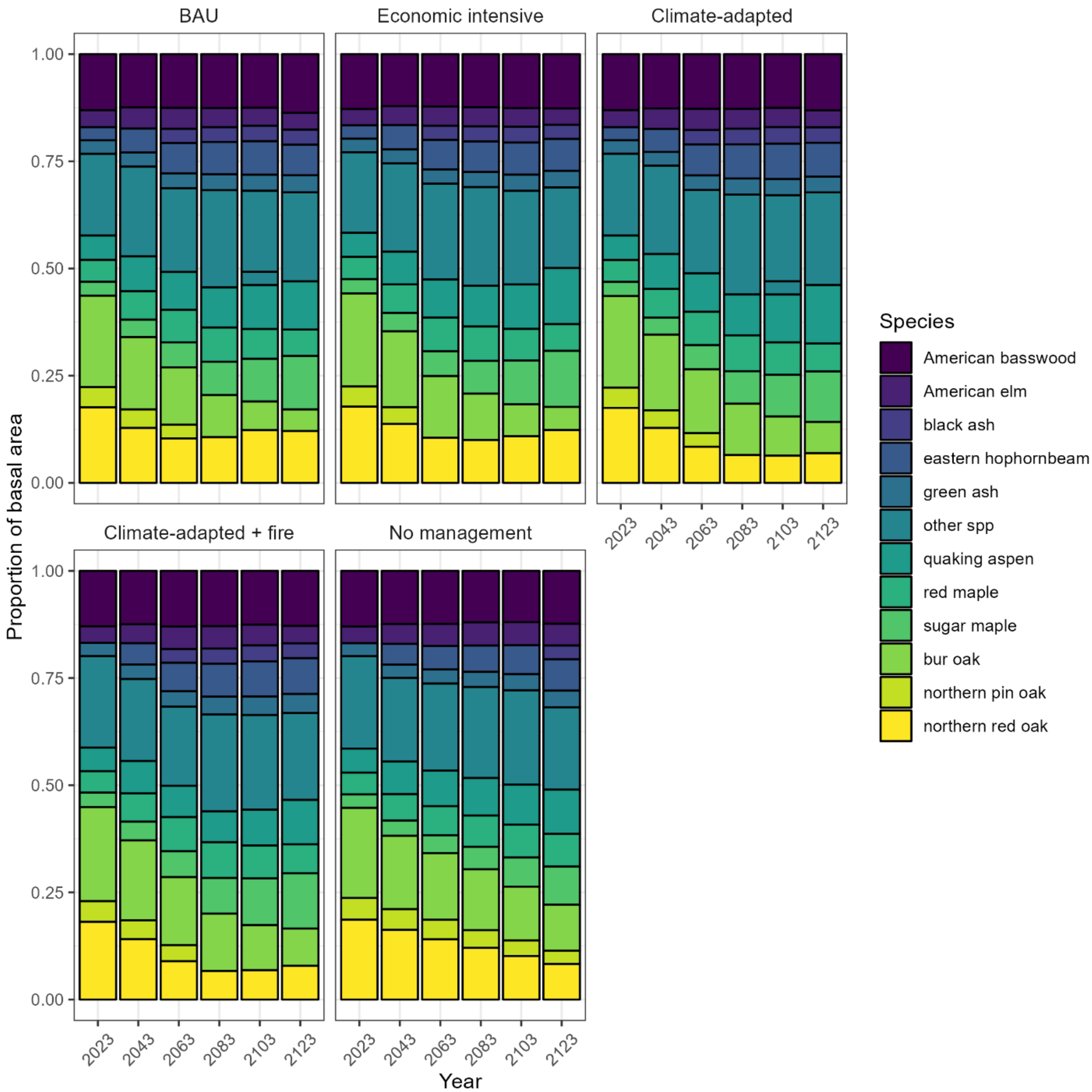


Figure 4.14. Changes in species composition for live trees in the oak forest type under four management scenarios.

4.2.6 Northern hardwoods

For all scenarios in northern hardwood carbon stocks developed similarly throughout the 100-year simulation. Average carbon storage at 100 years ranged from 164.5 tonnes CO_2-eq/ac in the Economic intensive scenario to 167.7 tonnes CO_2-eq/ac in the BAU scenario. Climate-adapted northern hardwood forests stored less carbon in standing and downed dead wood relative to other scenarios (Figures 4.15-4.16; Table 4.8). The proportion of red maple and sugar maple increases across all management scenarios throughout the simulation.

Across the 100-year simulation, average carbon stock change ranged from 0.24 tonnes CO_2-eq/ac/yr in the Climate-adapted scenario to 0.38 tonnes CO_2-eq/ac/yr in the Economic intensive scenario (Figure 4.15; Table 4.8).

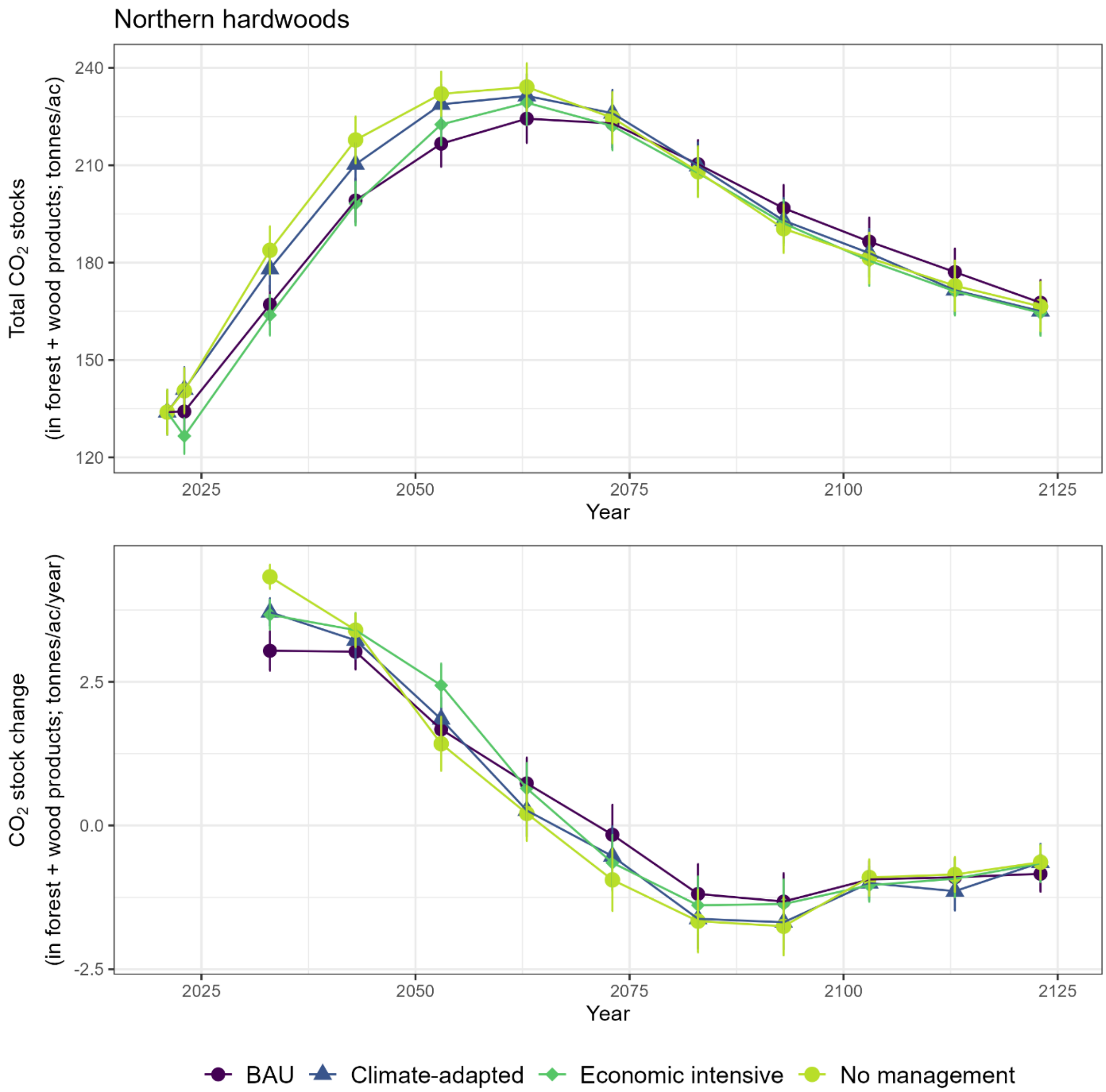


Figure 4.15. Mean carbon stocks and stock change (in forest and in harvested wood products) for the northern hardwoods forest type. Error bars show ± 2 standard errors.

Table 4.8. Forest carbon stocks and stock change for the northern hardwoods forest type (n = 261).

	Carbon stocks (tonnes/ac)				Carbon stock change over 100 years (tonnes/ac/yr)	
	Year 50		Year 100			
	Mean	SD	Mean	SD	Mean	SD
BAU	222.9	61.3	167.7	56.1	0.34	0.85
Climate-adapted	226.1	57.7	165.1	56.6	0.24	0.92
Economic intensive	222.1	60.2	164.5	56.6	0.38	0.83
No management	224.7	63.5	166.5	61.4	0.26	0.99

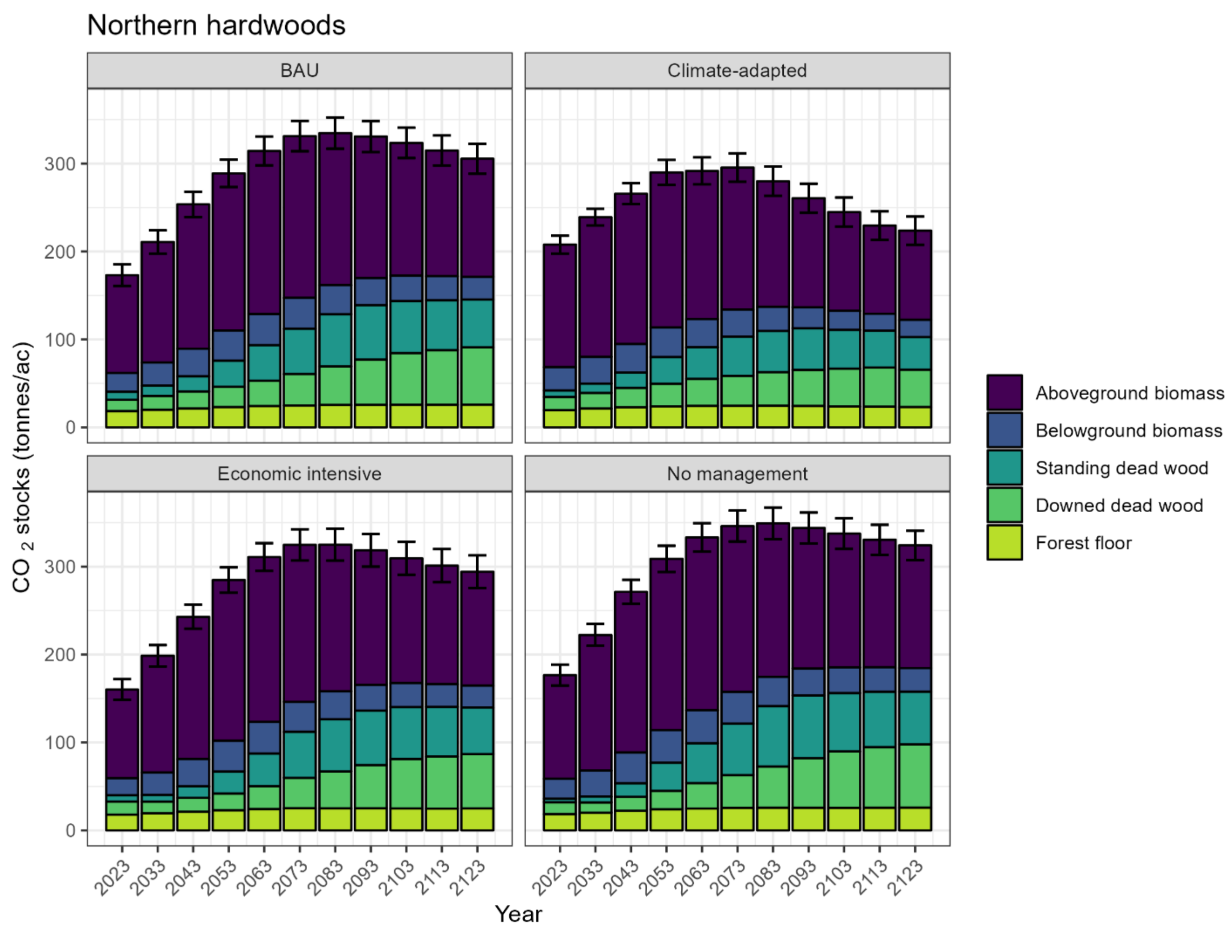


Figure 4.16. Mean carbon stored in various pools for the northern hardwoods forest type. Error bars show ± 2 standard errors of the total carbon in all five pools.

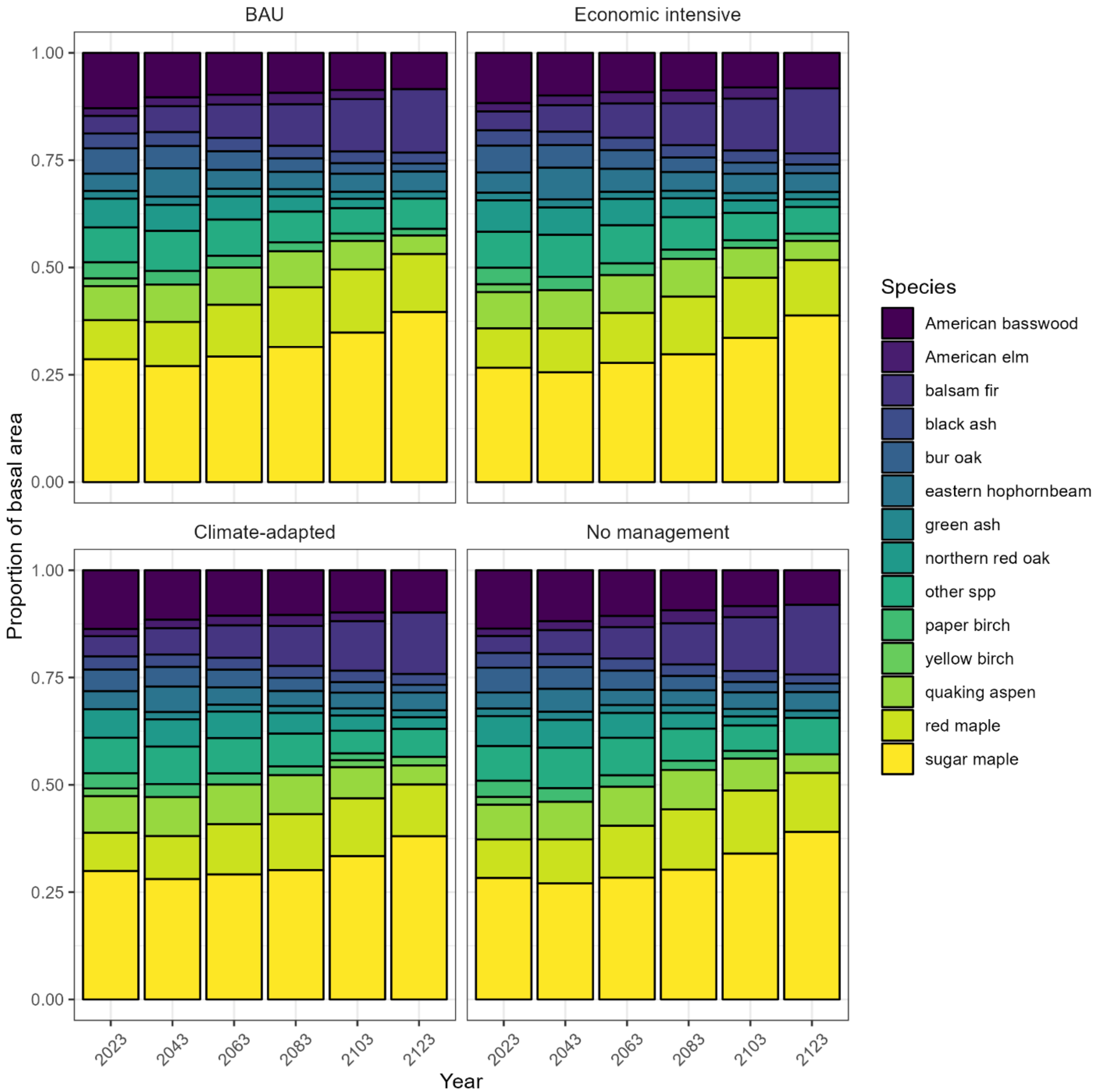


Figure 4.17. Changes in species composition for live trees in the northern hardwoods forest type under four management scenarios.

4.2.7 Lowland conifers

Lowland conifers saw differentiation among all scenarios through 100 years. Average carbon storage at 100 years ranged from 125.6 tonnes CO_2-eq/ac in the BAU/Economic intensive scenario to 140.4 tonnes CO_2-eq/ac in the No management scenario. Lowland conifers displayed relatively high proportions of carbon in the forest floor pool relative to other forest types (Figures 4.18-4.19; Table 4.9). Lowland conifer forests remain dominated by black spruce and tamarack, with increasing amounts of balsam fir and decreasing amounts of northern white-cedar across the simulations (Figure 4.20).

Across the 100-year simulation, average carbon stock change ranged from 0.77 tonnes CO_2-eq/ac/yr in the BAU/Economic intensive scenario to 0.99 tonnes CO_2-eq/ac/yr in the No management scenario (Figure 4.14; Table 4.9).

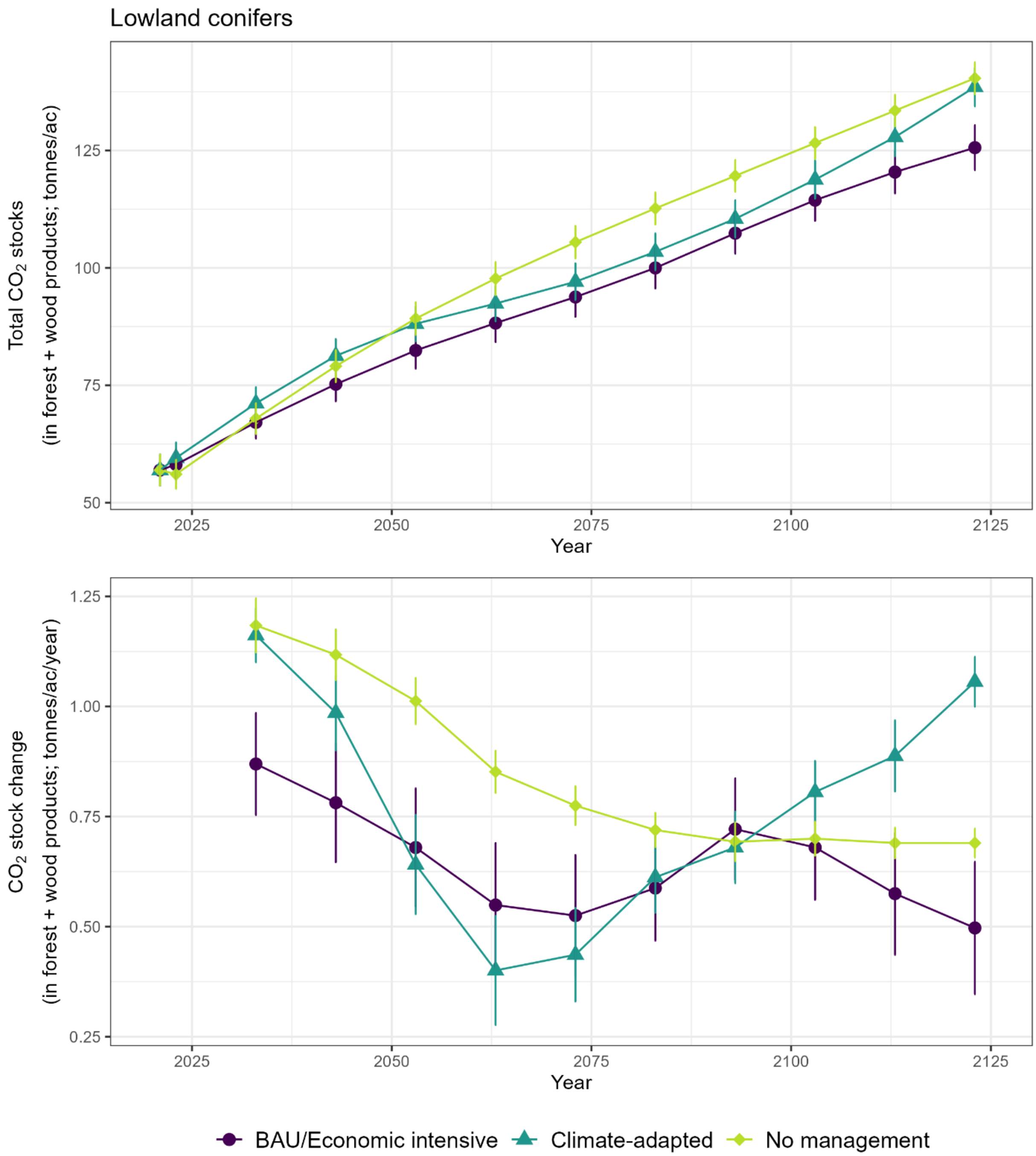


Figure 4.18. Mean carbon stocks and stock change (in forest and in harvested wood products) for the lowland conifers forest type. Error bars show ± 2 standard errors.

Table 4.9. Forest carbon stocks and stock change for the lowland conifers forest type (n = 771).

	Carbon stocks (tonnes/ac)				Carbon stock change over 100 years (tonnes/ac/yr)	
	Year 50		Year 100			
	Mean	SD	Mean	SD	Mean	SD
BAU/ Economic intensive	101.7	57.2	135.2	63.6	0.77	0.51
Climate-adapted	103.2	53.1	152.8	54.2	0.93	0.36
No management	116.8	50.9	158.5	51.4	0.99	0.34

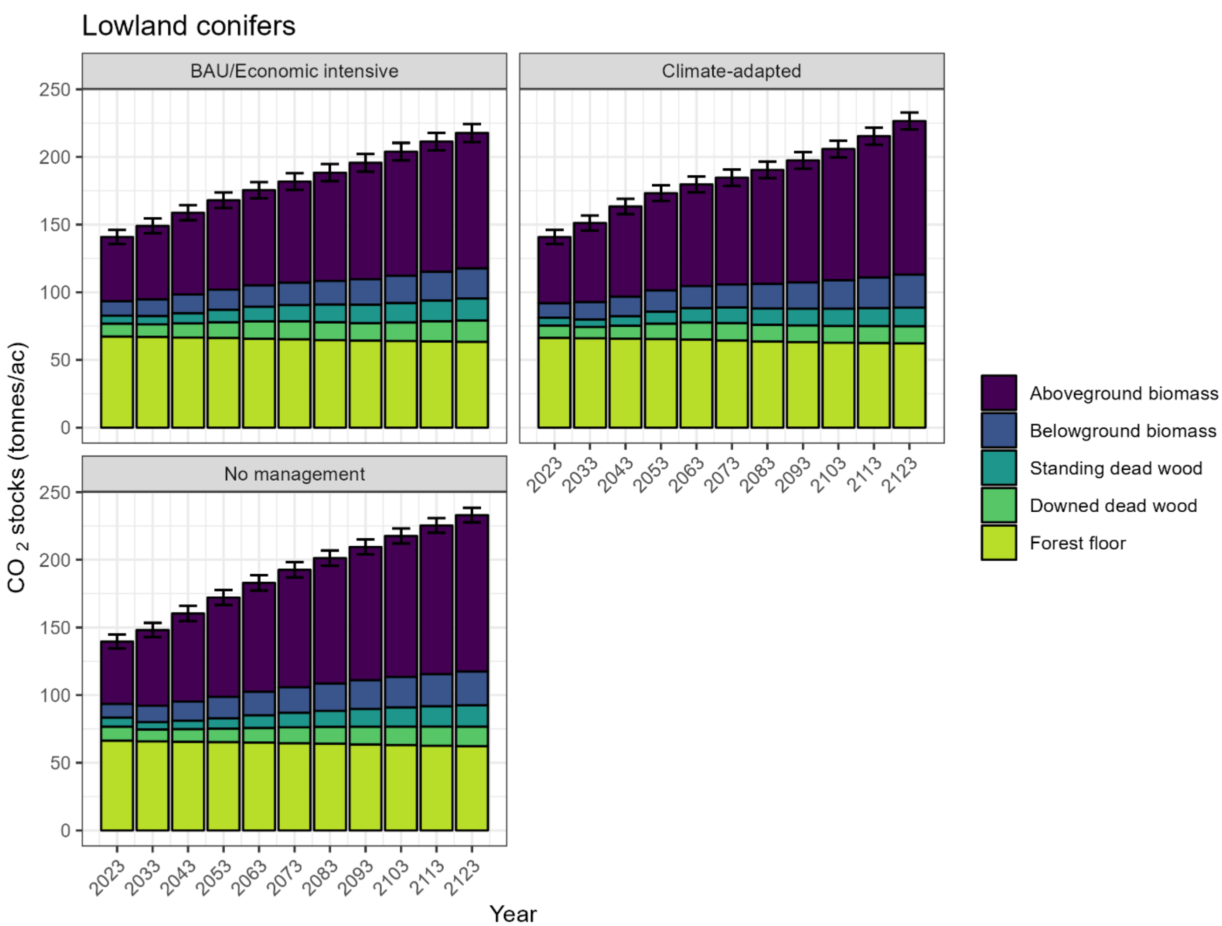


Figure 4.19. Mean carbon stored in various pools for the lowland conifers forest type. Error bars show ± 2 standard errors of the total carbon in all five pools.

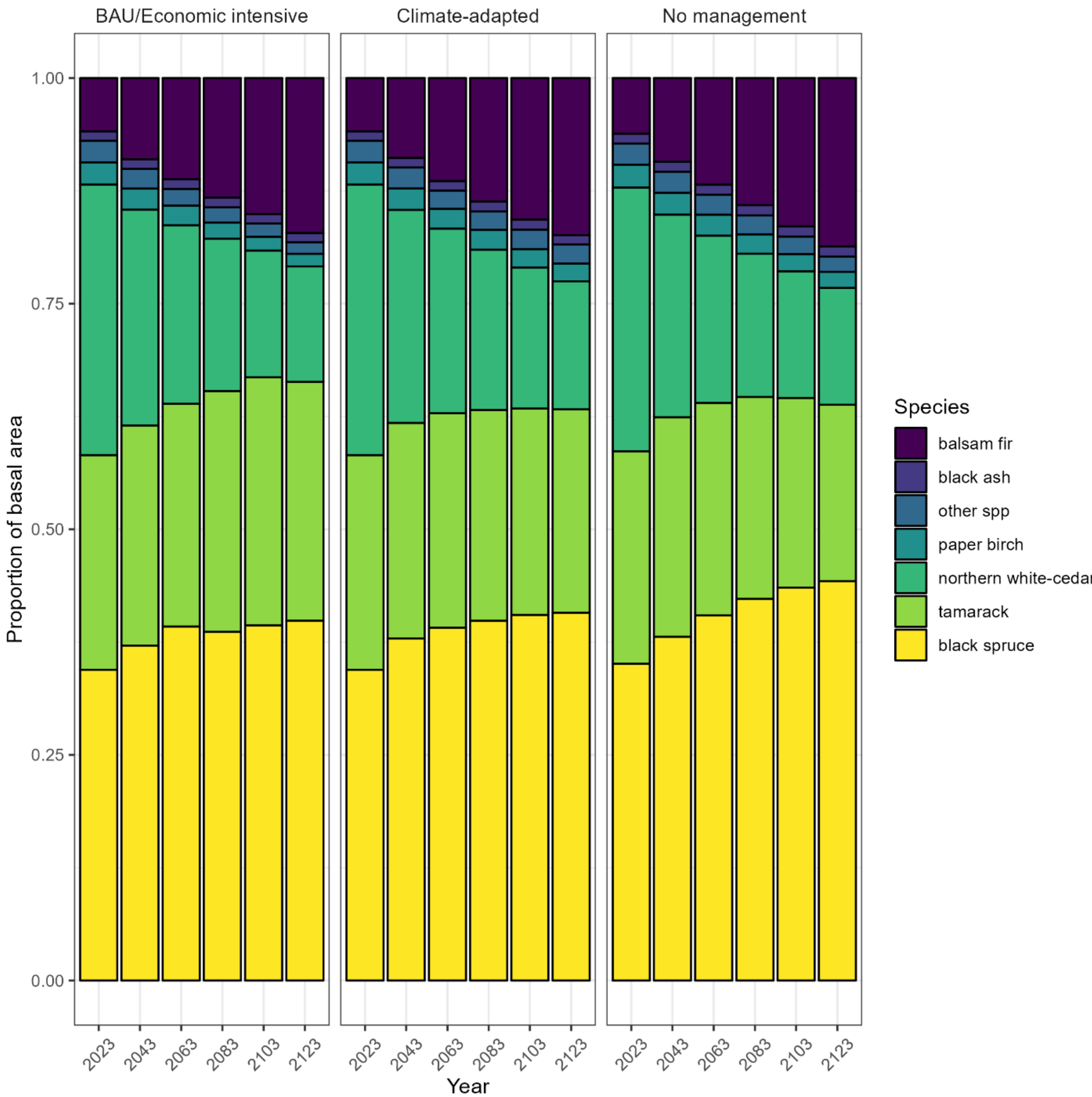


Figure 4.20. Changes in species composition for live trees in the lowland conifers forest type under four management scenarios.

4.2.8 Black ash

Of note in the black ash forest type is the immediate decrease in forest carbon stocks in the BAU/Climate-adapted + EAB mortality scenario, a reflection of the mortality applied to all ash species to reflect an emerald ash borer outbreak (Figure 4.21). This is evident in the large amount of carbon in standing dead wood in this scenario, followed by a transition to the downed dead wood pools (Figure 4.17). Average carbon storage at 100 years was similar across all scenarios, ranging from 79.9 tonnes CO_2-eq/ac in the BAU/Climate-adapted + EAB scenario to 96.3 tonnes CO_2-eq/ac in the No management scenario. Similar to lowland conifer forests, black ash forests displayed relatively high proportions of carbon in the forest floor pool. Black ash decreases in abundance in the BAU/Climate-adapted + EAB mortality treatment, being replaced by balsam fir and other species throughout the simulation (Figure 4.23).

Across the 100-year simulation, average carbon stock change ranged from 0 tonnes CO_2-eq/ac/yr in the BAU/Climate-adapted + EAB scenario to 0.10 tonnes CO_2-eq/ac/yr in the Economic intensive scenario (Figure 4.21; Table 4.10).

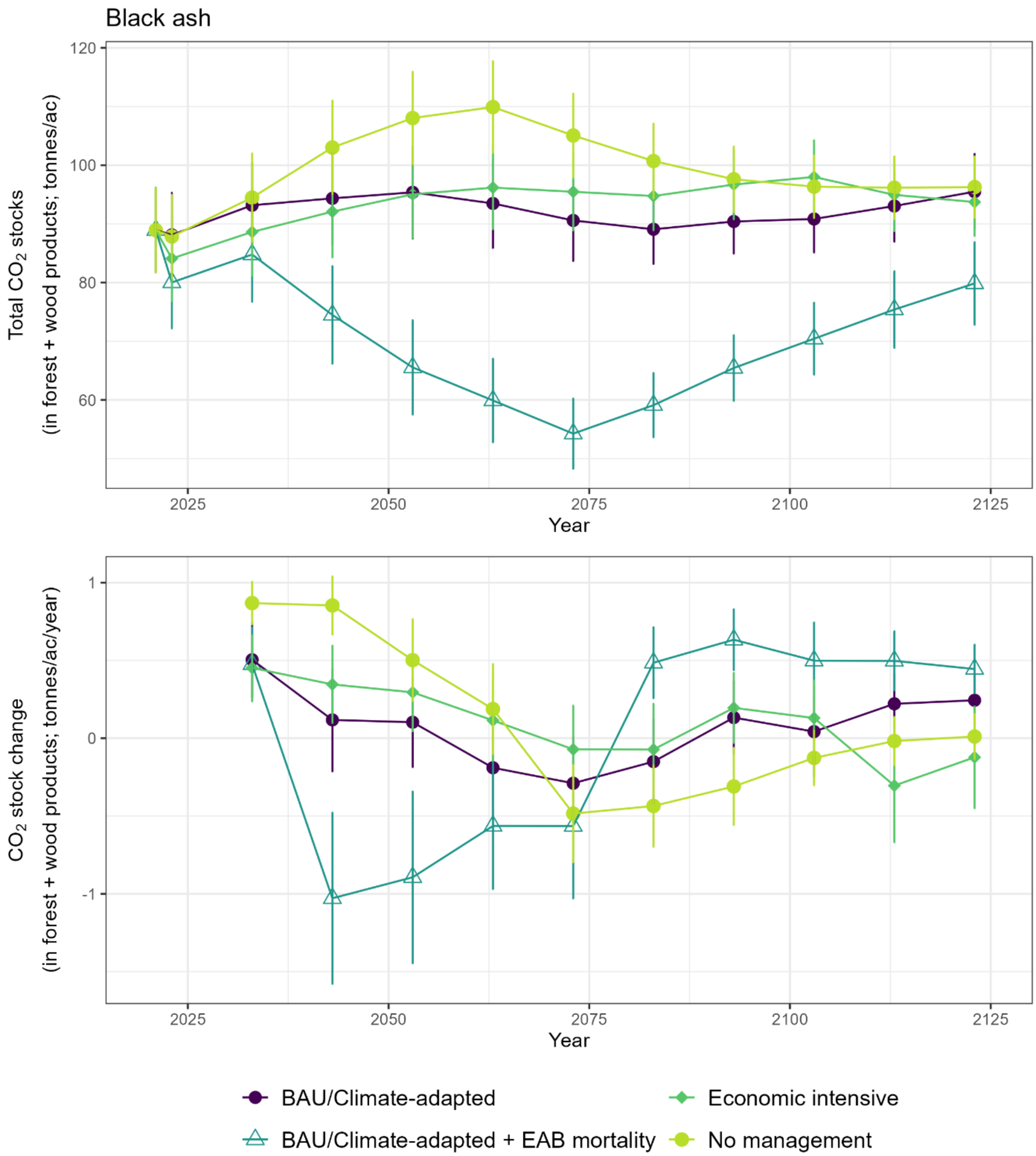


Figure 4.21. Mean carbon stocks and stock change (in forest and in harvested wood products) for the black ash forest type. Error bars show ± 2 standard errors.

Table 4.10. Forest carbon stocks and stock change for the black ash forest type (n = 144).

	Carbon stocks (tonnes/ac)				Carbon stock change over 100 years (tonnes/ac/yr)	
	Year 50		Year 100			
	Mean	SD	Mean	SD	Mean	SD
BAU/Climate-adapted	90.6	41.3	95.5	38.6	0.07	0.58
BAU/Climate-adapted + EAB mortality	54.3	35.7	79.9	42.0	0.00	0.62
Economic intensive	95.5	39.2	93.7	34.5	0.01	0.58
No management	105.1	42.6	96.3	31.4	0.08	0.54

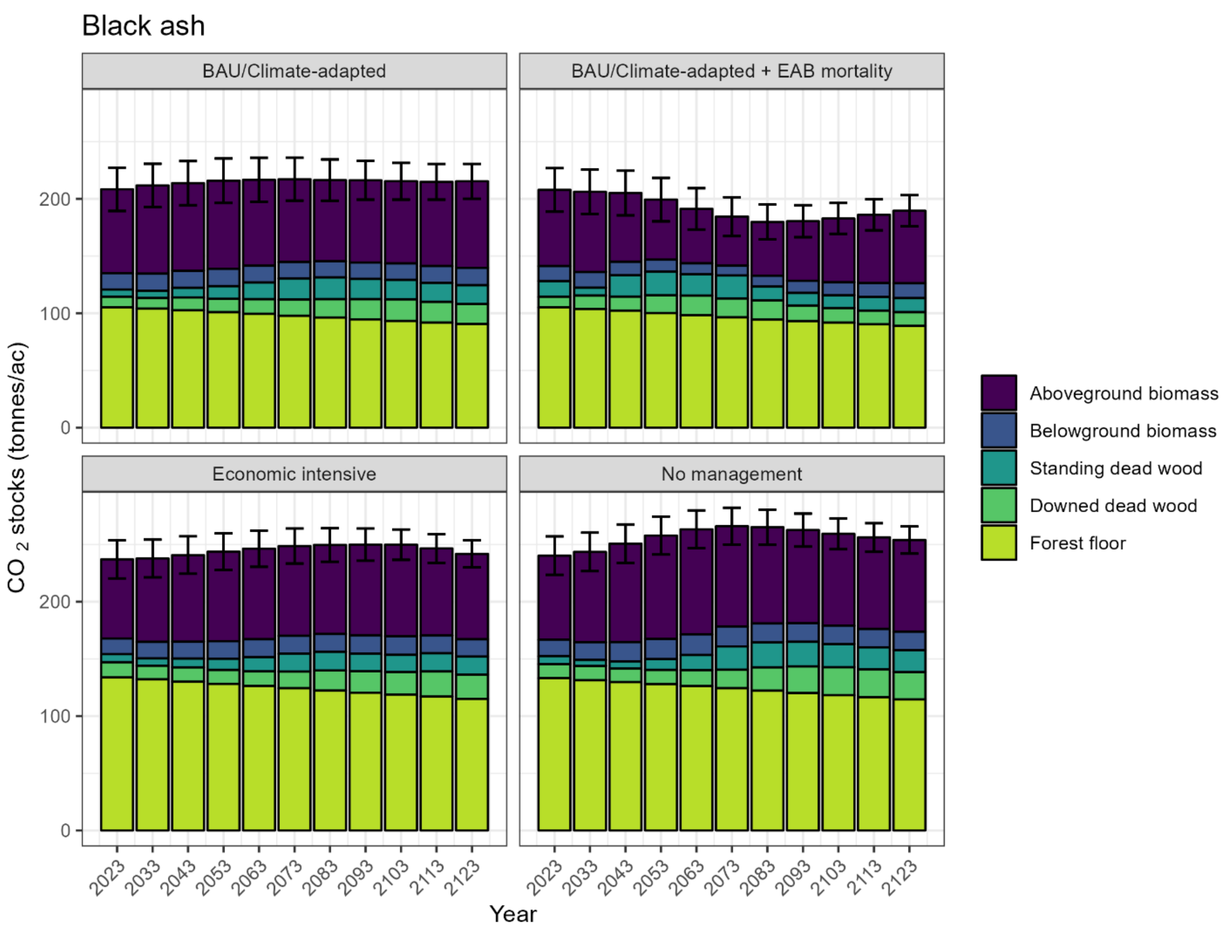


Figure 4.22. Mean carbon stored in various pools for the black ash forest type. Error bars show ± 2 standard errors of the total carbon in all five pools.

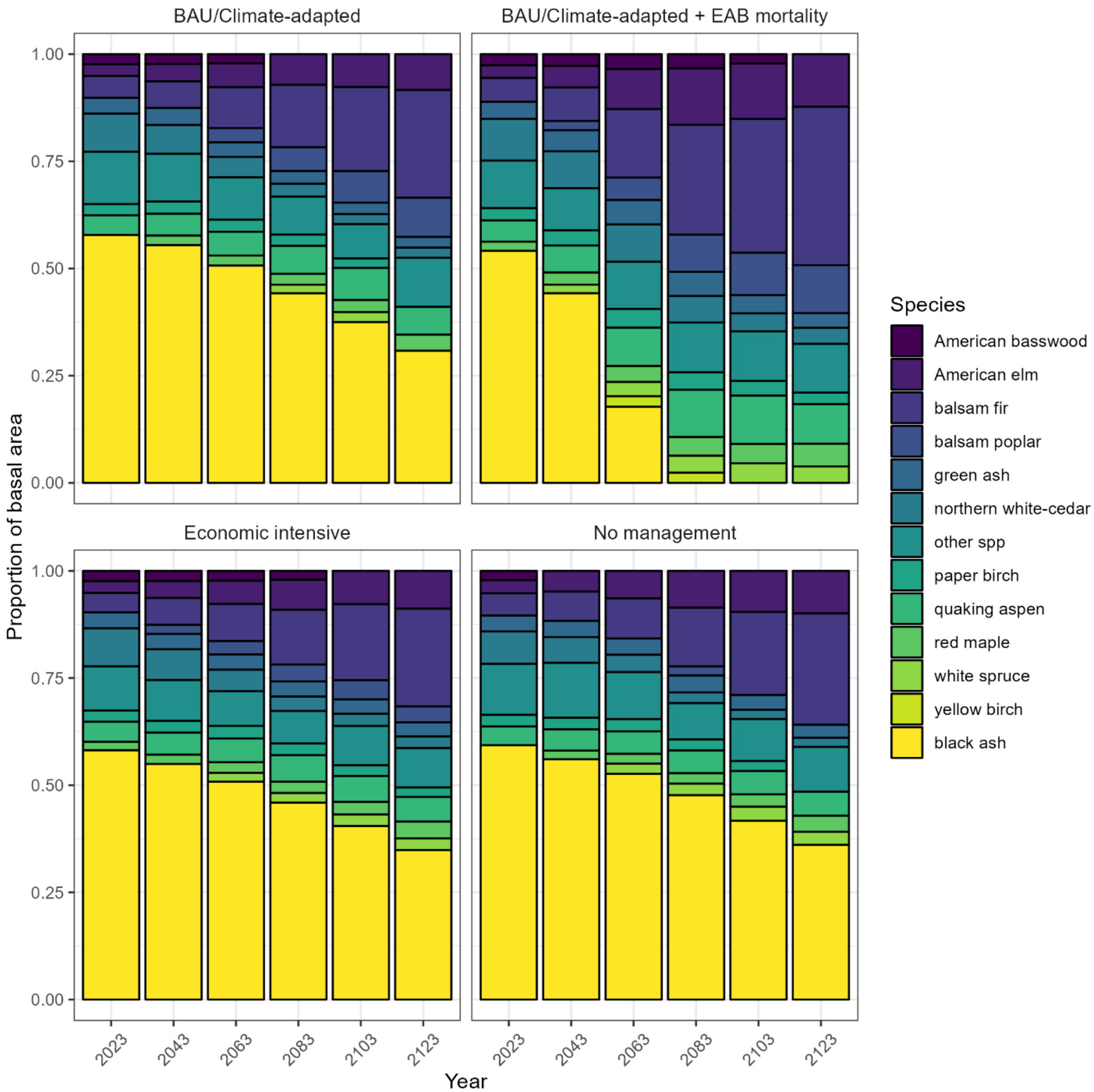


Figure 4.23. Changes in species composition for live trees in the black ash forest type under four management scenarios.

4.2.9 Other forest types

In other forest types, average carbon storage at 100 years ranged from 115.8 tonnes CO_2-eq/ac in the Economic intensive scenario to 155.1 tonnes CO_2-eq/ac in the No management scenario. These forest types displayed relatively high proportions of carbon in the standing and downed dead wood pools relative to other forest types (Figures 4.24-4.25; Table 4.11). Balsam fir, red maple, quaking aspen, and jack pine are the four most common species that occur in these forest types (Figure 4.26).

Across the 100-year simulation, average carbon stock change in other forest types ranged from 0.58 tonnes CO_2-eq/ac/yr in the Climate-adapted scenario to 0.78 tonnes CO_2-eq/ac/yr in the No management scenario (Figure 4.24; Table 4.11).

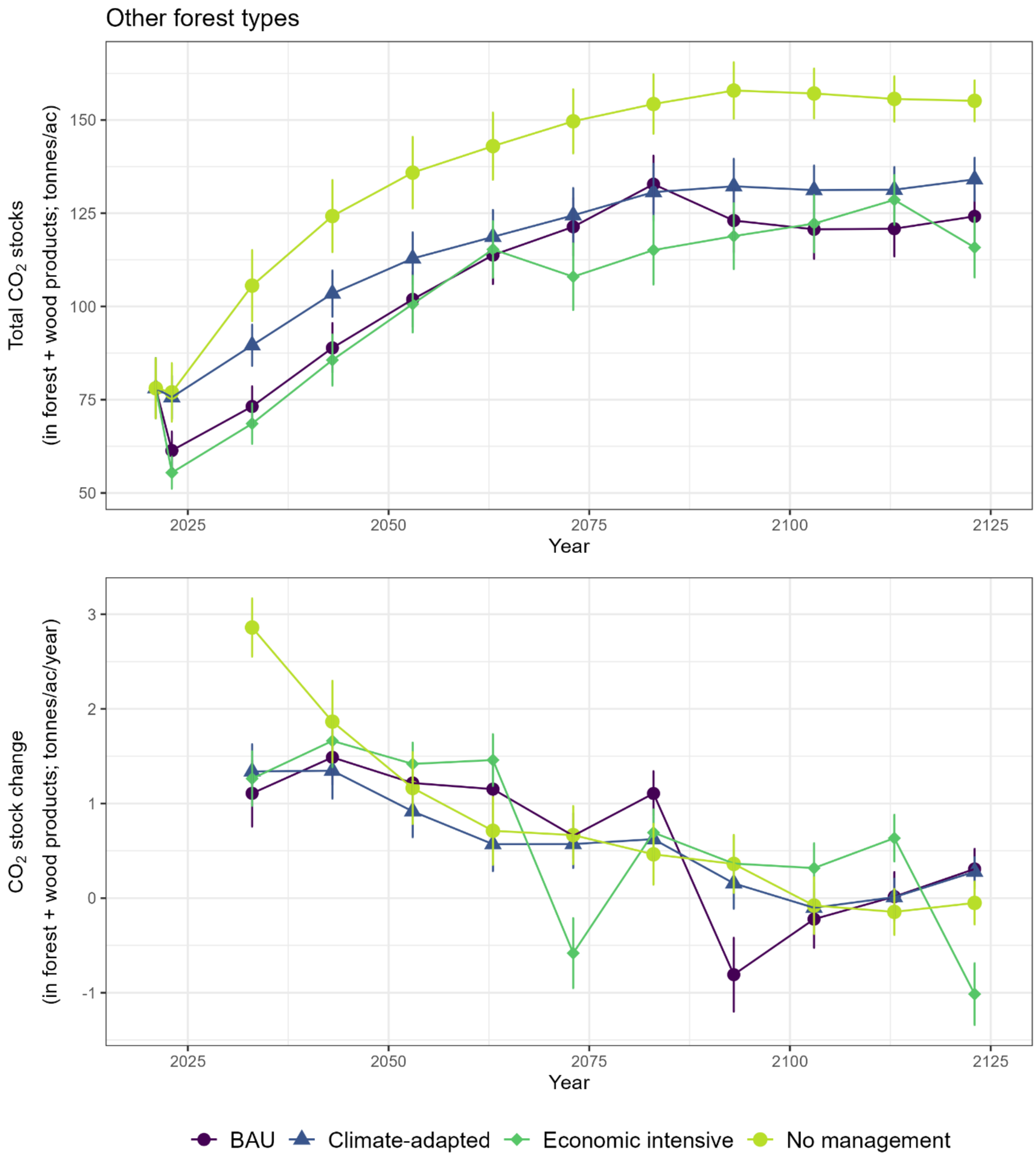


Figure 4.24. Mean carbon stocks and stock change (in forest and in harvested wood products) for other forest types. Error bars show ± 2 standard errors.

Table 4.11. Forest carbon stocks and stock change for other forest types (n = 290).

	Carbon stocks (tonnes/ac)				Carbon stock change over 100 years (tonnes/ac/yr)	
	Year 50		Year 100			
	Mean	SD	Mean	SD	Mean	SD
BAU	121.4	63.6	124.2	57.8	0.63	0.70
Climate-adapted	124.4	60.2	134.1	47.4	0.58	0.72
Economic intensive	108.0	73.6	115.8	66.1	0.60	0.67
No management	149.7	65.4	155.1	41.8	0.78	0.68

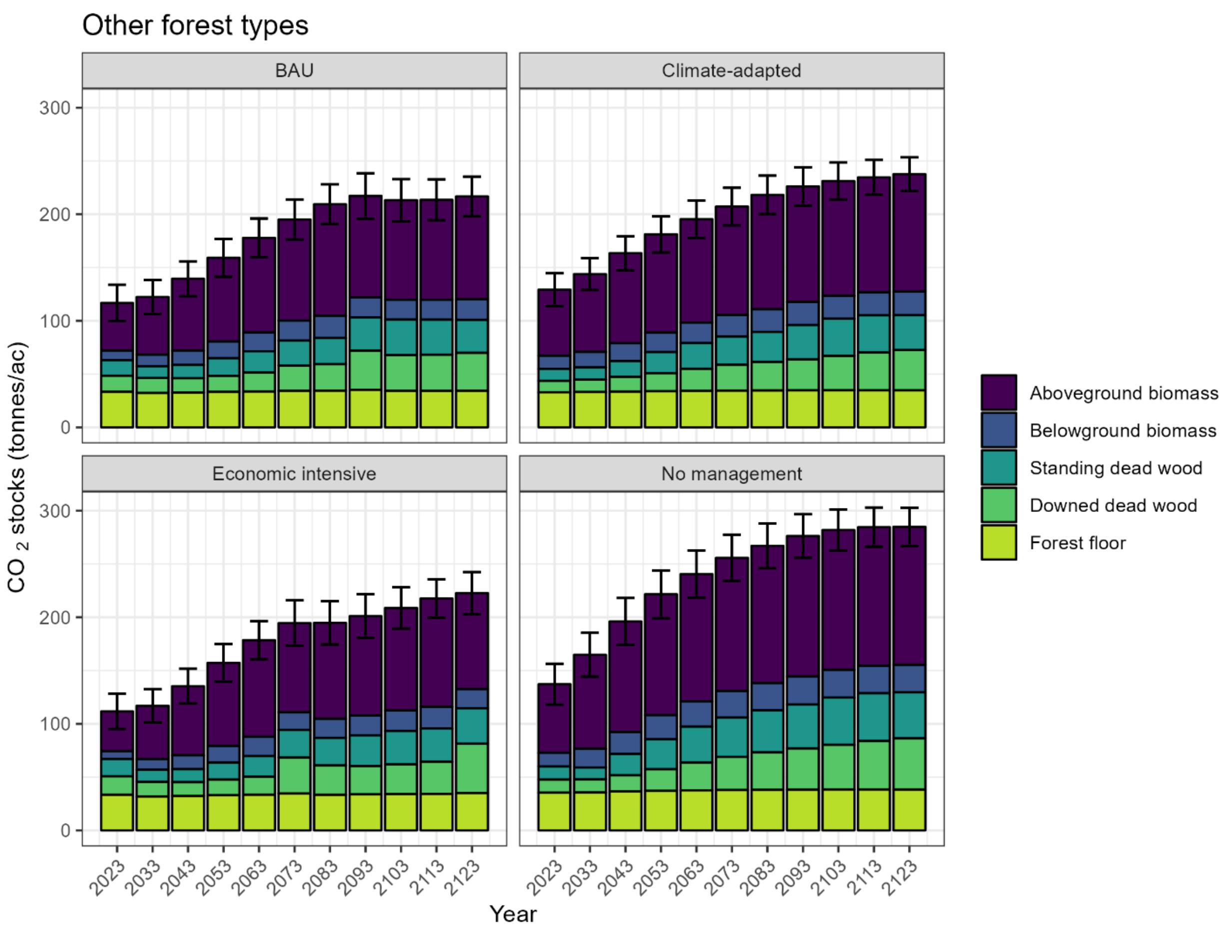


Figure 4.25. Mean carbon stored in various pools for other forest types. Error bars show ± 2 standard errors of the total carbon in all five pools.

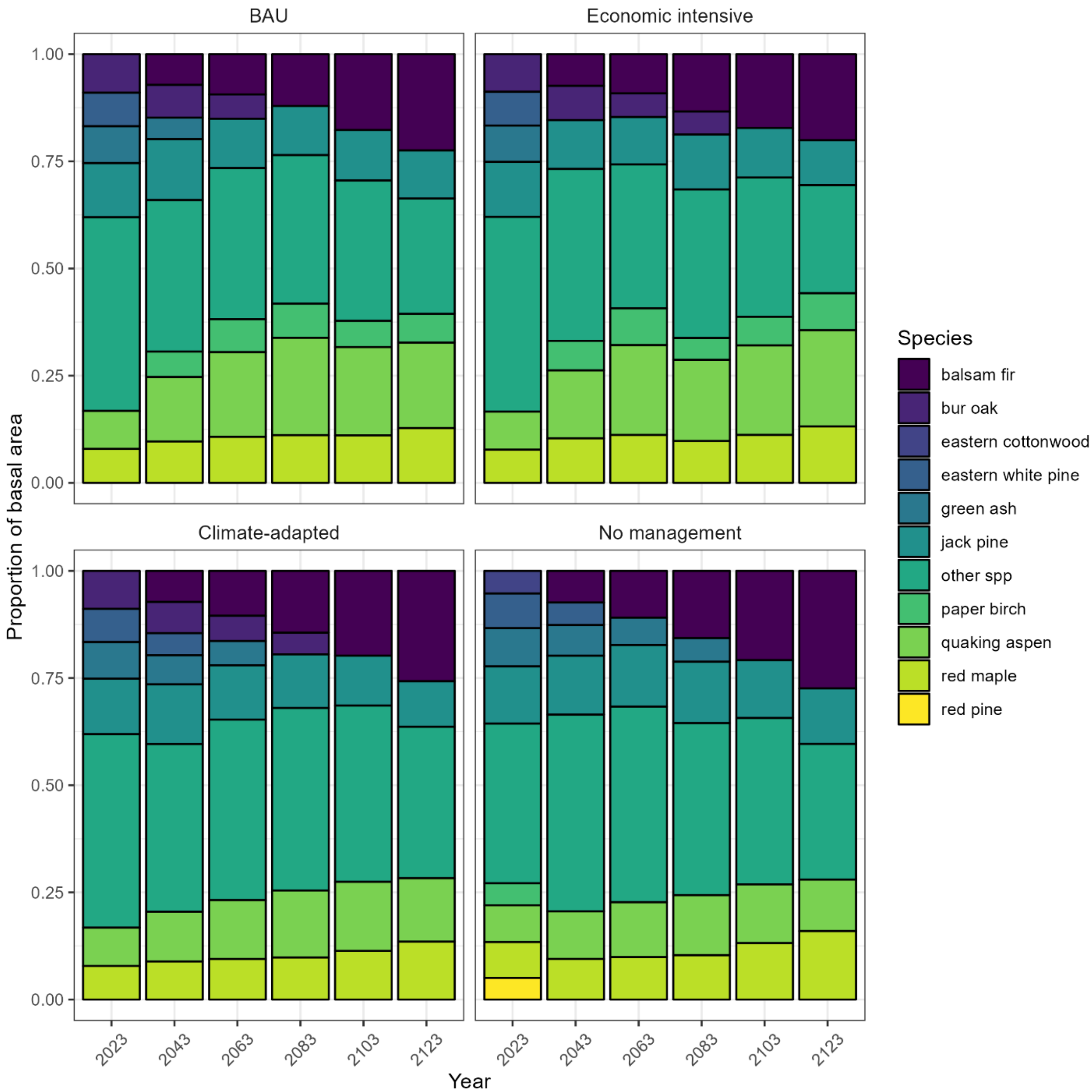


Figure 4.26. Changes in species composition for live trees in other forest types under four management scenarios.

5 LIFE CYCLE ANALYSIS ASSESSMENT

5.1 BACKGROUND

Producing all materials, renewable and non-renewable, has environmental impacts. Historically, a preferred environmental product was one that was made from renewable or recycled resources. Today, forest products are held to a higher standard of transparency that goes beyond their natural attributes. Wood-based products that have low embodied carbon and energy are sought out. Other functional aspects such as longevity, durability, recyclability, and disposal options other than landfilling are also desired. Life cycle assessments (LCA) have become increasingly important as they are used by all industries to inform product and process designs that minimize energy consumption and carbon release. Going forward, the need for credible, scientific, LCA-based information will be greater than ever.

The following sections present the LCA results for predominant forest management scenarios and harvested wood products (HWP) in Minnesota. The primary goal was to develop LCA results that can augment landscape level analyses by identifying which management scenario(s) are optimal for enhancing carbon removals and reducing carbon emissions. Also included in the LCA results are the carbon impacts of product specific end-of-life (EoL) scenarios and substitution analyses of selected wood products.

5.2 WHAT IS LIFE CYCLE ASSESSMENT

Life-cycle assessment (LCA) has evolved as an internationally accepted method to analyze complex impacts and outputs of a product or process and the corresponding effects they might have on the environment. LCA is an objective method to evaluate a product's life cycle by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials uses and releases on the environment; and to evaluate and implement opportunities to effect environmental improvements. LCA studies can evaluate full product life cycles, often referred to as "cradle-to-grave", or incorporate only a portion of the products life cycle, referred to as "cradle-to-gate", or "gate-to-gate". This study includes both a cradle-to-gate LCA as it includes forestry operations through production of the product ready for shipment as well as cradle-to-grave where we assumed various end of life scenarios depending on the product.

As defined by the International Organization for Standardization (ISO 2006a-b), LCA is a multiphase process consisting of a 1) Goal and Scope Definition, 2) Life Cycle Inventory (LCI), 3) Life Cycle Impact Assessment (LCIA), and 4) Interpretation (Figure 5.1). These steps are interconnected, and their outcomes are based on goals and purposes of a study.

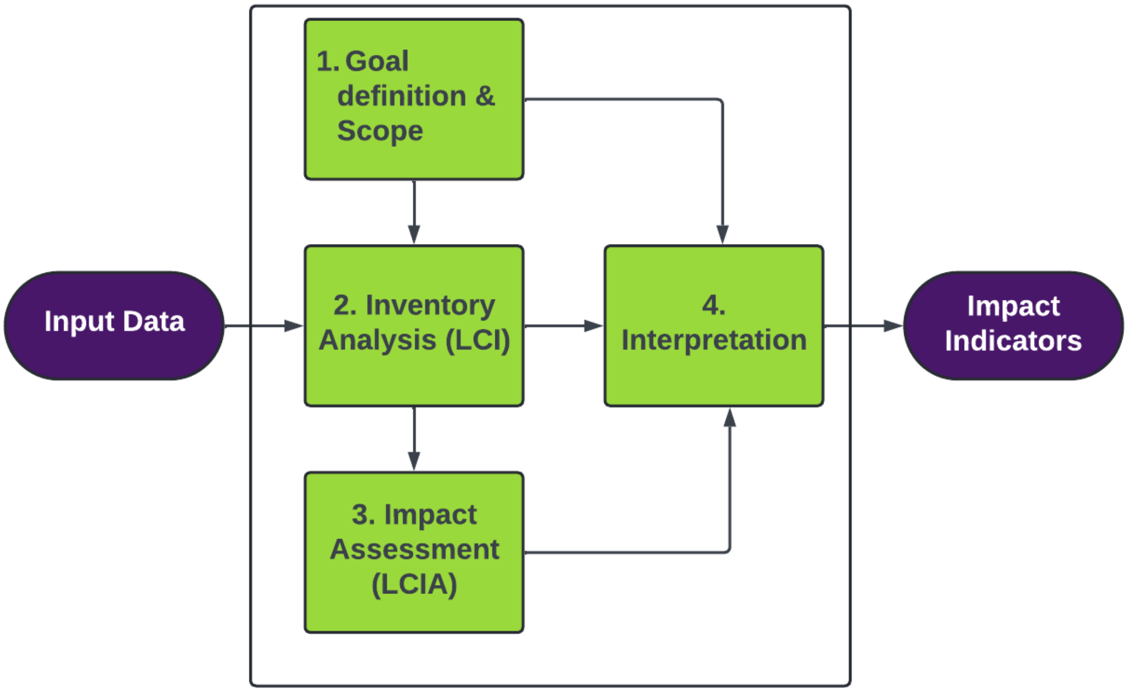


Figure 5.1. Steps involved in a life cycle assessment.

An LCA begins with a project goal, scope, functional unit, system boundaries, any assumptions and study limitations, method of allocation, and the impact categories that will be used.

The key component is the LCI which is an objective, data-based process of quantifying energy and raw material requirements, air emissions, waterborne effluents, solid waste, and other environmental releases occurring within the system boundaries. It is this information that provides a quantitative basis for comparing wood products, their manufacturing processes, and most importantly from the forest industry point of view, wood products performance against competitors who use other resources to create alternative products.

The LCIA process characterizes and assesses the effects of environmental releases identified in the LCI into impact categories such as global warming, acidification, eutrophication, ozone depletion, and smog.

The life cycle interpretation is a phase of LCA in which the findings of either the LCI or the LCIA, or both, are evaluated in relation to the defined goal and scope to reach conclusions and recommendations. This final step in an LCA involves an investigation of significant environmental aspects (e.g., energy use, greenhouse gases), their contributions to the indicators under consideration, and which unit processes in the system are generating the emissions. For example, if the results of a LCIA indicate a particularly high value for the global warming potential indicator, the analyst could refer to the inventory to determine which environmental flows are contributing to the high value, and which unit processes contribute to those outputs. This is also used as a form of *quality control*, and the results can be used to refine the scope definition to focus on the more important unit processes. This step also supports arriving at more certain conclusions and supportable recommendations.

5.3 METHODS

5.3.1 System Boundary

Information modules included in the LCA are shown in Figure 5.2. This LCA includes modules A1-A3 for cradle-to-gate analysis. Additional declared Modules include EoL stages (C2 & C4) to complete a cradle-to-grave module inclusions (ISO 21090). Both human activity and capital equipment were excluded from the system boundary. Human activity involved in the manufacturing of any wood product no doubt has a burden on the environment. However, the data collection required to properly quantify human involvement is particularly complicated and allocating such flows to the production of materials as opposed to other societal activities was not feasible for a study of this nature. Typically, human activity is only considered within the system boundary when value-added judgements or substituting capital for labour decisions are within the study scope. These types of decisions are outside the current goal and scope of this study. Figure 5.3 details the unique processes (management scenarios and products) which are all with the system boundary and modules included in this study.

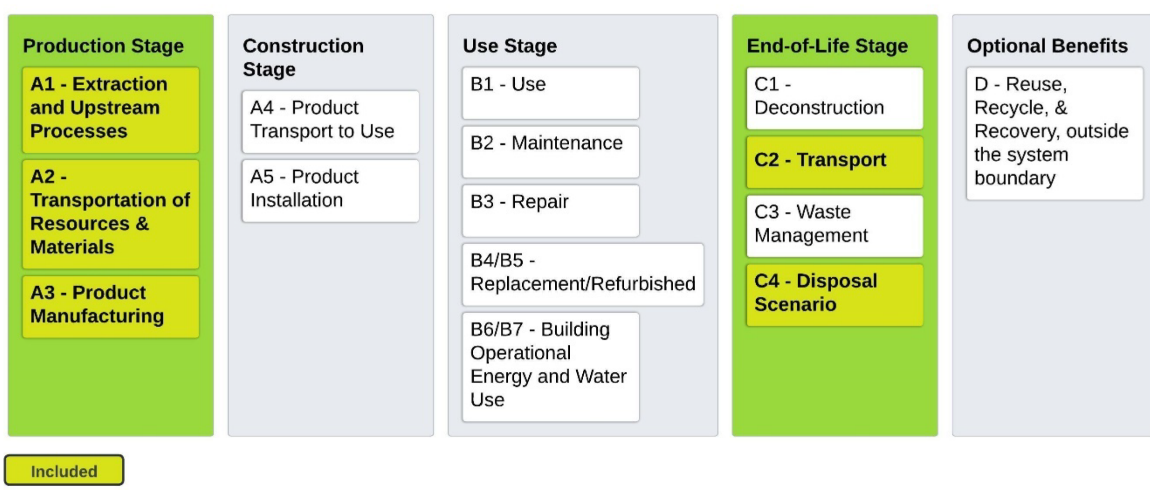


Figure 5.2. Description of the system boundary modules. Adapted from ISO 21930.

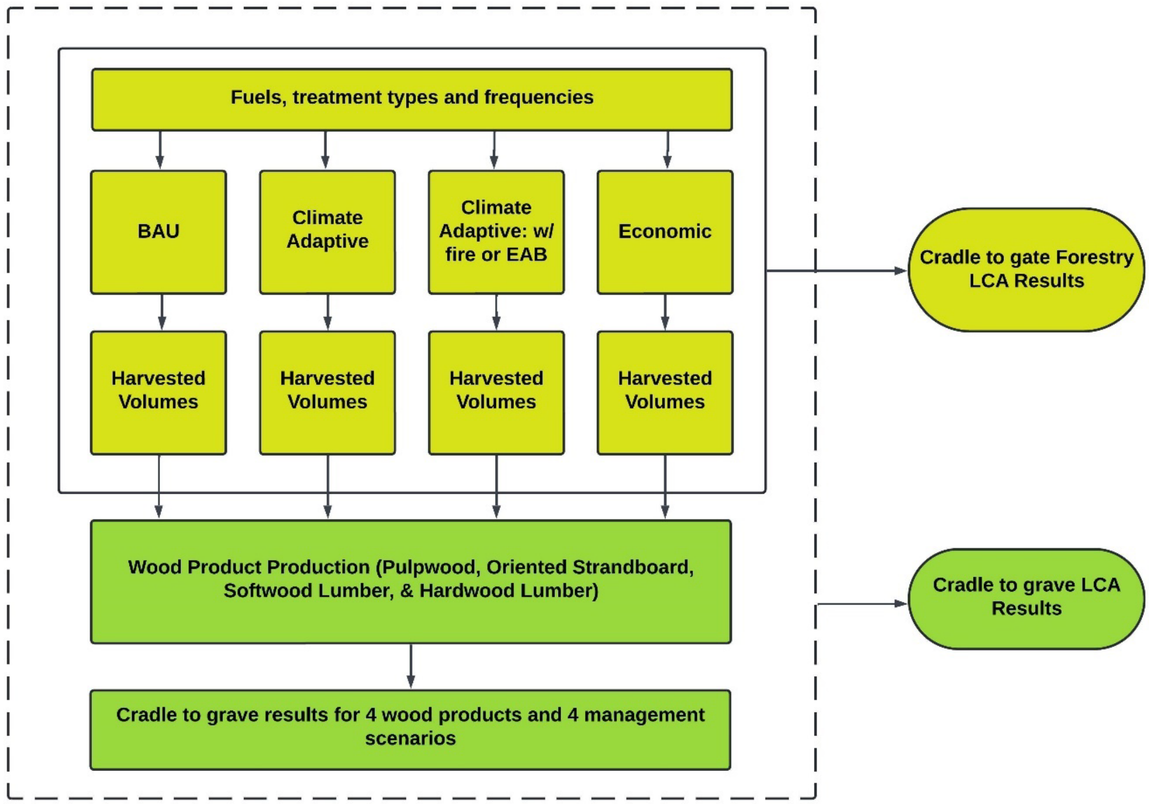


Figure 5.3. Cradle-to-gate system flow for all wood products and management scenarios.

For forestry operations, the system boundary is characterized by a mix of the components shown in Figure 5.4 consistent with the silvicultural system inputs and treatment scenarios for each forest type simulation. System boundaries for OSB and lumber are shown in Figure 5.5 and for pulpwood production in Figure 5.6.

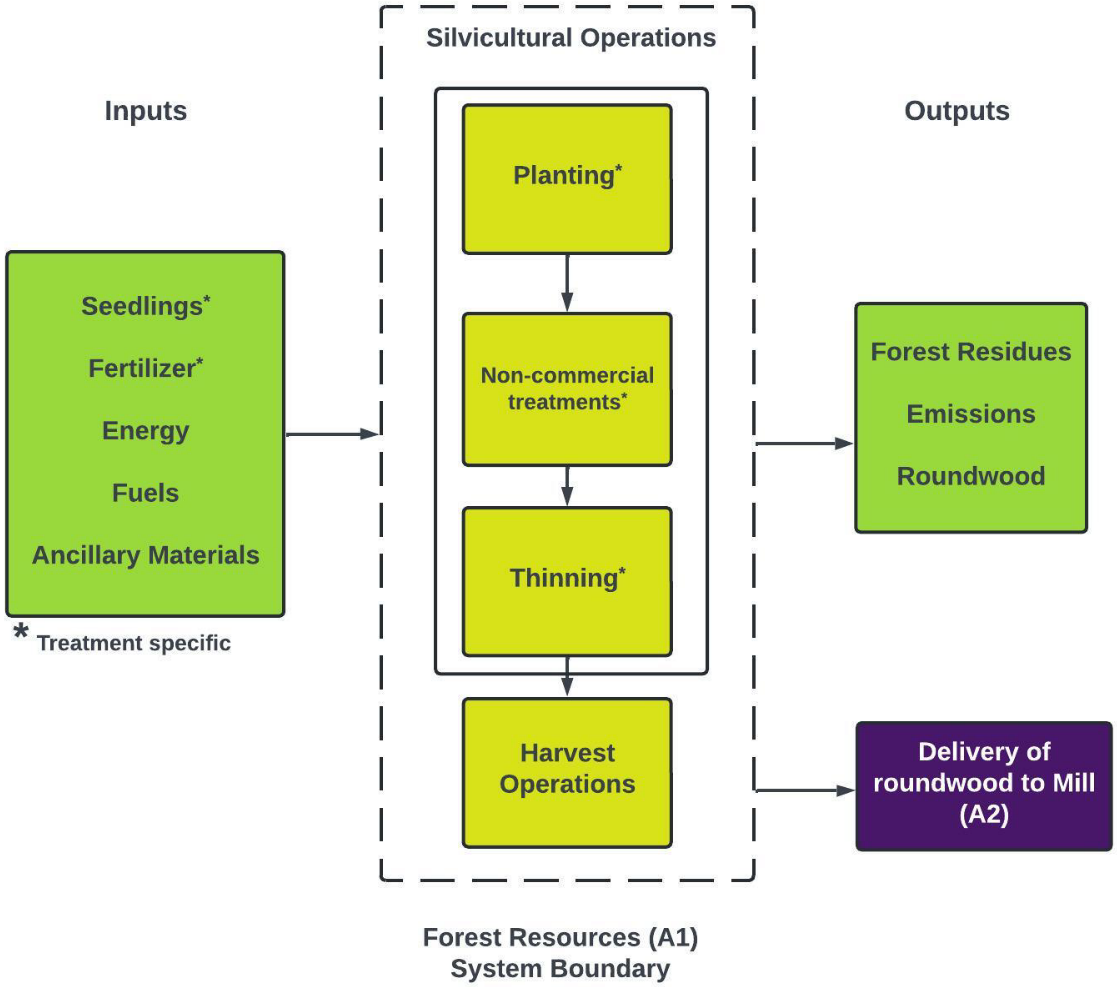


Figure 5.4. Forest Resources (A1 module) System Boundary

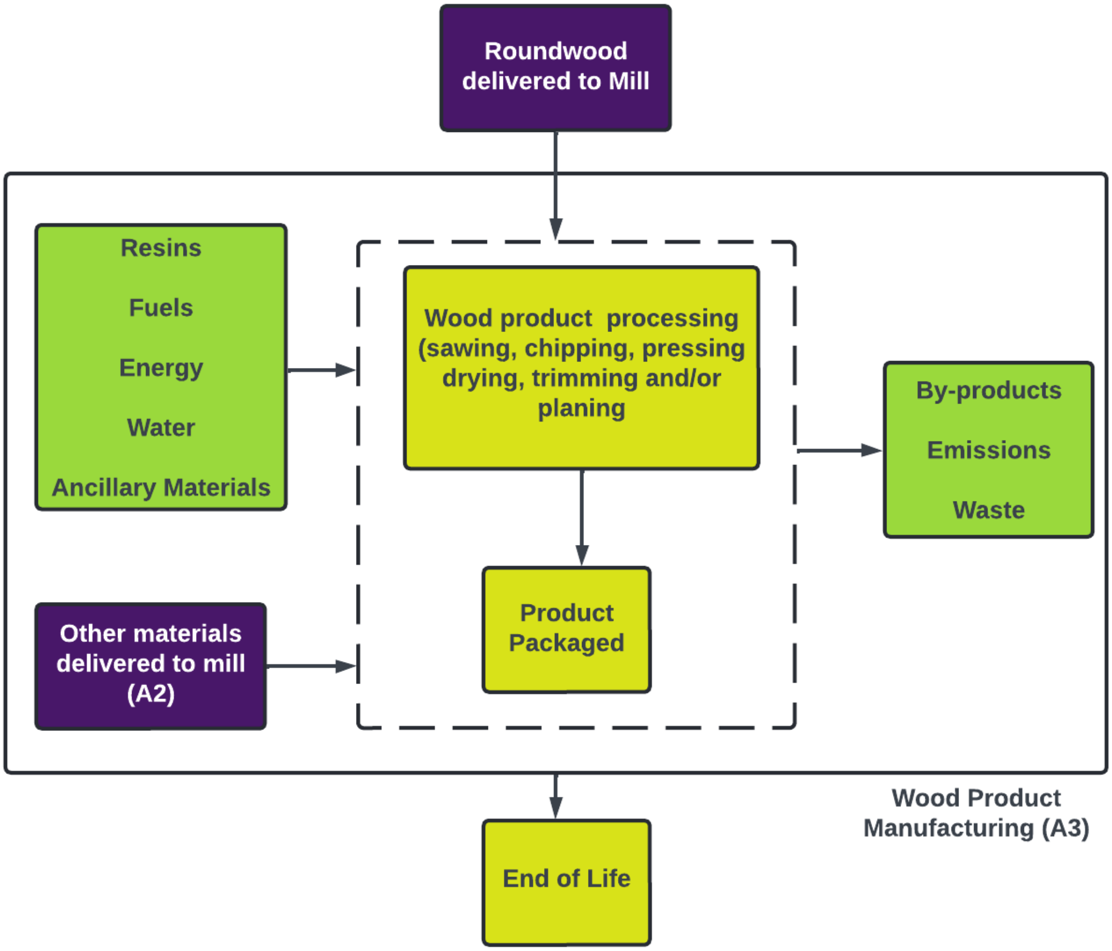


Figure 5.5. Wood Products (OSB and Lumber) (A3 module) System Boundary.

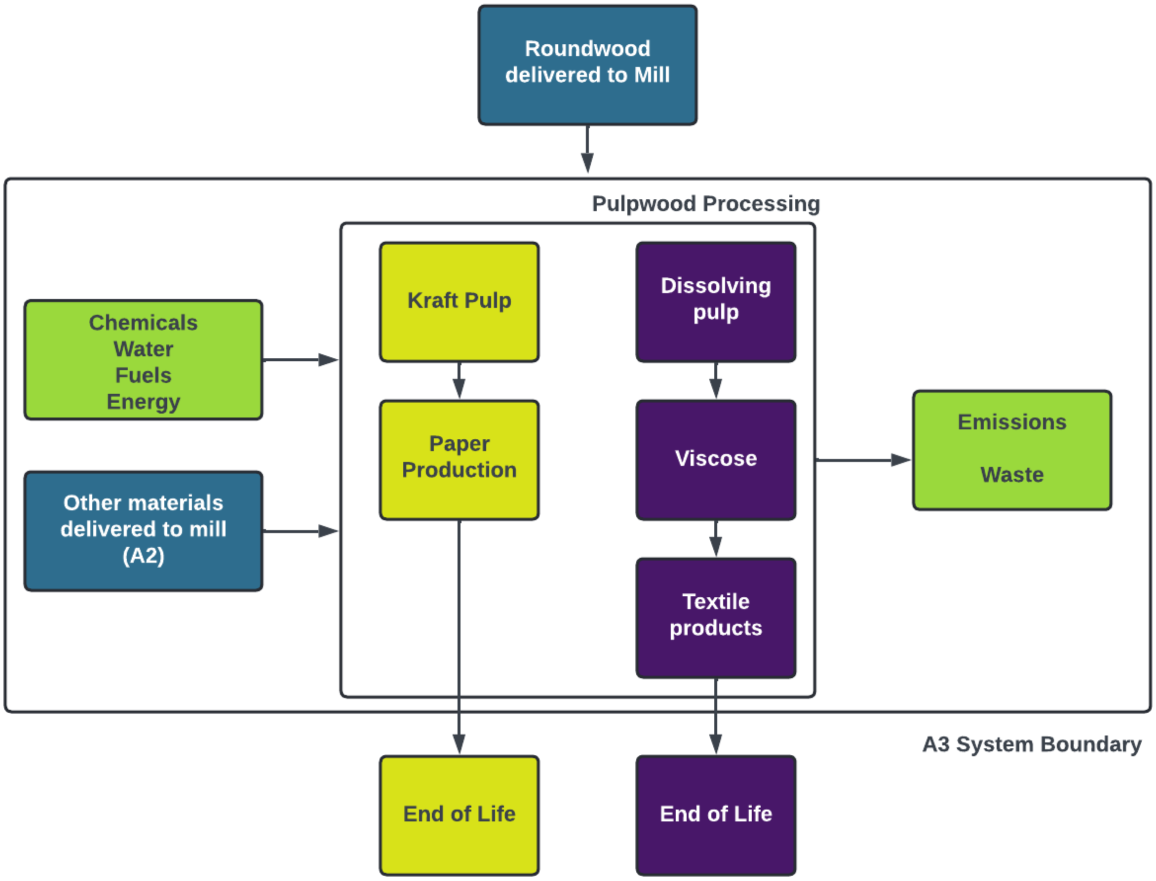


Figure 5.6. Paper and Textile production (A3 module) System Boundary.

5.3.2 Data Collection and LCA Model Development

This study integrated high quality state and regional wood volume production quantities (Timber Product Output (TPO) (2018)) with verified LCA data (www.corrim.org) and simulated yields (Chapter 4 inputs) in order to develop cradle-to-gate carbon flows and LCA environmental impacts for Minnesota. Specific data used are described in the following sections for Forest Resources Operations and Harvested Wood Products. All secondary data for chemicals, transportation, energy, fuels, and pulp, paper, and textile production utilized available literature and available LCI processes as part of Datasmart 2023 (LTS 2023), Ecoinvent (v3.8) (Wernet et al. 2016), and the USLCI dataset. All LCA modeling was performed using SimaPro software v. 9.5 (PRé 2020).

5.3.3 Forest Types and Wood Species

Forest types were described in Section 3 of this report and are represented in Table 5.1. Forest type data were further refined into species groups in Table 5.2. Using Timber Product Output (TPO) production data by species we were able combine the forest types of representation (Table

5.1) with species production outputs (Table 5.2). These same forest types were used in the forest inventory simulation (Section 4 results) to generate expected volumes for each forest type across five management scenarios: 1. Business as usual (BAU), 2. Climate-adapted, 3. Climate-adapted plus fire, 4. Climate-adapted plus EAB (emerald ash borer), and 5. Economic intensive. Note that since the BAU and Climate-adapted prescriptions are the same for black ash, the term Climate-adapted plus EAB is used throughout for that scenario. Harvest volume estimates for the 71 forest types, management scenario, and treatment type alternatives are provided in the Appendix, Tables 9.1-9.8.

Table 5.1. Forest types and harvest allocation for Minnesota based on TPO data (2018).

Forest Type	Allocation
Aspen/Birch	54.0%
Black Ash	3.3%
Lowland Conifers	2.4%
Northern Hardwoods	6.1%
Oak	4.7%
Red Pine	12.0%
Upland Spruce	13.1%
Other	4.4%
	100%

Table 5.2. Forest types, species, and allocation by species. Contributions were determined using TPO 2018 for Minnesota.

Forest Types	Species group	Percent species contribution within each forest type	Percent species contribution over all forest types
Aspen/Birch	Aspen	91.5%	49.4%
	Other birch	8.5%	4.6%
	Total	100.0%	
Black Ash	Ash	100.0%	3.3%
	Total	100.0%	
Lowland Conifers	Cedars	16.4%	0.4%
	Larch	83.6%	2.0%
	Total	100.0%	
Northern Hardwoods	Soft maple	44.2%	2.7%

Forest Types	Species group	Percent species contribution within each forest type	Percent species contribution over all forest types
	Basswood	35.8%	2.2%
	Hard maple	18.4%	1.1%
	Other hardwoods	0.3%	0.0%
	Yellow birch	1.3%	0.1%
	Total	100.0%	
Other	Black walnut	2.7%	0.1%
	Cottonwood	20.8%	0.9%
	Elm	1.6%	0.1%
	Hemlock	1.0%	0.0%
	Jack pine	53.7%	2.4%
	Other pines	0.8%	0.0%
	Sycamore	0.0%	0.0%
	White pine	18.3%	0.8%
	Black cherry	1.0%	0.0%
	Total	100.0%	
Oak	Hickory	1.1%	0.1%
	Select red oaks	67.5%	3.2%
	Select white oaks	31.3%	1.5%
	Total	100.0%	
Red Pine	Red pine	100.0%	12.0%
	Total	100.0%	
Upland Spruce/Fir	Spruce	72.1%	9.4%
	True firs	27.9%	3.6%
	Total	100.0%	
Total Over all Forest Types			100%

5.3.4 Forest Resources

Each component of the cradle-to-gate analysis includes detailed data supported by secondary data sources (Benjamin 2014, Benjamin et al. 2013, Gc et al. 2020, Gingras and Favreau 1996, Goychuk et al. 2011, Hiesl 2013, Hiesl and Benjamin 2013a,b, 2014, 2015, Luppold and Bumgardner 2018, Mason et al. 2008, Koirala et al. 2017, Oswalt et al. 2019, Ottmar and Vihnanek 1999, Quinn et al. 2020, Richardson and Makkonen 1994). The forest resources (A1) and hauling (A2) (Figure 5.7) components were derived from a combination of survey data on the Minnesota forest sector (Blinn et al. 2014, Blinn and Nolle 2023), simulation modeling generated for this project (Section 4), forest operations data adapted to Minnesota conditions from the NE/NC forest resources LCA report (Oneil 2021 and references therein), and fire emissions data from the Fuels and Fire Tools (FERA 2023) software. Cross validation of sources to published analyses of Minnesota forestry operations (Windmuller-Campione et al. 2020) suggests data used are representative of the sector. Therefore, no primary data using time motion studies or similar methods were collected for this project.

For each forest type by management scenario combination, detailed data on silvicultural inputs (planting, pre-commercial thinning, prescribed fire) and harvest alternatives (thinning, shelterwood, seed tree, clearcut) were developed to create the LCI for a ‘representative metric ton’ based on input data from the simulated scenarios. Data from Blinn and Nolle (2023) were mined to generate estimates for personnel transport distance, roundwood haul distance, opening size, and equipment utilization. These data were incorporated into the LCI models along with the harvest volumes from the simulation data to create a larger picture of the impacts of silviculture, harvesting, and hauling operations. Blinn and Nolle (2023) data combined with harvest statistics from the Minnesota Department of Natural Resources (MDNR), were used to generate Figure 5.6 which indicates that yearly harvest volume is distributed across unit sizes nearly proportional to their occurrence on the landscape. There were no data that permitted a refinement of this allocation among harvest unit sizes to specific forest types or utilization systems, therefore a weighted average unit size of 30 acres was chosen for all scenarios and a weighted average haul distance of 68.9 miles (110.9 km) was used for all scenarios and product types. Haul types were allocated between 6 axle trailers (67.8%) and self-loading truck/trailer (32.2%) based on the equipment profiles reported in Blinn and Nolle (2023). Estimated volume per truck load was generated based on calculations of forest type average specific gravity and moisture content up to the maximum haul weight (Table 9.16). Harvesting equipment was allocated to specific treatment/entry types based on a combination of recovered volume, green tree retention requirements noted in the prescription, and common system configurations.

Simulated harvest volume was assumed to be removed from the forest and sent into the product stream if there were more than 10.5 cords of logs/acre. This value translates to approximately 1 load/acre. Where simulated entries resulted in less volume per acre than this threshold, the management intervention is treated the same as any other non-commercial entry which carries a carbon footprint but yields no merchantable harvest volume. For stands with particularly high value timber or on larger harvest units, this assumption may be too conservative. However, it represents a much more aggressive recovery than occurs in other US regions where a 2-load minimum per acre is the norm. Table 5.3 provides the distribution of yield by entry type for all simulation data.

Table 5.3. Range of Yield by Harvest System.

Cubic meters per hectare per entry - variation by Harvest System			
Harvest System	**Minimum**	**Average**	**Maximum**
Cut to Length	54	118	281
Feller Buncher/ Skidder	174	282	443
Non-Commercial Treatment (NCT)	9	32	56

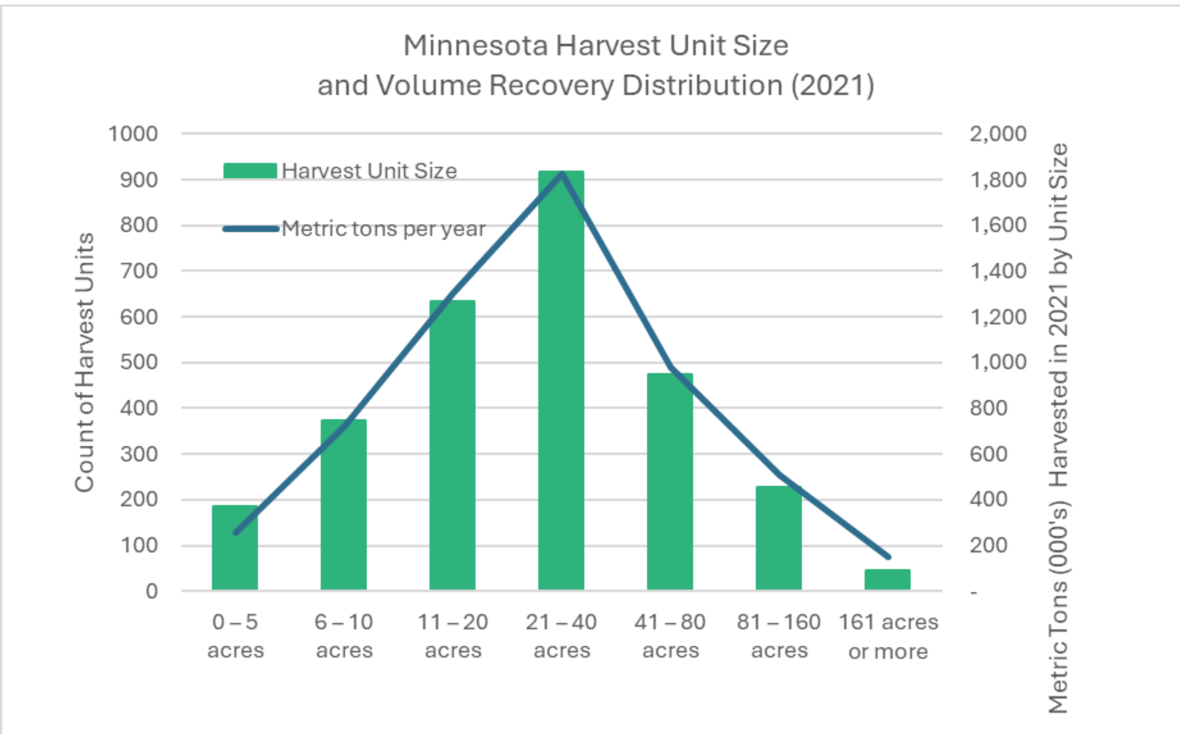


Figure 5.7. Distribution of Minnesota forest harvest operations by unit size and total volume recovery (derived from Blinn and Nolle 2023 and MNDNR harvest statistics)

5.3.5 Harvested Wood Products

For the harvested wood products manufacturing, CORRIM has collected regional wood products production data for over 20 years. These data served as the base data for the LCA on oriented strandboard (OSB), hardwood lumber, and softwood lumber (Puettmann et al. 2020, Hubbard et al. 2020, Puettmann 2020). Thus, the collection of primary production data (LCI input data) from wood product manufacturers in Minnesota was not needed. Each product used CORRIM LCI data and reporting with modifications to electricity grids and roundwood inputs (Forest Resources). The pulpwood model for the production of pulp for paper and pulp for textiles was developed using a variety of published sources and available LCI databases as part the Datasmart (LTS 2023) and Ecoinvent (v3.9) datasets within the SimaPro software.

Using TPO data for Minnesota, the allocation of forest type and product output was determined using a combination of Table 5.1 and Table 5.2. For Minnesota, several roundwood product types were listed in the TPO data (Table 5.4 and Figure 5.8, Table 9.17). Due to lack of LCI production data and information on certain products (e.g., Misc category) as well as their low contribution to Minnesota's overall wood production, the decision was made to focus on three product groups in this LCA (composite panel, pulpwood, and sawlogs) which represent 89.9% of total Minnesota forest product manufacturing (TPO 2018). Allocation for each forest type by product category specific to this LCA is shown in Table 5.4. In order to perform this LCA, additional assumptions were made on specific products included in each of the product groups based on feedback from MFRC.

Table 5.4. Allocation of pulpwood, oriented strandboard (OSB), hardwood lumber, and softwood lumber by forest type and species group (TPO 2018).

Forest Type	**OSB**	**Paper**	**Textiles**	**HW Lumber**	**SW Lumber**
Aspen/Birch	90.24%	63.83%	63.65%	30.12%	0.00%
Black ash	0.00%	2.85%	2.85%	7.98%	0.00%
Lowland conifers	2.79%	1.78%	1.78%	0.00%	2.71%
Northern hardwoods	1.19%	7.03%	7.01%	11.80%	0.00%
Other (softwood & hardwoods)	0.19%	1.60%	1.87%	10.37%	14.32%
Oak	0.00%	0.03%	0.03%	39.73%	0.00%
Red pine	5.59%	1.56%	1.56%	0.00%	68.82%
Upland spruce/fir	0.00%	21.32%	21.26%	0.00%	14.15%
	100.00%	100.00%	100.00%	100.00%	100.00%

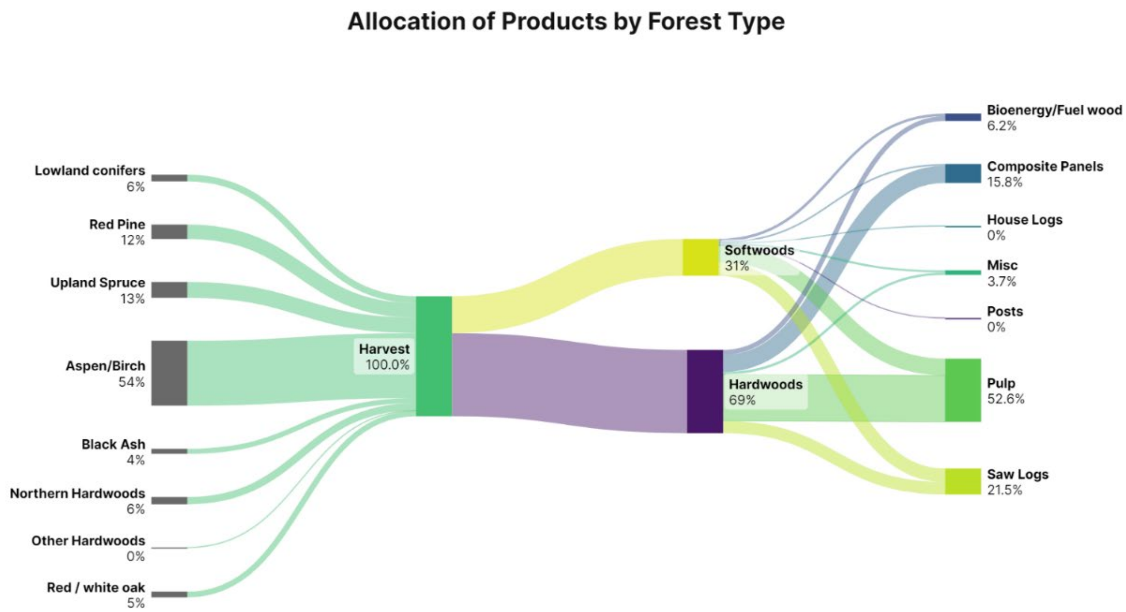


Figure 5.8. Allocation of wood products by forest type based on TPO data.

The hardwood and softwood allocations for each product are listed in Table 5.5. All harvested wood products data were used in accordance with ISO 14044/Amd1:2017/Amd2:2020 standards. Upstream secondary data on fuels and electrical grid inputs from the US database (Datasmart 2023) and European datasets (Ecoinvent 3.8) (LTS 2023, Wernet et al. 2016) were incorporated into the LCA.

Table 5.5. Allocation of pulpwood, oriented strandboard (OSB), hardwood lumber, and softwood lumber by species group (TPO 2018).

Species group	Pulpwood	Composite Panel	Sawlogs
Hardwoods	74%	91.42%	47.26%
Softwoods	26%	8.58%	52.74%

5.3.5.1 A1-A3 – Cradle-to-Gate – All Products

Two analyses under two system boundaries were considered. The first is a cradle-to-gate (A1-A3) (Figure 5.2). The A1-Forest Resources LCIA data was provided by management scenario which included the weighted average contribution to each forest type. For OSB and lumber, the forest resources data required a conversion of the LCIA data from per unit green metric ton to cubic meter volume, oven dry. Wood products production data (A3) includes all activities required to produce the unit of product. In addition, transportation (A2) of all chemicals, resins, and ancillary materials is also included in A3. ***Note: roundwood transport (A2) is included in the A1-Forest Resources module.*** The functional unit for OSB and lumber is one cubic meter (m^3) of final product ready for shipping. For paper and textile products, the functional unit is one kilogram (kg) of final product. For comparison across all product types, conversions were made to present all data on a per mass basis (kg).

Whereas solid wood products LCA were built from extant CORRIM data, new LCI models were built to assess the impacts of pulp production. Two products were considered in this LCA: 1) uncoated paper and 2) textiles produced from dissolved pulp/viscose fiber. The LCA modeling was conducted in two phases. In the first phase, the forest resource (A1) model was integrated with pulp production LCI using data from Echeverria et al. (2022). In the second phase, the model was extended to take production processes to either uncoated paper or textiles. Data for this phase used existing LCI datasets within the SimaPro software (Datasmart (2023), Ecoinvent (v3.9)) and modified them to reflect production in Minnesota (Buitrago et al. 2022, Echeverria et al. 2022, Shen et al. 2010, Shen et al. 2012).

5.3.5.2 Assumption behind the cradle-to-gate LCA Model

Key assumptions used in developing the cradle-to-grave (A1-A3) models are:

- Assumption: Composite panels (from TPO) represent 100 percent oriented strandboard production

- Reasoning: Minnesota has one facility producing OSB and one facility producing OSB-based siding.
- Assumption: Sawlogs (from TPO) represent 47 percent hardwood roundwood and 53 percent softwood.
  - Reasoning: Based on species allocation for sawlog from TPO data (2018)
- Assumption:
  - Pulpwood represents roundwood that would go to pulp production.
  - Pulp production would further be allocated to paper production and viscose/textiles production.
  - Pulpwood for dissolving pulp represented 73% of the total pulpwood. This volume is ultimately used for producing viscose fibers for the textile industry.
    - Reasoning: Pulp production allocation is based on personal communications with the MFRC panel members. Allocation of hardwood and softwoods to paper or textiles was not provided, therefore the TPO allocation of hardwoods and softwoods was used (74% hardwoods, 26% softwoods).
  - Pulpwood for paper production included 1.5% recycled pulp in the feedstock input. Source: databases and publication listed above.
    - Reasoning: We kept the recycled content (1.5%) as is in the results due to lack of information on Minnesota paper production. We performed an analysis that included a 100% recycled pulp input and found it decreased the cradle-to-gate (A1-A3) embodied carbon by 7.1%. The feedstock input (A1-A2) decreased by 36.8% and production (A3) by 3.6%.

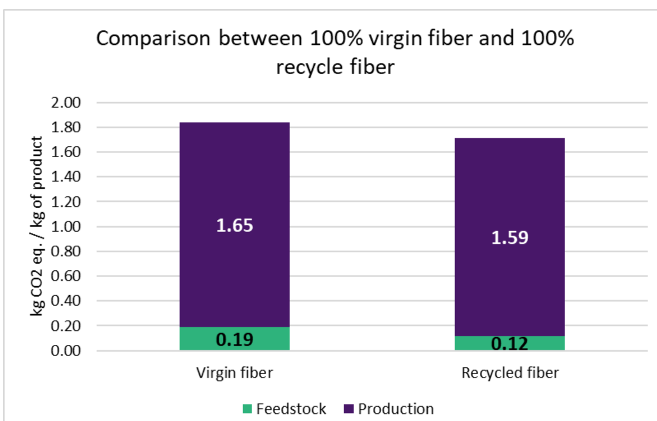


Figure 5.9. Comparison between 100% virgin fiber and 100% recycle fiber.

5.3.5.3 A1-C4 – Cradle-to-Grave – OSB and Lumber

The second system boundary included end-of-life (EoL) scenarios which included A1-A3 and C2/C4 (Figure 5.2). End-of-life analyses were performed on OSB, lumber, paper, and textiles. The underlying data and methods used are described in the following sections.

For OSB and lumber, the EoL analysis is a two-part analysis. The first part utilizes the A1-A3 LCIA results as inputs over average EoL scenarios. For this LCA the EoL includes modules C1-C4 in Figure 5.2. For the purposes of this LCA, C1 and C3 are null. After the product is removed from service there are several possible outcomes for its fate. The product can be disposed via landfill, incinerated, or reused/recycled (which may or may not require reprocessing). For EoL processing the weighted average of the typical waste treatment in the United States for durable wood products which is 82 percent landfill and 18 percent incineration (EPA 2019). The results presented include a 100 percent landfill scenario and a 100 percent incineration scenario and an average of the two EoL treatments based on disposal rates from the EPA (EPA 2019) (i.e. 82 % landfill and 18% incineration). For C2-Transportation, we used waste transport distances to a landfill, or a recovery facility reported in CORRIM reports. The C4-Disposal is assumed to be to a municipal landfill in the landfilling scenario, and to a recovery facility in the incineration scenario. C4 includes all fossil emissions generated at each of these facilities during disposal.

Assumptions for C2 & C4 for OSB and Lumber

- C2 Transportation: 80 km, hauling the oven dry mass of the primary product.
- C4 Disposal: municipal landfill

The second EoL analysis used a dynamic model based on radiative forcing emission profiles. The model used to produce the EoL analysis represented by net impact bar charts were developed by the University of Washington's CINTRAFOR lab to account for end-of-life emissions of wood products. In this model, dynamic life cycle assessment (LCA) methodology is used instead of traditional static LCA. The benefits of using dynamic LCA over static LCA is that it allows the model to account for the timing of emissions, which is a crucial component for end-of-life modeling, given that emissions occur at different points in the product's life cycle. In this analysis, production of the wood product is assumed to occur at year 0, and EoL processing is assumed to begin at year 100. Subsequently, two pulses of emissions are released: one at year 0, and one at year 100. Moreover, the landfill EoL scenario involves the continuous release of methane for the first 12 years after the product was landfilled (i.e., year 112). Methane emissions do not occur past year 12 after landfilling because the landfill is assumed to be topped with a clay topper at that point. This assumption is consistent with landfill conditions for wood products as described by Chen (2019) and the EPA's Waste Reduction Model (2020a).

The time horizon of the EoL dynamic analysis is 200 years. The product is assumed to be in use for the first 100 years, and the impacts of EoL processing are modeled for 100 years after to account for the environmental impacts of emitting long-lived greenhouse gases such as CO_2. Additionally, the benefit of storing biogenic carbon in the product during first life use and landfilling is accounted for using the Lashof carbon accounting approach over the 200-year time period (Fearnside et al. 2000). The Lashof accounting method assigns credit to temporary carbon storage that occurs as a result of delaying CO_2 emissions. The credit is derived from decay curves of greenhouse gases in the atmosphere.

5.3.5.3.1 End of Life Decay Curves

If 1 kg of CO_2 is emitted in year 0, it will follow the decay pattern of the purple line in Figure 5.10. LCA traditionally only accounts for 100 years of emissions, so the impact of emitting 1 kg of CO_2 is cut off at year 100. However, if the emission is delayed for 50 years, it will follow the decay pattern of the green line in Figure 5.10. This extends the time period from 100 years to 150 years. The portion of the curve beyond the initial 100 years (indicated with hash marks) is the carbon storage benefit: credit can be assigned by subtracting this area from the total global warming potential (GWP) impact.

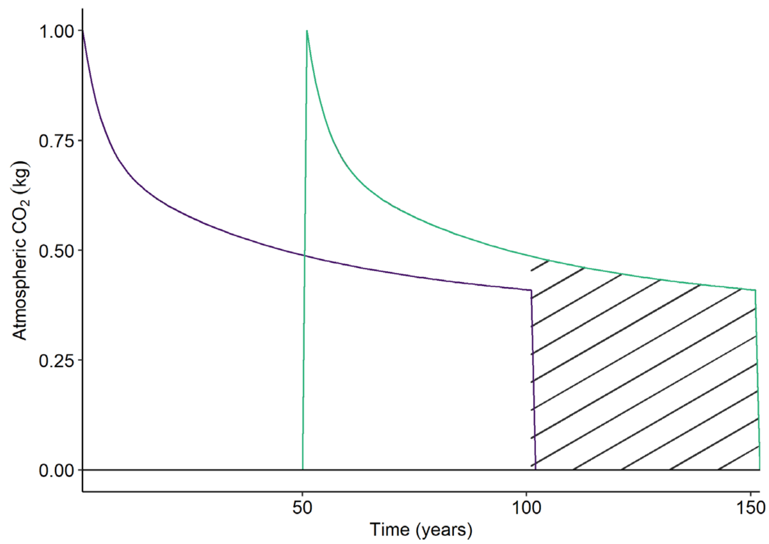


Figure 5.10. Atmospheric decay of a 1 kg CO_2 emission at year 0 (purple line) and at year 50 (green line).

In the case of this analysis, biogenic carbon emissions are delayed for 100 years while the product is in use. The Lashof decay curve corresponding to this assumption is shown in **Error! Reference source not found.** 5.11. Here, the entire portion under the green line (indicated with hash marks) is being credited to the carbon storage benefit, since the biogenic carbon was stored for 100 years.

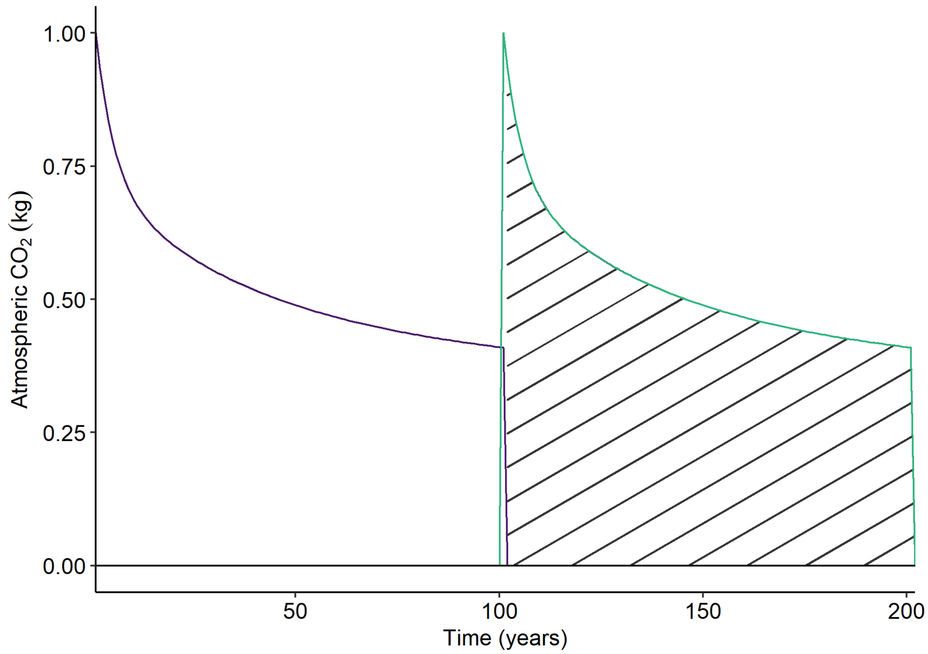


Figure 5.11. Atmospheric decay of a 1 kg CO_2 emission at year 0 (purple line) and at year 100 (green line).

Given that the carbon storage benefit is accounted for by subtracting the hashed areas in the decay curves from the total global warming impacts, this benefit can be shown as a negative impact. Thus, the decay curve can be portrayed as negative (Figure 5.12). All of the radiative forcing emission profiles for this analysis show the carbon storage benefit for wood products in a similar manner to Figure 5.12.

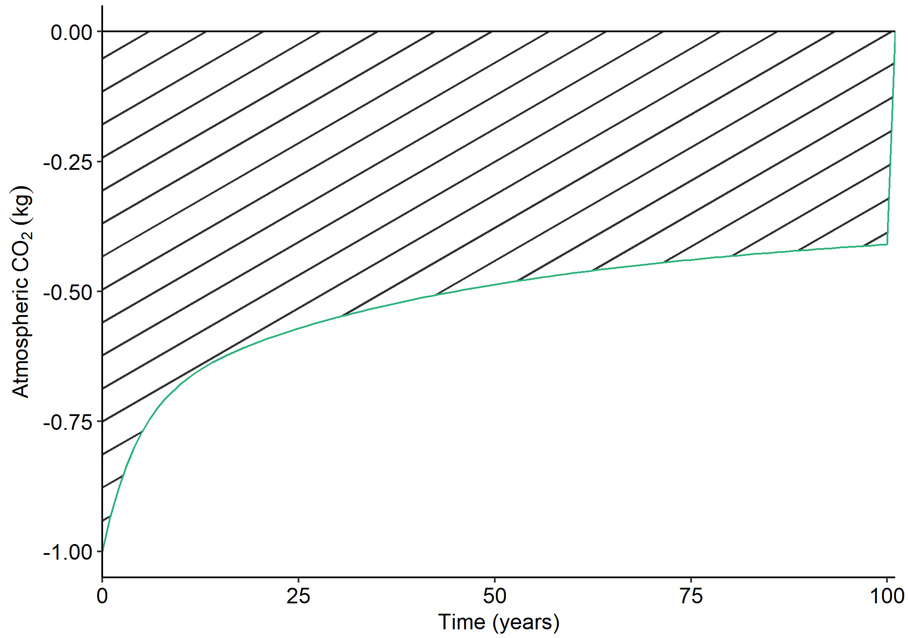


Figure 5.12. Biogenic carbon storage benefit derived from delaying an emission of 1 kg CO_2 for 100 years.

5.3.5.4 A1-C4 – Cradle-to-Grave – Paper and Textiles

The cradle-to-grave analysis of paper and textile products included A1-A3, C2/C4 modules (Figure 5.1). There are three EoL stages considered for paper and textile products (Table 5.6). As described for OSB and lumber, the EoL model was based on the Waste Reduction Model (WARM; EPA 2020b) using national averages for the landfilling, methane capture, and decay of paper and textiles. Due to lack of information specific to textile landfilling, we have used information on municipal solid waste to model the EoL of textile products. For EoL processing a weighted average of typical waste treatments in the United States for paper and textiles was applied (EPA 2019). At the end of the product's first life, three scenarios were used: disposed via landfill, incinerated, or reused/recycled. Included in the EoL model is the collection of materials, transportation of waste material (assumed 80 km hauling), and disposal of waste.

Table 5.6. End-of-life (EoL) options for paper and textile products (EPA 2019).

EOL options	Paper + paperboard	Textile (Durable)
Landfill	42.3%	58.7%
Recycle/reuse	47.4%	15.0%
Combusted with Energy Recovery	10.3%	26.4%

5.3.6 Allocation Rules

Allocation is the method used to partition the environmental load of a process when several products or functions come from that process. The input material for producing the wood products is a round log with bark. Processing the log involves multiple steps, all of which generate by-products. For all wood products in this study, a mass allocation was used for the primary product and subsequent by-products. Some by-products are used internally for on-site energy generation. For specifics on the inputs and outputs used and the allocation of products and by-products for OSB, hardwood lumber, and softwood lumber see the full reports on www.corrim.org.

5.3.7 Impact Categories / Impact Assessment

The life cycle impact assessment (LCIA) phase establishes links between the LCI results and potential environmental impacts. The LCIA calculates impact indicators, such as global warming potential and smog. ***These impact indicators provide general, but quantifiable, indications of potential environmental impacts.*** The target impact indicator, the impact category, and means of characterizing the impacts are summarized in Table 5.7.

Environmental impacts are determined using several methods obtained with the SimaPro software package, including the North American TRACI method (US Environmental Protection Agency's (EPA) TRACI 2.1 v1.08 (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) (Bare 2012)). Additional impact indicators were generated using the European CML Baseline, and Cumulative Energy Demand (CED, LHV, v.1.0) as well as several indicators calculated from the LCI results. This LCIA does not make value judgments about the impact indicators, meaning a comparison of indicator values is not valid. Additionally, each impact indicator value is stated in units that are not comparable to others. For the same reasons, indicators should not be combined or added. Additionally, the LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks.

Cumulative Energy Demand is based on fuels' lower heating values (LHV). Cumulative Energy Demand is calculated from data published by Ecoinvent and expanded by Pré (2020) for energy resources available in the SimaPro database. Characterization factors are given for six impact categories: 1. Non-renewable, fossil, 2. Non-renewable, nuclear, 3. Non-renewable, biomass, 4. Renewable, biomass, 5. Renewable, wind, solar, geothermal, and 6. Renewable, water. The primary fuels are categorized into non-renewable (fossil and nuclear) and renewable (biomass, geothermal, solar, wind, and hydro). Table 5.7 summarizes the source and scope of each impact category reported in this report. These impact categories are consistent with the requirements of, and in conformance with the wood product PCR (UL 2018, 2020) and ISO 21930 (ISO 2017).

Table 5.7. Selected impact category indicators and inventory parameters.

Impact Indicators per ISO 21930	Abbreviation	Units	Method
Core Mandatory Impact Indicator			
Global warming potential, Total	GWP_{TOTAL}	kg CO_2-eq	$GWP_{BIOGENIC}$ + GWP_{FOSSIL}
Global warming potential, Biogenic [a/]	$GWP_{BIOGENIC}$	kg CO_2-eq	TRACI 2.1 V1.08+ LCI Indicatory
Global warming potential, Fossil	GWP_{FOSSIL}	kg CO_2-eq	TRACI 2.1 V1.08
Depletion potential of the stratospheric ozone layer	ODP	kg CFC11e	TRACI 2.1 V1.08
Acidification potential of soil and water sources	AP	kg SO_2e	TRACI 2.1 V1.08
Eutrophication potential	EP	kg PO_4e	TRACI 2.1 V1.08
Formation potential of tropospheric ozone	SFP	kg O_3e	TRACI 2.1 V1.08
Abiotic depletion potential (ADP fossil) for fossil resources;	ADPf	MJ, NCV	CML-IA Baseline V3.08
Fossil fuel depletion	FFD	MJ Surplus	TRACI 2.1 V1.08
Use of Primary Resources			
Renewable primary energy carrier used as energy	RPRE	MJ, NCV [b/]	CED (LHV) V1.00
Renewable primary energy carrier used as material	RPRM	MJ, NCV	LCI Indicator
Non-renewable primary energy carrier used as energy	NRPRE	MJ, NCV	CED (LHV) V1.00
Renewable primary energy carrier used as material	NRPRM	MJ, NCV	LCI Indicator
Secondary material, secondary fuel and recovered energy			
Secondary material	SM	kg	LCI Indicator
Renewable secondary fuel	RSF	MJ, NCV	LCI Indicator
Non-renewable secondary fuel	NRSF	MJ, NCV	LCI Indicator
Recovered energy	RE	MJ, NCV	LCI Indicator
Mandatory Inventory Parameters			
Consumption of freshwater resources;	FW	m^3	LCI Indicator
Indicators Describing Waste			
Hazardous waste disposed	HWD	kg	LCI Indicator
Non-hazardous waste disposed	NHWD	kg	LCI Indicator
High-level radioactive waste, conditioned, to final repository	HLRW	m^3	LCI Indicator
Intermediate- and low-level radioactive waste, conditioned, to final repository	ILLRW	m^3	LCI Indicator
Components for re-use	CRU	kg	LCI Indicator
Materials for recycling	MR	kg	LCI Indicator
Materials for energy recovery	MER	kg	LCI Indicator
Recovered energy exported from the product system	EE	MJ, NCV	LCI Indicator

[a/] This indicator includes both biogenic and fossil-based carbon released. The TRACI method was modified to include CO_2, biogenic removals, and emissions.
[b/] NCV-Net Caloric Value

5.4 RESULTS – A1-A3 LIFE CYCLE IMPACT ASSESSMENT

This section reports on the cradle-to-gate results for forest resources, and the downstream uses of harvested wood including pulpwood, OSB, and hardwood and softwood lumber. Selected TRACI and CED impact indicators are reported to characterize the flows to - and from - the environment. When reporting carbon emissions in this section, global warming potential (GWP), embodied carbon, and CO_2-eq are used interchangeably. Results are presented in units of metric tonne (MT) and kilogram (kg) one metric tonne = 1,000 kg or 2,204.6 lbs).

5.4.1 A1-A2 – Statewide Forest Resources

This section reports on the cradle-to-gate LCIA results for growing, harvesting, and hauling logs to milling facilities (Figure 5.13). LCIA results shown in Table 5.8 and Table 5.9 are weighted consistent with statewide TPO data on harvesting by forest type as shown in Figure 5.8 and Table 5.1 to generate a statewide estimate. These LCIA values are reported per metric ton on a green weight. The LCIA results for individual forest types in each scenario are shown in Table 9.13 and Table 9.14 in the Appendix. Since inputs to individual products have different species and forest type mixes and are reported on an oven-dry basis, the values cannot be directly input into downstream processes without adjustment. The embodied carbon (GWP kg CO_2-eq) for A1-A2 by scenario and forest type is shown in Figure 5.13a and 5.13b, including scenarios with repeated fire treatments that exclude biogenic emissions from the fires, but do include emissions associated with fire management, and non-CO_2-eq emissions from the fires themselves. Allocated values for the BAU, Climate-adapted, and Economic intensive scenarios show some variability around an average value of 30.9 kg CO_2-eq /metric ton of logs produced.

The outlier in this scenario analysis is the Climate-adapted plus fire scenario, which shows substantially higher emissions. These higher emissions result from increased emissions related to additional treatments over the 100-year period coupled with significant reductions of recoverable volume due to the repeated under-burns in the red pine and oak forest types in these scenario analyses. The prescriptions for red pine climate plus fire scenario called for underburns 2 years and 5 years post thinning. There were 6 thinnings prior to final harvest in this scenario, resulting in 12 burns over the simulation period. The prescription for the oak climate plus fire scenario called for 3 fire entries over the simulation period. In both cases emissions from these silviculture burns are allocated over total harvested volume across all stand entries as representative of the forest type for the fire scenario.

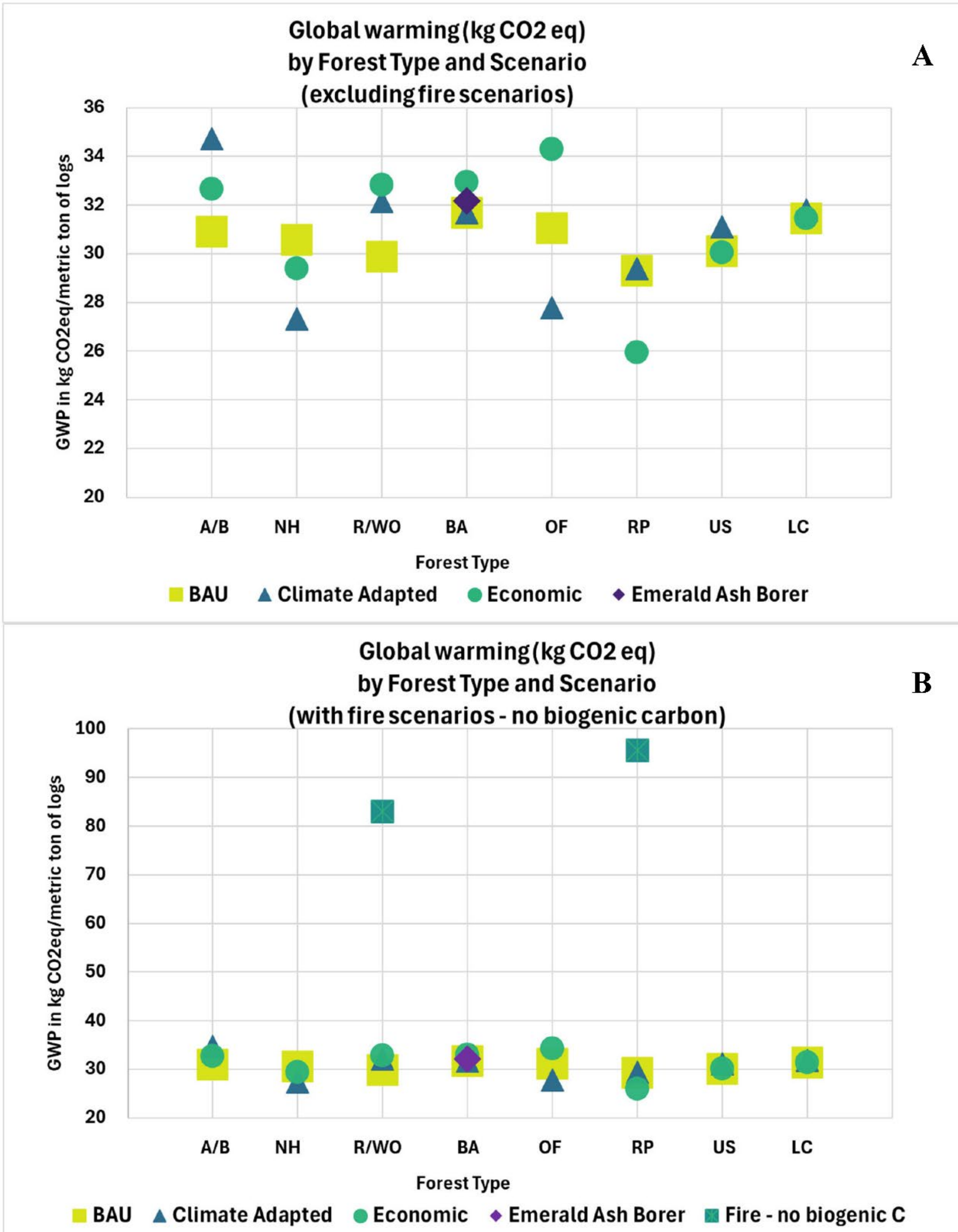


Figure 5.13. (A) Embodied carbon (kg CO_2-eq) per metric ton of green logs delivered to the mill. Reported by scenario and forest type. A/B = Aspen/Birch; NH = Northern Hardwoods, R/WO = Oak; BA = Black Ash; OF = Other Forest types; RP = Red Pine; US= Upland Spruce, LC = Lowland Conifer. (B) includes Climate-adapted plus fire scenario, without biogenic carbon. Not shown – Climate-adapted plus fire scenario, including biogenic carbon.

Emission profiles for fire adapted scenarios for red pine and oak forest types were generated using the Fuel and Fire Tools (FFT) (FERA 2023). The Fuel and Fire Tools App integrates multiple USFS fire management tools including the Fuel Characteristics Classification System (FCCS - version 4.0), Consume (version 5.0), Fire Emission Production Simulator (FEPS - version 2.0), Pile Calculator, and the Digital Photo Series. It reflects conditions for multiple fuel bed and forest types in each US region. For this project we used the default values for consumed biomass/acre in the FFT app of 10.94 tons/acre for red pine and 15.6 tons per acre for oak. These values were similar to the unweighted average fuel loads by forest type and fuel type estimated from the digital photo series data as replicated in Table 9.12 (Appendix) for red pine and oak fuel types. The emission profiles per acre from the Fuel and Fire Tools App (Table 9.15) were generated using standard fuel bed estimates, spring burn conditions (moist fuels), and assumptions of consumption of 75% of shrub layer, 1% of canopy, and 50% of any piles/residues remaining post-harvest. Emission profiles were input into the LCA software as emissions per acre which are then allocated across total volume removed per acre.

Because the fire scenarios generated relatively little volume and had multiple burns over the 100-year scenario, the emissions per metric ton of green logs are very high, even when excluding biogenic carbon emissions (Figure 5.13b). Emissions are an order of magnitude higher (1,049 vs 83 kg CO_2-eq per metric ton for oak, and 1,670 vs 96 kg CO_2-eq per metric ton for red pine) when biogenic carbon is included (Figure 9.13 of the appendix). Full details of the LCIA impacts of fire scenarios are shown in Table 9.13 of the appendix under Climate-adapted with fire and Climate-adapted with EAB scenarios.

In addition to greenhouse gas emissions from burning itself, the LCA includes transport of fire personnel and fire truck tenders for prescribed fire operations. These operational parameters were based on reported personnel and equipment for the 66 acre Otter Creek treatment unit (data provided by UMN team members) as representative of underburning operations in these forest types. While these impacts per ton of harvested material are representative of treatment scenarios, scaling them to the landscape level is problematic as the operations would be constrained by limitations on suitable fire weather conditions during the spring burn period.

The unallocated forest type x scenario LCIA values were then allocated for each scenario based on the relative harvest volume by forest type from TPO (2018) harvest data. The values in Table 5.8 and 5.9 show the range of impacts for reportable TRACI impacts (Table 5.8) and cumulative energy demand (Table 5.9) for each scenario.

Table 5.8. Comparing Forest Resource (A1-A2) LCIA results across scenarios.

Statewide A1-A2 Weighted by Forest Type for each Scenario					
Impact category	**Unit / green metric ton**	**BAU**	**Climate-adapted**	**Climate-adapted plus fire**	**Economic intensive**
Ozone depletion	kg CFC-11 eq	1.51E-07	1.61E-07	1.64E-07	1.56E-07
Global warming	kg CO_2-eq $_{FOSSIL}$	30.56	32.48	42.84[1/]	31.34
Smog	kg O3 eq	10.10	10.49	24.69	10.45
Acidification	kg SO2 eq	0.32	0.34	1.13	0.34
Eutrophication	kg N eq	2.20E-02	2.37E-02	7.16E-02	2.27E-02

[1]/ Includes biogenic carbon emissions due to burning

Table 5.9. Cumulative Energy Demand for Forest Resource (A1-A2) across scenarios.

Statewide A1-A2 weighted by Forest Type for each Scenario					
Impact category	**Unit / green metric ton**	**BAU**	**Climate-adapted**	**Climate-adapted plus fire**	**Economic intensive**
Nonrenewable	MJ	421.78	453.22	455.75	432.29
Renewable	MJ	0.37	0.75	0.76	0.37

5.4.2 Paper and Textile

The cradle-to-gate (A1-A3) LCIA results for paper and textile are presented in (Tables 5.10 and 5.11). The contribution of manufacturing, A3 life cycle stage, for both paper and textile are so dominant over most impact categories, that the difference between the forest resources life cycle stage and manufacturing is negligible except for smog[3] (Figures 5.13 and 5.14). Among the various forest management scenarios, the contribution of forest resources (A1) varied from <1-34 percent of the total (A1-A3) embodied impacts of paper and textiles depending on the impact category. The highest impact of forestry was the climate-adapted plus fire management scenario due to burning of red pine. However, this still only represented about 1.6 percent of the pulpwood input, Tables 5.10 and 5.11, Figure 5.14 and Figure 5.15)

The cradle-to-gate environmental impacts of textiles were more than 3-10 times higher than that of the paper except for ozone depletion. For example, the BAU embodied carbon to produce textile product was around 3.3 times the embodied carbon of uncoated paper. This was due to more pulpwood input per unit of dissolving pulp, as well as production inputs such as higher energy consumption (A3-23 MJ/kg for paper and 91 MJ/kg for textiles) and chemical use differences between the two products (Figure 5.16).

[3] The red pine and northern hardwood forest types contributed to the smog impact indicator as result of forest silvicultural activities cut-to-length and frequency of activity. Transportation of the roundwood to facilities was also a significant contributor to the smog impact category. In a "normal" modules (A1. A2, and A3) LCA, the transportation would be a standalone module or part of the A3 module.

Table 5.10. Cradle-to-gate (A1-A3) LCIA results for one kilogram of paper under each management scenario, absolute basis.

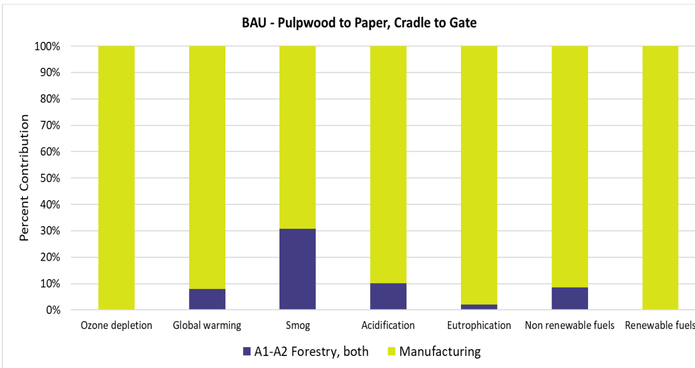
	BAU Management Scenario			
Impact category	**Unit per kg**	**A1-A2 Forestry**	**A3 Paper Manufacturing**	**Paper Total A1-A3**
Ozone depletion	kg CFC-11 eq	6.86E-10	2.96E-06	2.97E-06
Global warming	kg CO_2-eq $_{FOSSIL}$	1.39E-01	1.63E+00	1.77E+00
Smog	kg O3 eq	4.60E-02	1.04E-01	1.50E-01
Acidification	kg SO2 eq	1.48E-03	1.32E-02	1.46E-02
Eutrophication	kg N eq	1.00E-04	4.81E-03	4.91E-03
Nonrenewable fuels	MJ	1.91E+00	2.04E+01	2.23E+01
Renewable fuels	MJ	2.19E-03	2.51E+00	2.51E+00
	Climate-adapted Management Scenario			
Ozone depletion	kg CFC-11 eq	7.49E-10	2.96E-06	2.97E-06
Global warming	kg CO_2-eq $_{FOSSIL}$	1.50E-01	1.63E+00	1.78E+00
Smog	kg O3 eq	4.86E-02	1.04E-01	1.52E-01
Acidification	kg SO2 eq	1.59E-03	1.32E-02	1.48E-02
Eutrophication	kg N eq	1.10E-04	4.81E-03	4.92E-03
Nonrenewable fuels	MJ	2.10E+00	2.04E+01	2.25E+01
Renewable fuels	MJ	4.20E-03	2.51E+00	2.52E+00
	Climate-adapted plus fire Management Scenario			
Ozone depletion	kg CFC-11 eq	7.50E-10	2.96E-06	2.97E-06
Global warming (includes biogenic carbon)	kg CO_2-eq $_{TOTAL}$	2.42E-01	1.63E+00	1.87E+00
Smog	kg O3 eq	5.37E-02	1.04E-01	1.57E-01
Acidification	kg SO2 eq	1.85E-03	1.32E-02	1.50E-02
Eutrophication	kg N eq	1.26E-04	4.81E-03	4.93E-03
Nonrenewable fuels	MJ	1.85E+00	2.04E+01	2.23E+01
Renewable fuels	MJ	2.28E-03	2.51E+00	2.51E+00
	Climate-adapted plus Emeral Ash Borer Management Scenario			
Ozone depletion	kg CFC-11 eq	7.49E-10	2.96E-06	2.97E-06
Global warming (includes biogenic carbon)	kg CO_2-eq $_{FOSSIL}$	1.50E-01	1.63E+00	1.78E+00
Smog	kg O3 eq	4.86E-02	1.04E-01	1.52E-01
Acidification	kg SO2 eq	1.59E-03	1.32E-02	1.48E-02

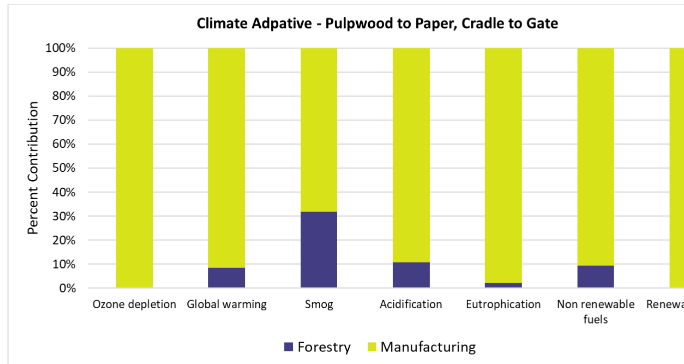
Eutrophication	kg N eq	1.10E-04	4.81E-03	4.92E-03
Nonrenewable fuels	MJ	1.83E+00	2.04E+01	2.22E+01
Renewable fuels	MJ	2.25E-03	2.51E+00	2.51E+00
	Economic Intensive Management Scenario			
Ozone depletion	kg CFC-11 eq	7.18E-10	2.96E-06	2.97E-06
Global warming	kg CO_2-eq FOSSIL	1.43E-01	1.63E+00	1.77E+00
Smog	kg O3 eq	4.80E-02	1.04E-01	1.52E-01
Acidification	kg SO2 eq	1.54E-03	1.32E-02	1.47E-02
Eutrophication	kg N eq	1.04E-04	4.81E-03	4.91E-03
Nonrenewable fuels	MJ	1.99E+00	2.04E+01	2.24E+01
Renewable	MJ	2.21E-03	2.51E+00	2.51E+00

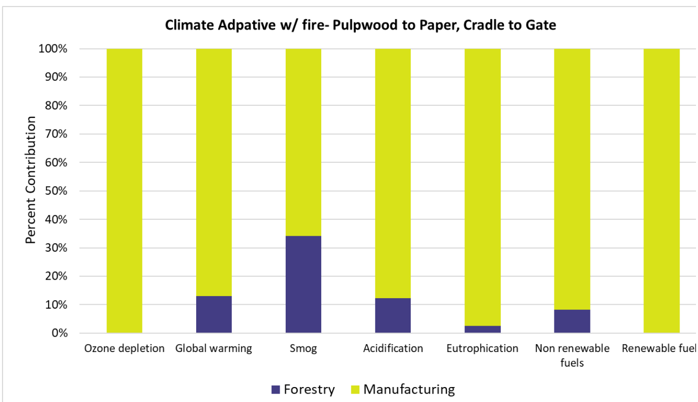
Table 5.11. Cradle-to-gate (A1-A3) LCIA results for one kilogram of textile under each management, absolute basis.

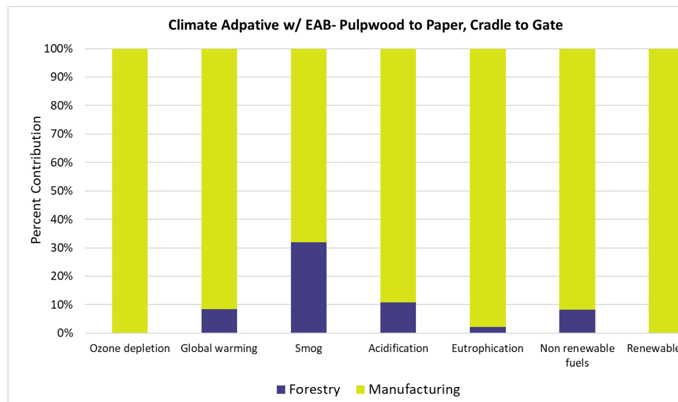
	BAU Management Scenario			
Impact category	**Unit per kg**	**A1-A2 Forestry**	**A3 Textile Manufacturing**	**Textile Total A1-A3**
Ozone depletion	kg CFC-11 eq	1.71E-09	1.86E-07	1.88E-07
Global warming	kg CO_2-eq FOSSIL	3.46E-01	5.44E+00	5.79E+00
Smog	kg O3 eq	1.15E-01	2.50E-01	3.65E-01
Acidification	kg SO2 eq	3.68E-03	4.57E-02	4.94E-02
Eutrophication	kg N eq	2.50E-04	2.63E-02	2.65E-02
Nonrenewable fuels	MJ	4.77E+00	7.58E+01	8.06E+01
Renewable fuels	MJ	5.46E-03	1.60E+01	1.60E+01
	Climate-adapted Management Scenario			
Ozone depletion	kg CFC-11 eq	1.86E-09	1.86E-07	1.88E-07
Global warming	kg CO_2-eq FOSSIL	3.75E-01	5.44E+00	5.82E+00
Smog	kg O3 eq	1.21E-01	2.50E-01	3.71E-01
Acidification	kg SO2 eq	3.96E-03	4.57E-02	4.97E-02
Eutrophication	kg N eq	2.73E-04	2.63E-02	2.66E-02
Nonrenewable fuels	MJ	5.22E+00	7.58E+01	8.10E+01
Renewable fuels	MJ	1.04E-02	1.60E+01	1.60E+01
	Climate-adapted plus fire Management Scenario			
Ozone depletion	kg CFC-11 eq	1.87E-09	1.86E-07	1.88E-07

Global warming (includes biogenic carbon)	kg CO_2-eq TOTAL	6.03E-01	5.44E+00	6.04E+00
Smog	kg O3 eq	1.34E-01	2.50E-01	3.84E-01
Acidification	kg SO2 eq	4.61E-03	4.57E-02	5.03E-02
Eutrophication	kg N eq	3.13E-04	2.63E-02	2.66E-02
Nonrenewable fuels	MJ	4.61E+00	7.58E+01	8.04E+01
Renewable fuels	MJ	5.68E-03	1.60E+01	1.60E+01
	Climate-adapted plus Emeral Ash Borer Management Scenario			
Ozone depletion	kg CFC-11 eq	1.87E-09	1.86E-07	1.88E-07
Global warming	kg CO_2-eq FOSSIL	3.75E-01	5.44E+00	5.82E+00
Smog	kg O3 eq	1.21E-01	2.50E-01	3.71E-01
Acidification	kg SO2 eq	3.96E-03	4.57E-02	4.97E-02
Eutrophication	kg N eq	2.74E-04	2.63E-02	2.66E-02
Nonrenewable fuels	MJ	4.55E+00	7.58E+01	8.04E+01
Renewable fuels	MJ	5.59E-03	1.60E+01	1.60E+01
	Economic Intensive Management Scenario			
Ozone depletion	kg CFC-11 eq	1.79E-09	1.86E-07	1.88E-07
Global warming	kg CO_2-eq FOSSIL	3.57E-01	5.44E+00	5.80E+00
Smog	kg O3 eq	1.20E-01	2.50E-01	3.70E-01
Acidification	kg SO2 eq	3.84E-03	4.57E-02	4.96E-02
Eutrophication	kg N eq	2.59E-04	2.63E-02	2.66E-02
Nonrenewable fuels	MJ	4.95E+00	7.58E+01	8.08E+01
Renewable fuels	MJ	5.49E-03	1.60E+01	1.60E+01









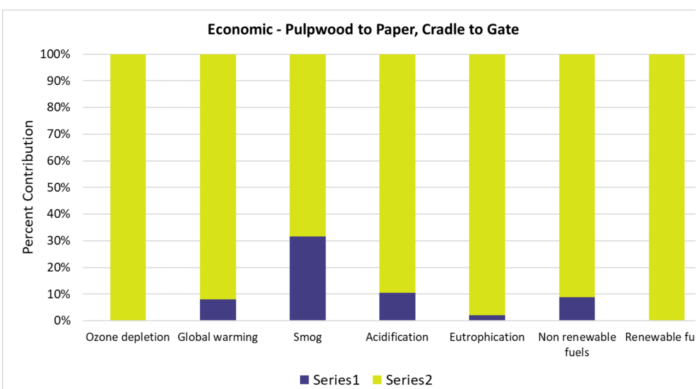
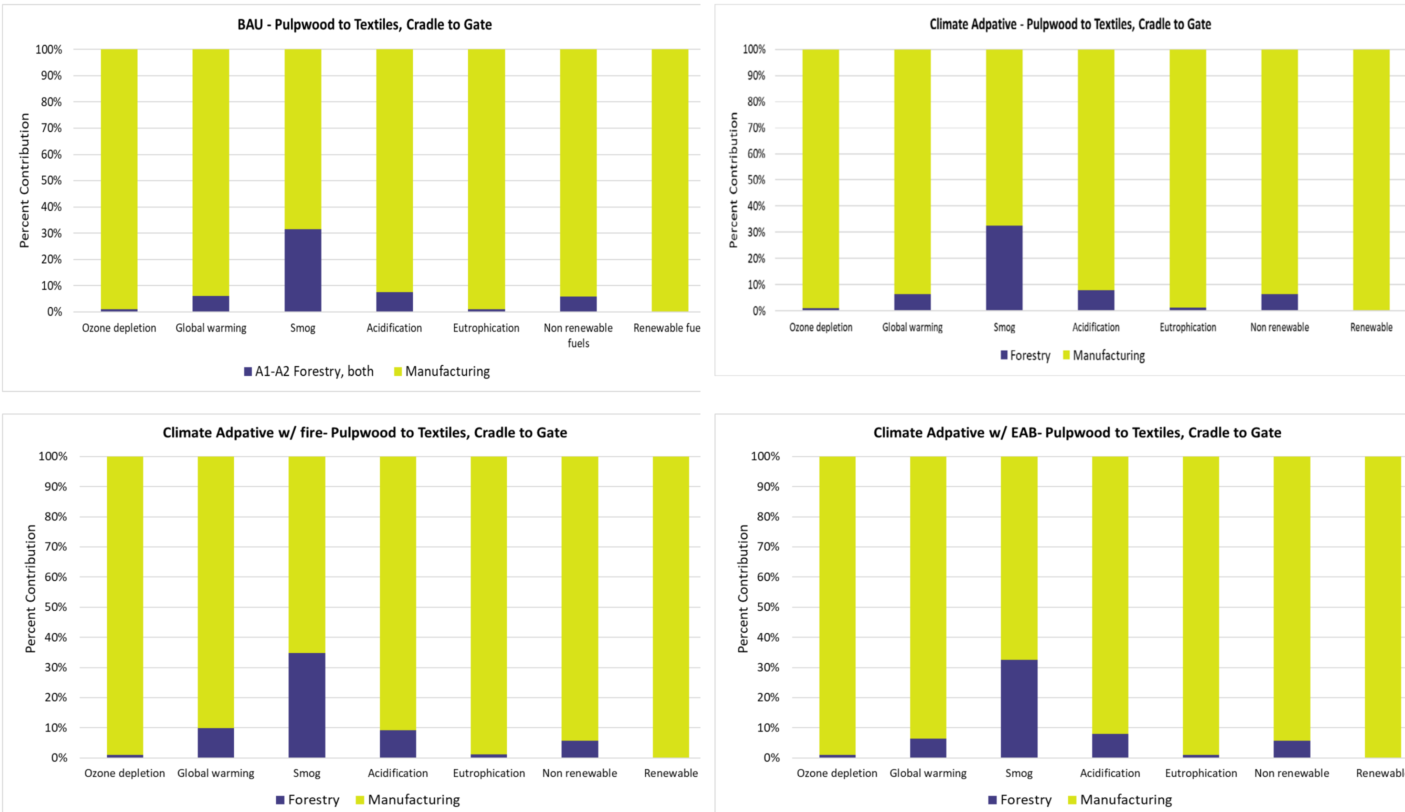


Figure 5.14. Cradle-to-gate (A1-A3) LCIA results one kilogram of uncoated paper production for Business as usual (BAU), Climate-adapted, Climate-adapted plus fire, Climate-adapted plus emerald ash borer (EAB), and Economic intensive management scenario, relative basis. Climate-adapted with fire includes biogenic carbon emissions in the Global Warming impact and subsequent burning emission in the other applicable impact categories



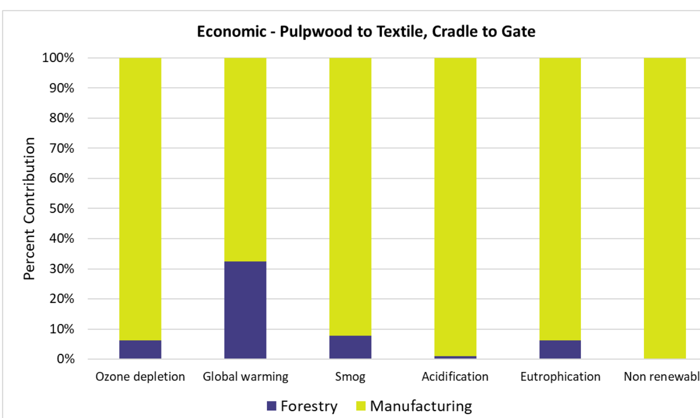
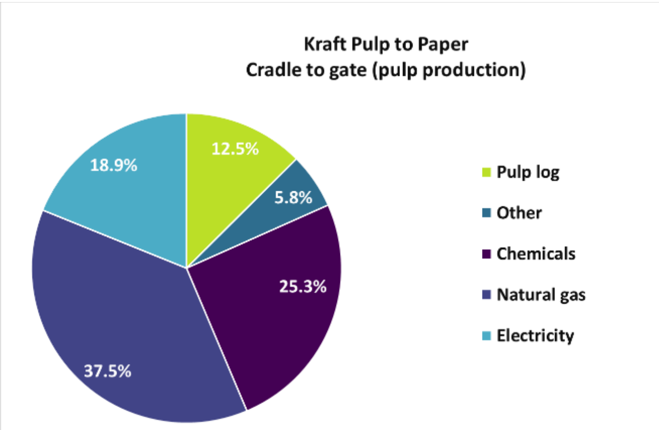


Figure 5.15. Cradle-to-gate (A1-A3) LCIA results one kilogram of textile production for Business as usual (BAU), Climate-adapted, Climate-adapted plus fire, and Economic intensive management scenario, relative basis. Climate-adapted with fire includes biogenic carbon emissions in the Global Warming impact and subsequent burning emission in the other applicable impact categories



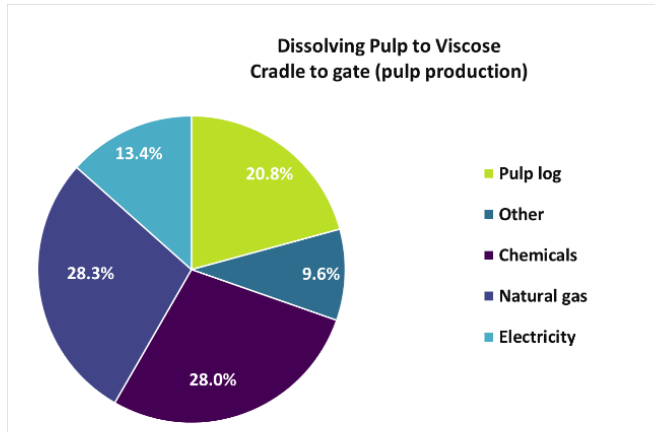


Figure 5.16. Cradle-to-gate embodied carbon (kg CO_2-eq) for the production of kraft pulp and dissolving pulp.

5.4.3 Oriented Strandboard

This section discusses the cradle-to-gate (A1-A3) LCIA results for growing, harvesting, hauling logs to milling facilities, and production of the product (Figure 5.5). The TRACI and CED LCIA methods were used to characterize the flows to and from the environment. LCA results shown in Table 5.12 are weighted consistent with TPO data by forest type. All reporting is on a per cubic meter basis, the standard unit for reporting LCA results for structural wood products (UL 2020). Over most impact categories, manufacturing of the product contributes the most (Table 5.12). The exception is smog potential, where forestry resources activities (A1) contribute slightly more to this impact (41-66% depending on the management scenario). Global warming potential (embodied carbon) for the manufacturing module is considerably higher ,representing 47-75% of the total A1-A3 impact depending on the management scenario. This higher impact is a direct result of the fossil fuel use consumed during manufacturing and resin production. Oriented strandboard had the highest embodied carbon over all the wood products (except paper and textiles). On the other hand, OSB stores more carbon because it is a denser wood product and can utilize roundwood not suitable for lumber. Past LCA surveys have shown that OSB is primarily produced using roundwood versus by-products from other wood manufacturing processes. This is primarily due to the strand sizing required for proper OSB manufacturing. In the OSB LCA, there was little difference between the forest management scenarios (Figures 5.16) with the exception of Climate-adapted plus fire, where a large increase in impact categories due to the burn activities in A1. The manufacturing stage (A3) remained constant over all scenarios; the assumption was no additional roundwood was supplied to the facilities changing the production values. Again, since no primary data was collected, the previously published LCA study on OSB was used and modified as described in the Methods in the report. Additional reporting over all forest types by management scenario can be found in the Appendix Figure 9.4.

Table 5.12. Cradle-to-gate (A1-A3) LCIA results one cubic meter of oriented strandboard (OSB) for Business as usual (BAU), Climate-adapted, Climate-adapted plus fire, and Economic intensive management scenario, absolute basis.

	BAU Management Scenario			
Impact category	**Unit per m3**	**A1-A2 Forestry**	**A3 OSB Manufacturing**	**OSB Total A1-A3**
Ozone depletion	kg CFC-11 eq	3.17E-07	1.05E-06	1.36E-06
Global warming	kg CO_2-eq $_{FOSSIL}$	6.51E+01	1.96E+02	2.61E+02
Smog	kg O3 eq	2.14E+01	1.58E+01	3.72E+01
Acidification	kg SO2 eq	6.89E-01	8.03E-01	1.49E+00
Eutrophication	kg N eq	4.65E-02	7.10E-01	7.57E-01
Nonrenewable fuels	MJ	1.01E+03	4.12E+03	5.13E+03
Renewable fuels	MJ	1.94E+00	3.80E+03	3.80E+03
	Climate-adapted Management Scenario			
Ozone depletion	kg CFC-11 eq	3.58E-07	1.05E-06	1.41E-06
Global warming	kg CO_2-eq $_{FOSSIL}$	7.25E+01	1.96E+02	2.68E+02
Smog	kg O3 eq	2.31E+01	1.58E+01	3.89E+01
Acidification	kg SO2 eq	7.59E-01	8.03E-01	1.56E+00
Eutrophication	kg N eq	5.29E-02	7.10E-01	7.63E-01
Nonrenewable fuels	MJ	1.01E+03	4.12E+03	5.13E+03
Renewable fuels	MJ	1.96E+00	3.80E+03	3.80E+03
	Climate-adapted plus fire Management Scenario			
Ozone depletion	kg CFC-11 eq	3.60E-07	1.05E-06	1.41E-06
Global warming (includes biogenic CO2)	kg CO_2-eq $_{TOTAL}$	2.18E+02	1.96E+02	4.13E+02
Smog	kg O3 eq	3.11E+01	1.58E+01	4.69E+01
Acidification	kg SO2 eq	1.17E+00	8.03E-01	1.97E+00
Eutrophication	kg N eq	7.81E-02	7.10E-01	7.88E-01
Nonrenewable fuels	MJ	1.01E+03	4.12E+03	5.13E+03
Renewable fuels	MJ	1.96E+00	3.80E+03	3.80E+03
	Economic Intensive Management Scenario			
Ozone depletion	kg CFC-11 eq	3.39E-07	1.05E-06	1.39E-06
Global warming	kg CO_2-eq $_{FOSSIL}$	6.82E+01	1.96E+02	2.64E+02
Smog	kg O3 eq	2.28E+01	1.58E+01	3.86E+01
Acidification	kg SO2 eq	7.32E-01	8.03E-01	1.53E+00
Eutrophication	kg N eq	4.92E-02	7.10E-01	7.59E-01

Nonrenewable fuels	MJ	9.36E+02	4.12E+03	5.05E+03
Renewable fuels	MJ	7.93E-01	3.80E+03	3.80E+03

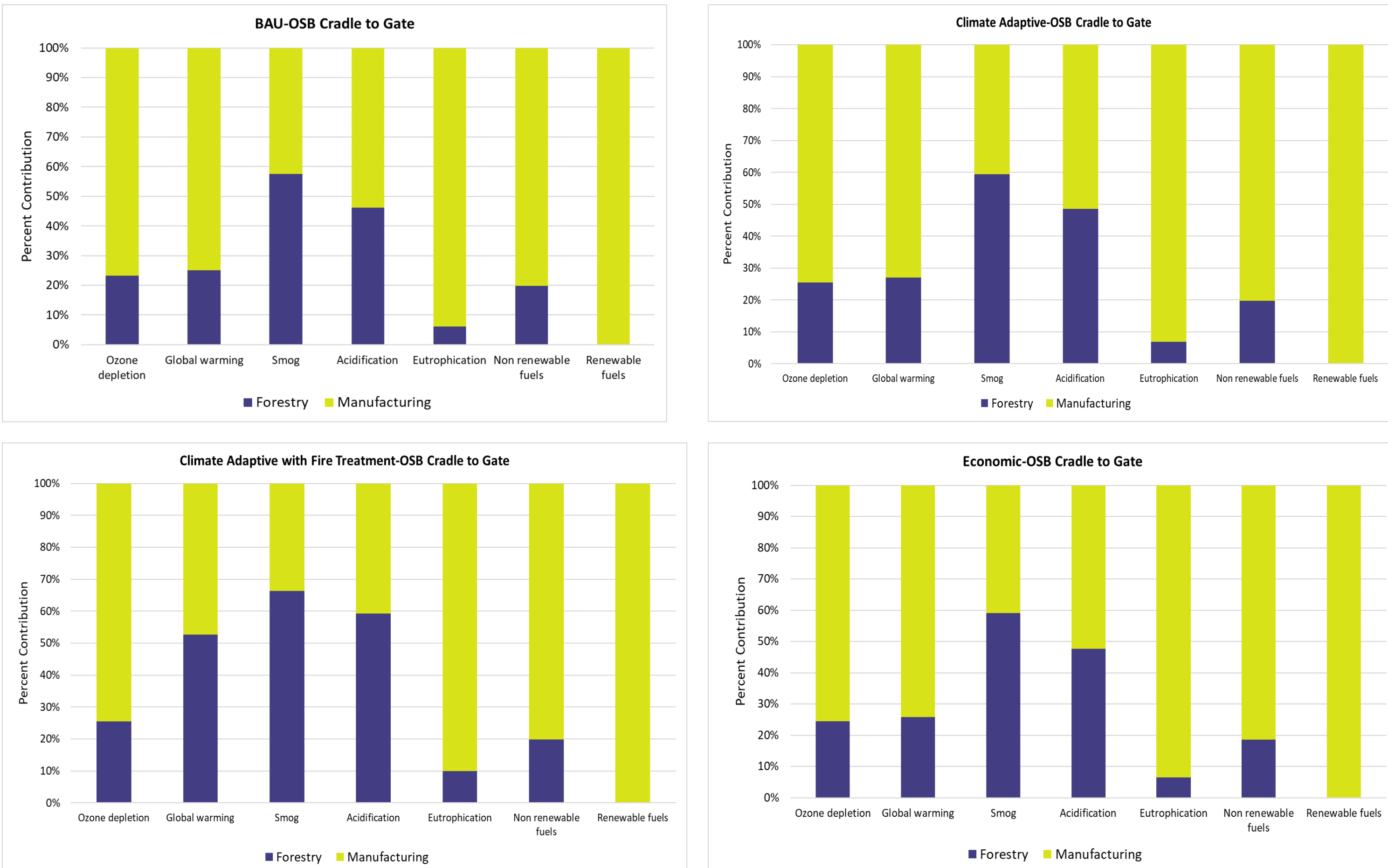


Figure 5.17. Cradle-to-gate (A1-A3) LCIA results one cubic meter of oriented strandboard (OSB) for Business as usual (BAU), Climate-adapted, Climate-adapted plus fire, and Economic intensive management scenario, relative basis. Climate-adapted with fire includes biogenic carbon emissions in the Global Warming impact and subsequent burning emission in the other applicable impact categories.

5.4.4 Hardwood Lumber

The LCIA results for hardwood lumber are shown in Table 5.13 and are weighted consistent with TPO data by forest type. All reporting is on a per cubic meter basis. All impact categories for manufacturing hardwood lumber were higher than the A1 forest resources module. Eutrophication had the highest relative to A1 with 96 percent of the impact occurring during manufacturing (A3) (Table 5.13, Figure 5.18). Similar to what was presented for OSB, there was little difference between the forest management scenarios (Figure 5.18) with the exception of Climate-adapted plus fire, where a large increase in impact categories due to the burn activities in A1. The manufacturing stage (A3) remained constant over all scenarios; the assumption was not additional roundwood was supplied to the facilities changing the production values. Again, since no primary data was collected, the previously published LCA study on hardwood lumber was used and modified as described in the Methods in the report. Additional reporting over all forest types by management scenario can be found in the Appendix Figure 9.4.

Table 5.13. Cradle-to-gate (A1-A3) LCIA results one cubic meter of hardwood lumber (HW) Business as usual (BAU), Climate-adapted, Climate-adapted plus fire, Climate-adapted plus emerald ash borer (EAB), and Economic intensive management scenario, absolute basis.

	BAU Management Scenario			
Impact category	**Unit per m3**	**A1-A2 Forestry**	**A3 HW Lumber Manufacturing**	**HW Lumber Total A1-A3**
Ozone depletion	kg CFC-11 eq	1.98E-07	4.82E-07	6.80E-07
Global warming	kg CO_2-eq FOSSIL	4.21E+01	1.53E+02	1.96E+02
Smog	kg O3 eq	1.33E+01	1.87E+01	3.20E+01
Acidification	kg SO2 eq	4.29E-01	7.32E-01	1.16E+00
Eutrophication	kg N eq	2.96E-02	6.91E-01	7.21E-01
Nonrenewable fuels	MJ	5.76E+02	2.11E+03	2.68E+03
Renewable fuels	MJ	8.74E-01	3.95E+03	3.95E+03
	Climate-adapted Management Scenario			
Ozone depletion	kg CFC-11 eq	2.12E-07	4.82E-07	6.94E-07
Global warming	kg CO_2-eq FOSSIL	4.45E+01	1.53E+02	1.98E+02
Smog	kg O3 eq	1.40E+01	1.87E+01	3.27E+01
Acidification	kg SO2 eq	4.56E-01	7.32E-01	1.19E+00
Eutrophication	kg N eq	3.16E-02	6.91E-01	7.23E-01
Nonrenewable fuels	MJ	6.08E+02	2.11E+03	2.72E+03
Renewable fuels	MJ	1.15E+00	3.95E+03	3.95E+03
	Climate-adapted plus fire Management Scenario			
Ozone depletion	kg CFC-11 eq	2.23E-07	4.82E-07	7.05E-07

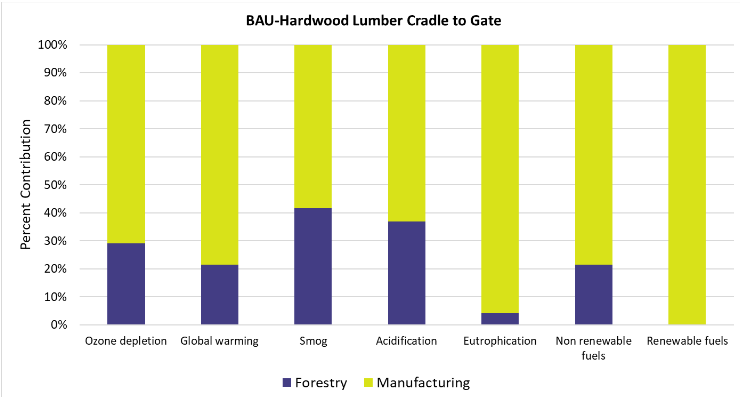
Global warming (includes biogenic CO2)	kg CO_2-eq TOTAL	5.64E+02	1.53E+02[1/]	7.17E+02
Smog	kg O3 eq	5.05E+01	1.87E+01	6.91E+01
Acidification	kg SO2 eq	3.03E+00	7.32E-01	3.76E+00
Eutrophication	kg N eq	1.82E-01	6.91E-01	8.74E-01
Nonrenewable fuels	MJ	5.36E+02	2.11E+03	2.64E+03
Renewable fuels	MJ	1.10E+00	3.95E+03	3.95E+03
	Climate-adapted plus EAB Management Scenario			
Ozone depletion	kg CFC-11 eq	2.12E-07	4.82E-07	6.94E-07
Global warming	kg CO_2-eq FOSSIL	4.45E+01	1.53E+02	1.98E+02
Smog	kg O3 eq	1.40E+01	1.87E+01	3.27E+01
Acidification	kg SO2 eq	4.56E-01	7.32E-01	1.19E+00
Eutrophication	kg N eq	3.16E-02	6.91E-01	7.23E-01
Nonrenewable fuels	MJ	3.87E+02	2.11E+03	2.49E+03
Renewable fuels	MJ	8.95E-01	3.95E+03	3.95E+03
	Economic Intensive Management Scenario			
Ozone depletion	kg CFC-11 eq	2.16E-07	4.82E-07	6.98E-07
Global warming	kg CO_2-eq FOSSIL	4.48E+01	1.53E+02	1.98E+02
Smog	kg O3 eq	1.45E+01	1.87E+01	3.32E+01
Acidification	kg SO2 eq	4.67E-01	7.32E-01	1.20E+00
Eutrophication	kg N eq	3.19E-02	6.91E-01	7.23E-01
Nonrenewable fuels	MJ	6.14E+02	2.11E+03	2.72E+03
Renewable fuels	MJ	8.60E-01	3.95E+03	3.95E+03

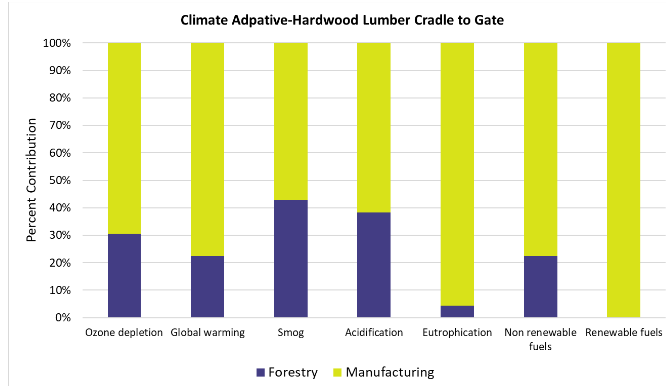
[1/] includes biogenic carbon emissions from burning

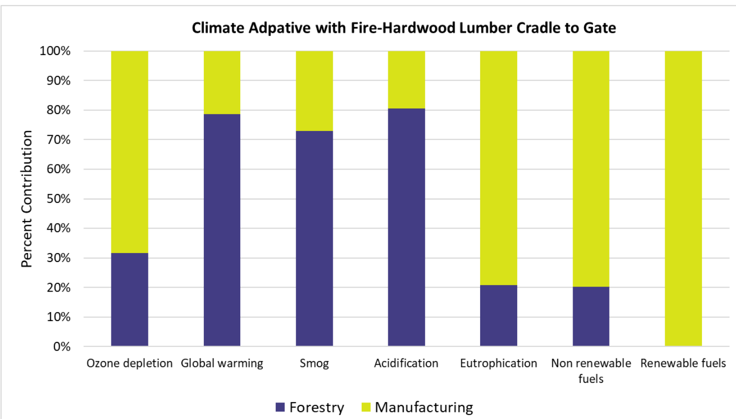
The management scenario "Climate-adapted plus emerald ash borer" only applied to paper, textiles, and hardwood lumber. Oriented strandboard did not use any black ash (TPO 2018). The differences between the three Climate-adapted management scenarios was negligible for paper and textiles, while for hardwood lumber, the Climate-adapted with fire had a significant contribution to embodied carbon (A1-A3) (Table 5.14). Paper and textiles only utilized 2.85% of black ash over all forest types, while hardwood lumber utilized 7.98%. Since fire treatments only applied to oak and red pine forest types, the red pine contribution to paper and textiles was only increased by 5% although the red pine contribution to 21% to each of these products. The oak contribution to hardwood lumber was 40% and it increased the embodied carbon by 262% from the Climate-adapted to Climate-adapted plus fire scenario. The difference in the large increase for hardwood lumber is two-fold; 1.) The contribution of oak to hardwood lumber (40%) and 2.) the overall impact of burning oak compared to red pine.

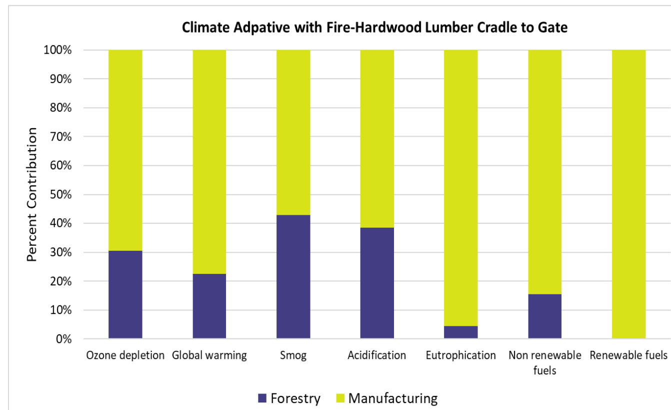
Table 5.14. Differences between paper, textile, and hardwood lumber production over the three climate-adapted management scenarios. EAB = Emerald Ash Borer

	Climate-adapted Management Scenario			% Use over all forest types		
	CA	**CA + EAB**	**CA + Fire**	**Black Ash**	**Oak**	**Red Pine**
	kg CO_2-eq / kg product					
Paper	1.7784	1.7785	1.8703	2.85%	0.03%	21.32%
Textiles	5.8157	5.8159	6.0446	2.85%	0.03%	21.32%
Hardwood lumber	0.3424	0.3425	1.2409	7.98%	39.73%	0%









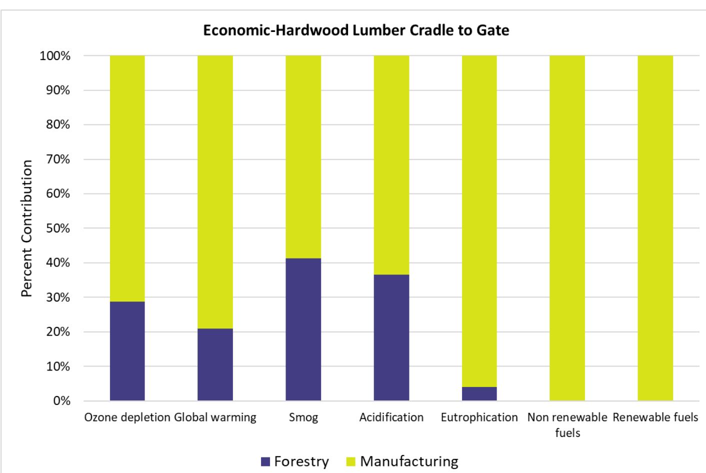


Figure 5.18. Cradle-to-gate (A1-A3) LCIA results one cubic meter of Hardwood Lumber for Business as usual (BAU), Climate-adapted, Climate-adapted plus fire, and Economic intensive management scenario, relative basis. Climate-adapted with fire includes biogenic carbon emissions in the Global Warming impact and subsequent burning emission in the other applicable impact categories.

5.4.5 Softwood Lumber

The LCIA results for softwood lumber are shown in Tables 5.14 and are weighted consistent with TPO data by forest type. All reporting is on a per cubic meter basis. The LCIA results for manufacturing of softwood lumber reflect relative impact on manufacturing and more on forestry. This is most likely to the allocation methods used in the softwood lumber. The data are based on an average regional lumber production in Northeast – North central region of the United States. Since mass allocation was applied, the survey data reported a low lumber recovery meaning most of the log went to by-products that either left the system (sold) or were used internally for heat energy. Global warming represented 4-61 percent for the manufacturing stage (A3) depending on the management scenario (Figure 5.19). Similar to what was presented for the other products, there was little difference between the forest management scenarios (Figures 5.16-5.19) with the exception of Climate-adapted plus fire, where a large increase in impact categories due to the burn activities in A1 of the red pine (embodied carbon = 96% for A1). Additional reporting over all forest types by management scenario can be found in Appendix Figure 9.6.

Table 5.15. Cradle-to-gate (A1-A3) LCIA results for one cubic meter of softwood lumber (SW) Business as usual (BAU), Climate-adapted, Climate-adapted plus fire, and Economic intensive scenario, absolute basis.

	BAU Management Scenario			
Impact category	**Unit per m3**	**A1-A2 Forestry**	**A3 SW Lumber Manufacturing**	**SW Lumber Total A1-A3**
Ozone depletion	kg CFC-11 eq	1.26E-07	5.02E-07	6.29E-07
Global warming	kg CO_2-eq $_{FOSSIL}$	2.48E+01	3.83E+01	6.31E+01
Smog	kg O3 eq	8.37E+00	6.85E+00	1.52E+01
Acidification	kg SO2 eq	2.69E-01	2.12E-01	4.81E-01
Eutrophication	kg N eq	1.82E-02	3.04E-01	3.22E-01
Nonrenewable fuels	MJ	3.46E+02	5.42E+02	8.87E+02
Renewable fuels	MJ	3.05E-01	1.72E+03	1.72E+03
	Climate-adapted Management Scenario			
Ozone depletion	kg CFC-11 eq	1.24E-07	5.02E-07	6.26E-07
Global warming	kg CO_2-eq $_{FOSSIL}$	2.46E+01	3.83E+01	6.29E+01
Smog	kg O3 eq	8.07E+00	6.85E+00	1.49E+01
Acidification	kg SO2 eq	2.62E-01	2.12E-01	4.74E-01
Eutrophication	kg N eq	1.81E-02	3.04E-01	3.22E-01
Nonrenewable fuels	MJ	3.46E+02	5.42E+02	8.87E+02
Renewable fuels	MJ	4.64E-01	1.72E+03	1.72E+03

	Climate-adapted plus fire Management Scenario			
Ozone depletion	kg CFC-11 eq	1.31E-07	5.02E-07	6.33E-07
Global warming (includes biogenic CO2)	kg CO_2-eq $_{TOTAL}$	9.49E+02	3.83E+01	9.87E+02
Smog	kg O3 eq	5.90E+01	6.85E+00	6.58E+01
Acidification	kg SO2 eq	2.86E+00	2.12E-01	3.08E+00
Eutrophication	kg N eq	1.78E-01	3.04E-01	4.82E-01
Nonrenewable fuels	MJ	3.47E+02	5.42E+02	8.88E+02
Renewable fuels	MJ	4.71E-01	1.72E+03	1.72E+03
	Economic intensive Management Scenario			
Ozone depletion	kg CFC-11 eq	1.32E-07	5.02E-07	6.34E-07
Global warming	kg CO_2-eq $_{FOSSILL}$	2.60E+01	3.83E+01	6.43E+01
Smog	kg O3 eq	8.80E+00	6.85E+00	1.57E+01
Acidification	kg SO2 eq	2.83E-01	2.12E-01	4.95E-01
Eutrophication	kg N eq	1.90E-02	3.04E-01	3.23E-01
Nonrenewable fuels	MJ	3.22E+02	5.42E+02	8.63E+02
Renewable fuels	MJ	3.13E-01	1.72E+03	1.72E+03

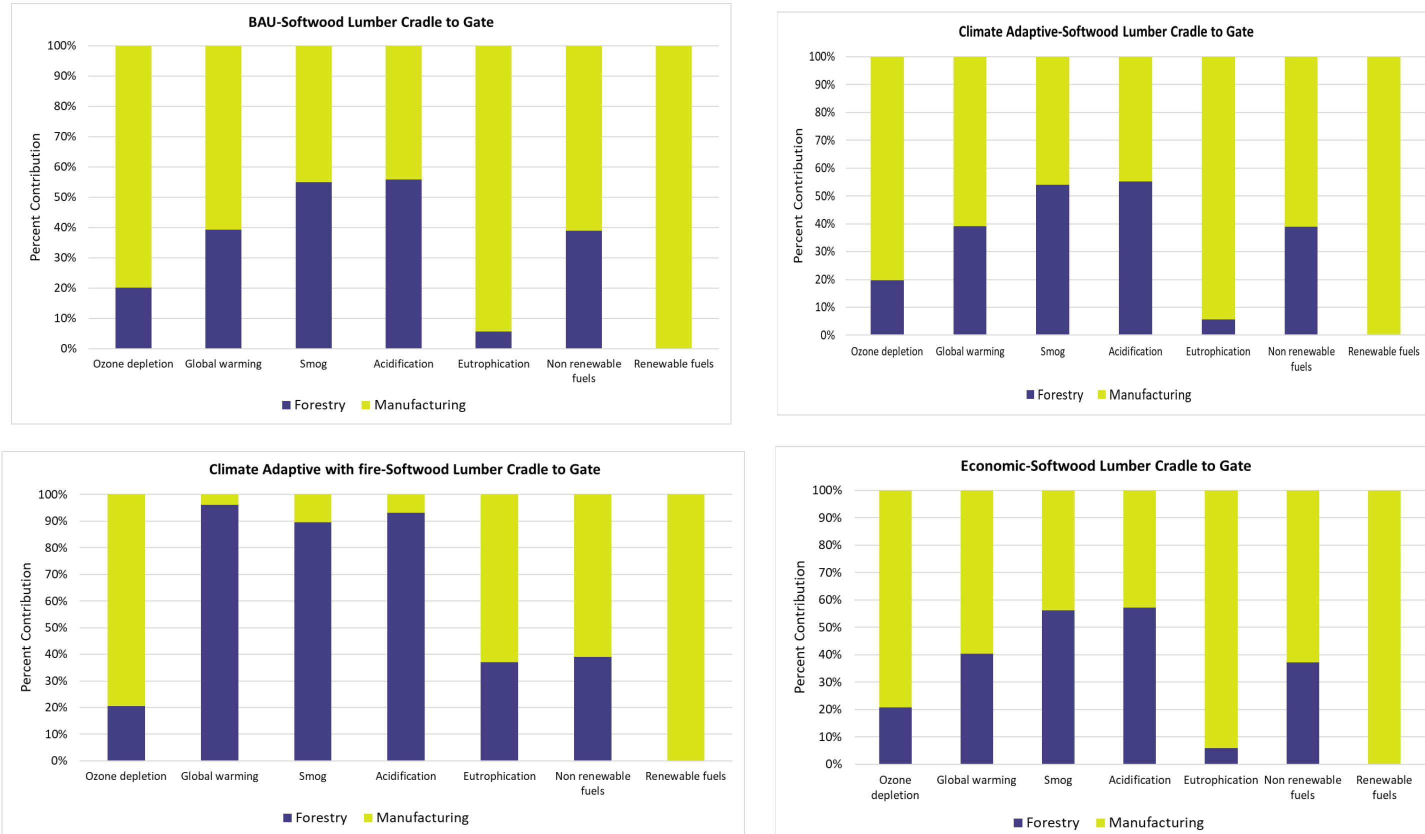


Figure 5.19. Cradle-to-gate (A1-A3) LCIA results for Softwood Lumber for Business as usual (BAU), Climate-adapted, Climate-adapted plus fire, and Economic intensive management scenario, relative basis. Climate-adapted with fire includes biogenic carbon emissions in the Global Warming impact and subsequent burning emission in the other applicable impact categories

5.4.6 Carbon Accounting

All carbon dioxide flows (kg CO_2-eq) presented in the following figures are allocated to the products and do not include any by-products leaving the system boundary. The carbon accounting reported uses the embodied carbon and the carbon stored in the wood product. The exception to this is the Climate-adapted plus fire (Fire) management scenario where biogenic carbon emission (CO_2-eq $_{BIOGENIC}$) is included to show the impact of burning practices over the no burn scenarios. Carbon storage is based on the carbon content of the wood product converted to CO_2-eq.

Discussing only the BAU management scenario for each product, the net carbon storage for a cubic meter of OSB, hardwood lumber, and softwood lumber is -866, -864, and -733 kg CO_2-eq, respectively (Figure 5.20). Again, emphasizing comparisons of net carbon storage between wood products is negligible. In addition, the forest management scenarios also showed little impact differences as well, with the exception of the Climate-adapted plus fire where the emissions were much higher. ***Note: in the A1-A3 analysis, biogenic carbon emissions were <u>included</u> in the Climate-adapted plus fire scenario.*** The authors understand including the biogenic carbon emission for fire scenario does not "exactly" allow for equal comparisons because we are not considering the biogenic carbon emission that occurred during wood production under all scenarios. The decision to include biogenic carbon emissions was to emphasize the difference between burn and no burn for the Climate-adapted management scenario.

According to ISO 21930:2017 section 7.2.7 and 7.2.12 the biogenic carbon enters the product system (removal). Carbon removal is considered a negative emission. The biogenic carbon leaves the system (emission) as a product, coproducts, and directly to the atmosphere when combusted. These mass flows of biogenic carbon from and to nature are balanced and normally reported unallocated in a verified LCA in terms of kg CO_2-eq [4].

In an LCA, the LCI flow of biogenic carbon removal is characterized with a factor of -1 kg CO_2-eq/kg CO_2-eq of biogenic carbon in the calculation of the GWP[5]. Likewise, the LCI flow of biogenic carbon emission is characterized with a factor of +1 kg CO_2-eq / kg CO_2-eq of biogenic carbon in the calculation of the GWP. Emissions other than CO_2 associated with biomass combustion (e.g., methane or nitrogen oxides) are characterized by their specific radiative forcing factors in the calculation of the GWP.

The UL Product Category Rule for wood products (2020) specifies TRACI as the default method for GWP. The **TRACI method does not account for the removals or emissions of biogenic CO_2**.

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[4] To convert of mass of biomass to CO2 = mass of product x carbon content x 44/12. We assume a carbon content of 50 percent for all solid wood products, 32 percent for paper, and 42 percent for textiles.

[5] ISO 21930 requires a demonstration of forest sustainability to characterize carbon removals with a factor of -1 kg CO_2e/kg CO_2. ISO 21930 Section 7.2.1 Note 2 states the following regarding demonstrating forest sustainability: "Other evidence such as national reporting under the United Nations Framework Convention on Climate Change (UNFCCC) can be used to identify forests with stable or increasing forest carbon stocks." Canada's UNFCCC annual report Table 6-1 provides annual net GHG Flux Estimates for different land use categories. This reporting indicates non-decreasing forest carbon stocks and thus the source forests meet the conditions for characterization of removals with a factor of -1 kg CO_2e/kg CO_2.

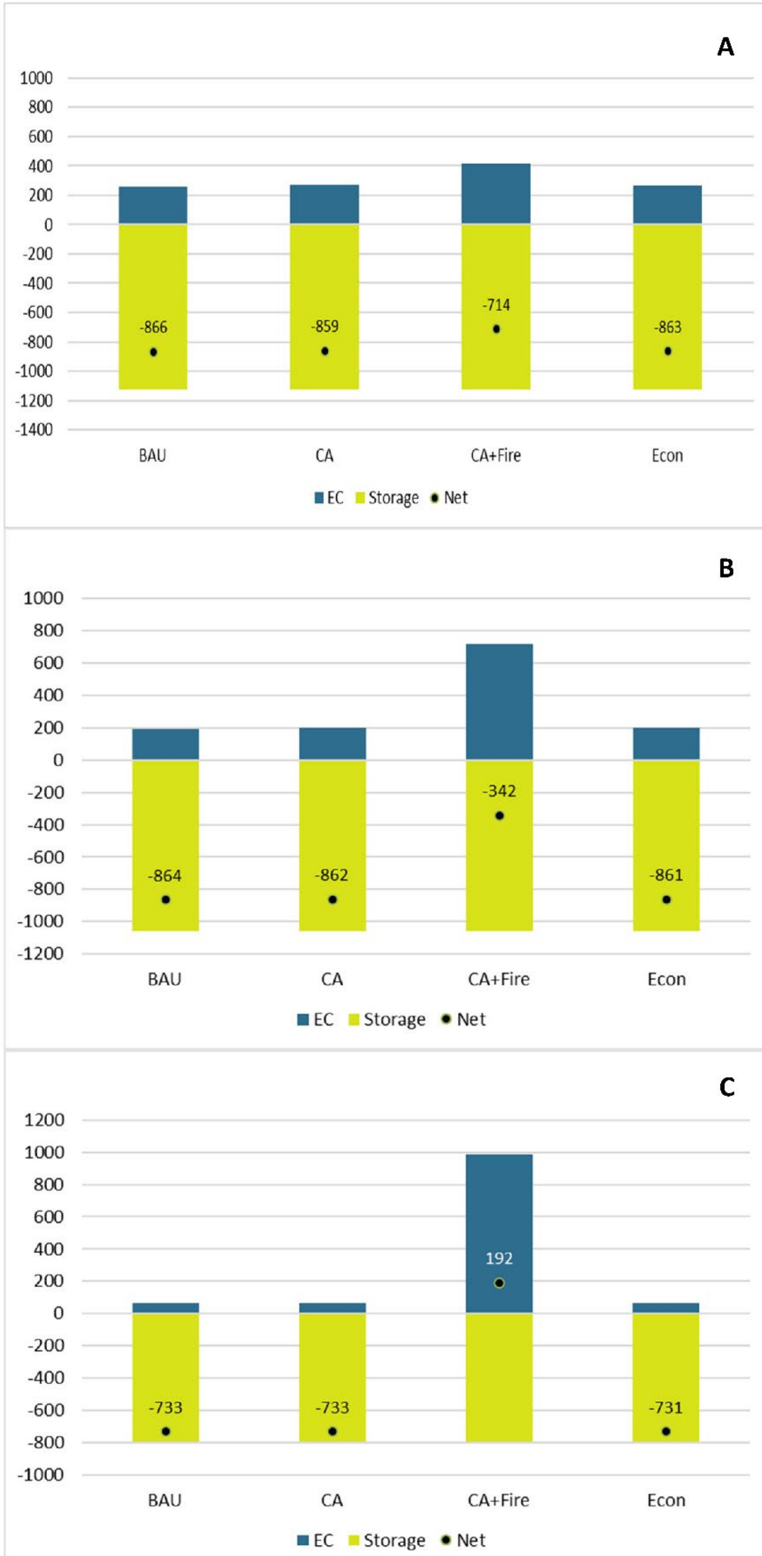

Figure 5.20. 100-year impacts for cradle-to-gate (A1-A3) carbon accounting for 1 cubic meter of (A) oriented strandboard (OSB), (B) hardwood lumber, and (C) softwood lumber over the four management scenarios. BAU-Business as usual, CA-Climate-adapted, Fire – Climate-adapted plus fire, Econ-Economic intensive.

When the wood volume is scaled up to annual production (TPO 2018), the differences in net carbon emission between the products shift in scale (Figure 5.21). According to the TPO data (2018), more sawlog volumes were harvested than roundwood for composite panels (for this LCA OSB was assumed to represent 100% of the composite panel product category in TPO), but when sawlog volumes are allocated to hardwoods and softwoods, their production volumes lowered, therefore lowering the overall carbon storage of wood products produced.

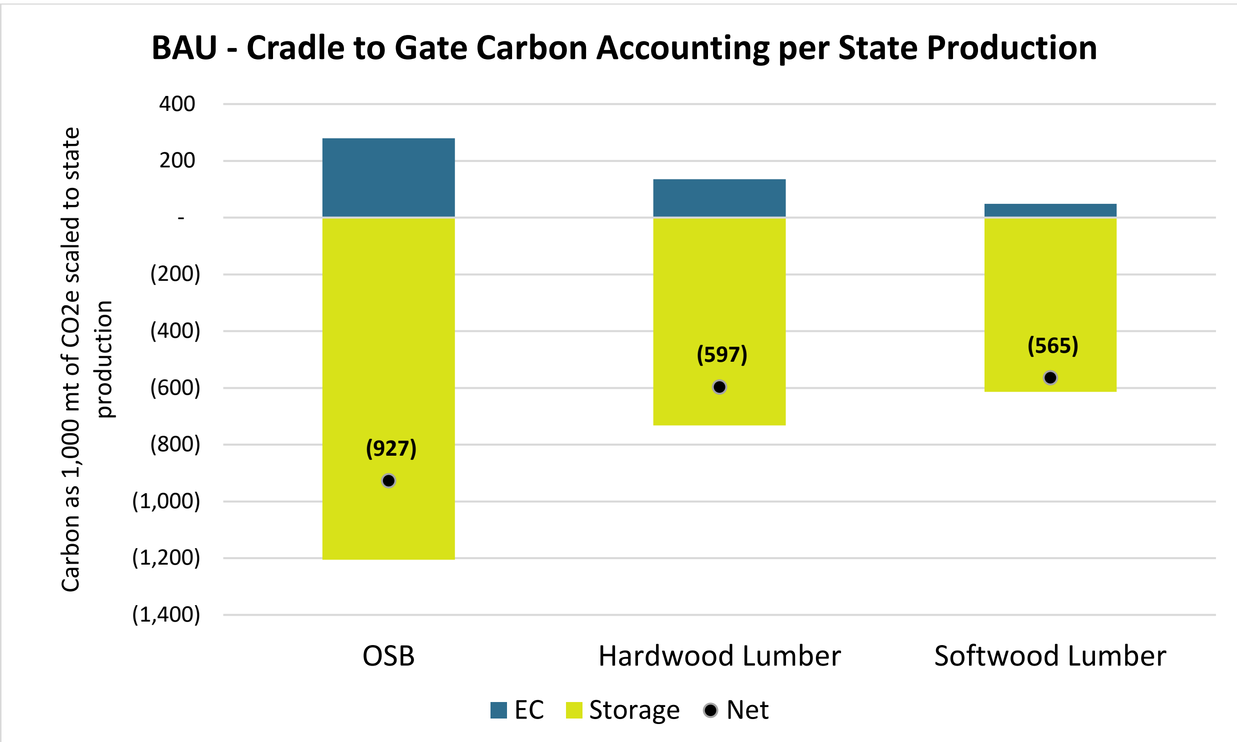

Figure 5.21. Cradle-to-gate (A1-A3) carbon accounting scaled to annual roundwood volumes for oriented strandboard, hardwood lumber and softwood lumber for the BAU-Business as usual management scenarios.

As mentioned in the methods, the model to create the following figures was developed by the University of Washington's CINTRAFOR lab to account for end-of-life emissions of wood products. The model follows the Lashof accounting method (Fearnside et al. 2020) to calculate GWP. This method accounts for the radiative forcing (RF) caused by all GHG emissions over time. The RF values (one per year) are determined based on the concentration of the GHG emitted, the radiative efficiency of the GHG and the atmospheric residence time of the GHG. The RF values can then be used to create a function to model the decay of the GHG in the atmosphere over time. The following figures are based on dynamic LCA modeling (Figure 5.22, 5.23, 5.24) for OSB, hardwood lumber, and softwood lumber. Using OSB as an example to explain Figures 5.22 – 5.24, OSB is produced at year zero and its service life ends at year 100

(Figure 5.22). The embodied emissions are delayed for 100 years while the product is in service. The emissions that occur at year zero follow a decay pattern of the blue bar. The impact of emitting CO_2-eq is cut off at year 100. The yellow bar represents the benefit of delayed emissions, it applies the delayed decay emissions of the product and subtracts this from the embodied carbon and is shown by the yellow bar in Figure 5.22 as a negative decay curve for OSB. The main differences between Figures 5.22 – 5.24 for OSB, hardwood lumber, and softwood lumber, is the embodied carbon each product releases at year zero.

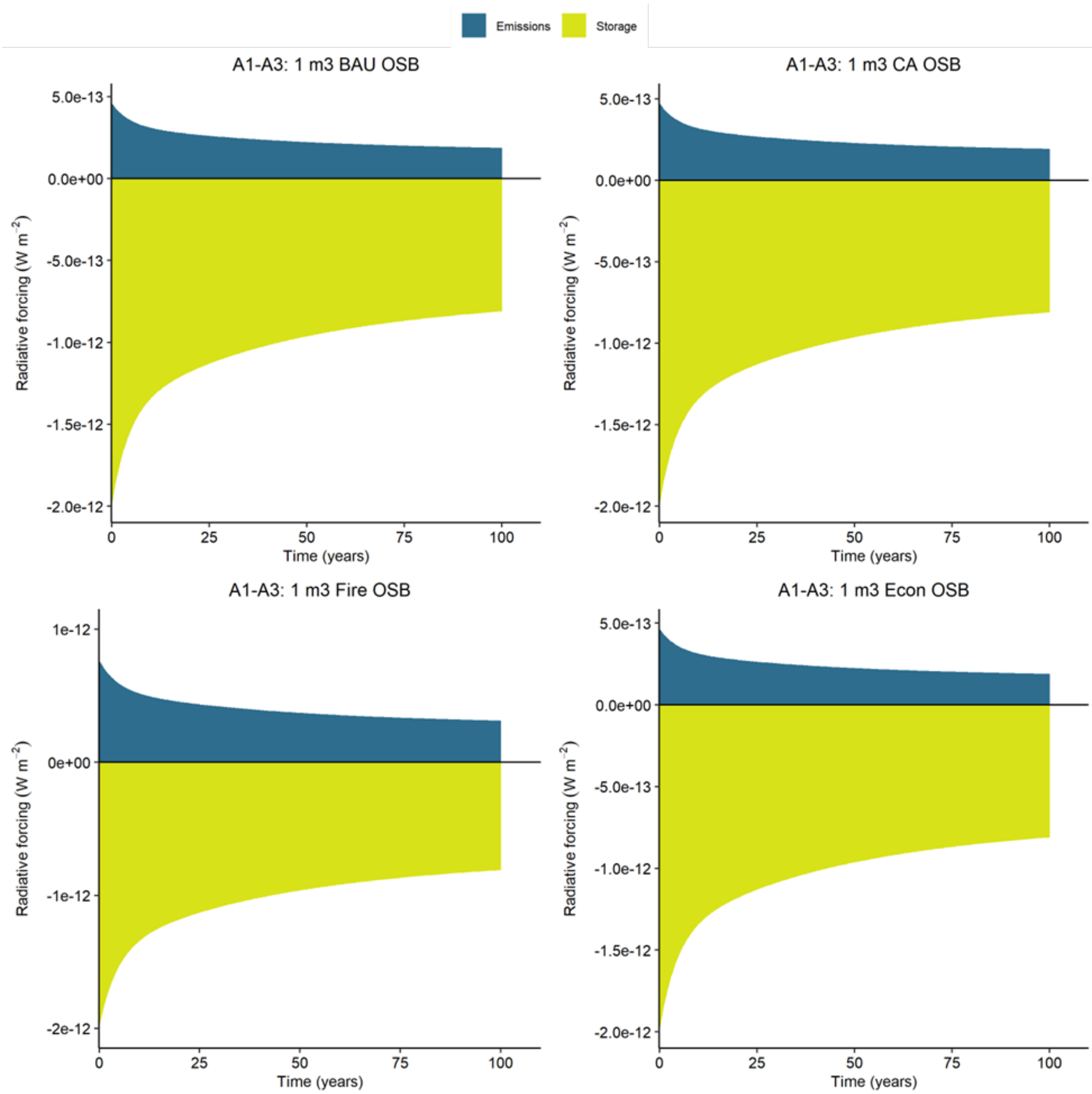

Figure 5.22. The atmospheric decay of carbon dioxide and the carbon storage benefit at year 0 and year 100 for Oriented strandboard (OSB) over all management scenarios (BAU-Business as usual, CA – Climate-adapted, Fire – Climate-adapted plus fire, and Econ – Economic intensive).

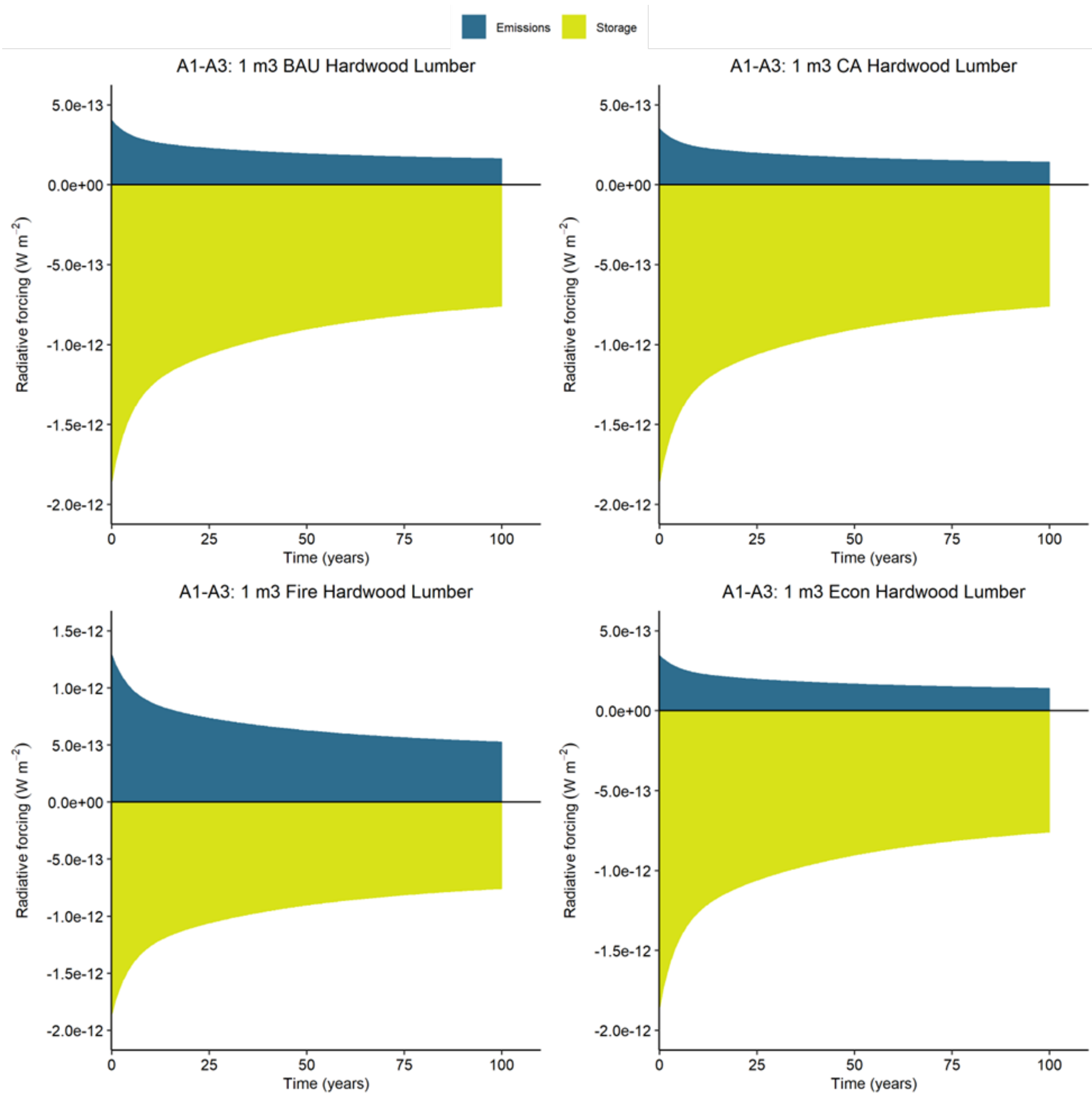

Figure 5.23. The atmospheric decay of carbon dioxide and the carbon storage benefit at year 0 and year 100 for hardwood lumber overall management scenarios (BAU-Business as usual, CA – Climate-adapted, Fire – Climate-adapted plus fire, and Econ – Economic intensive).

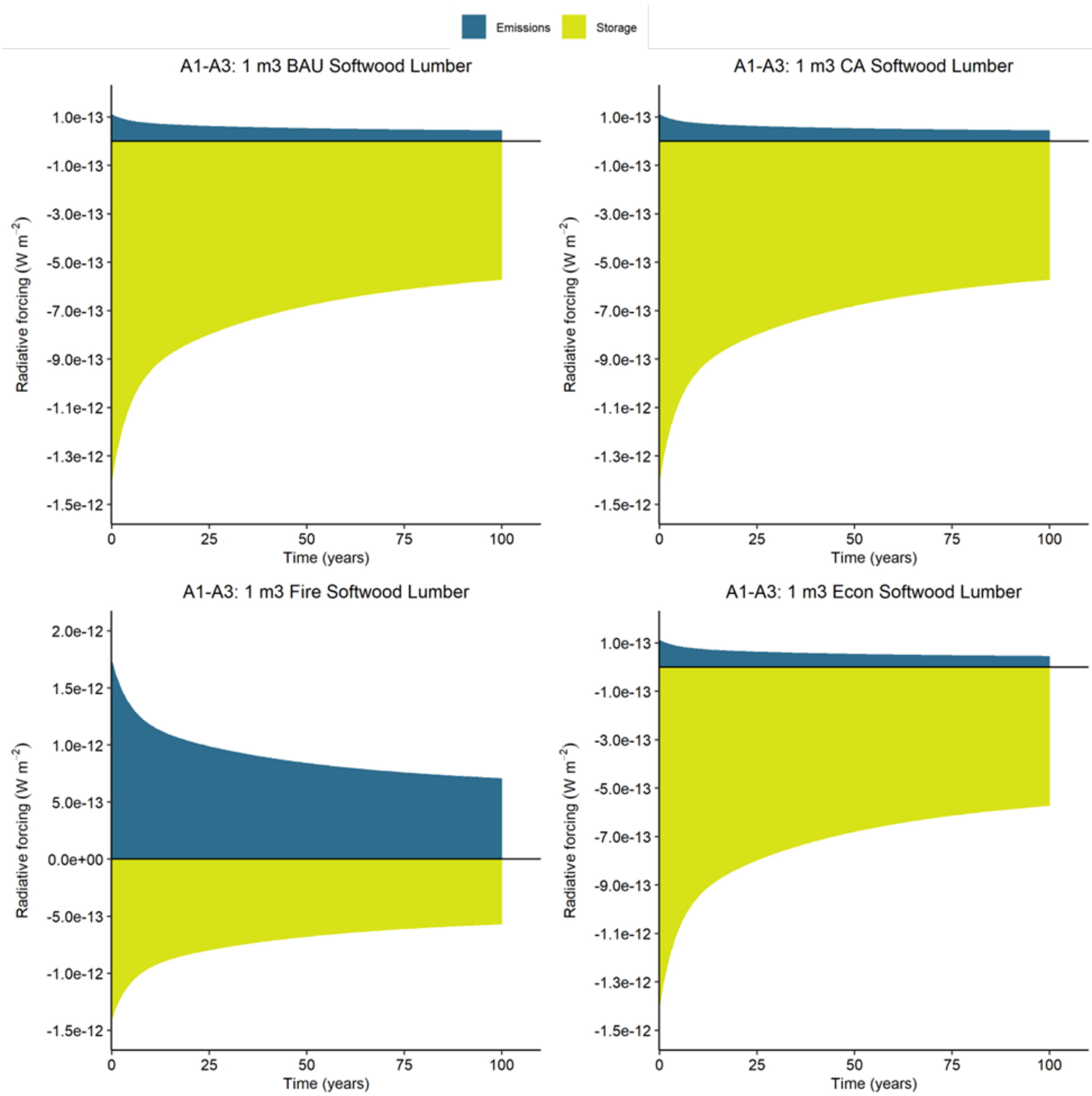

Figure 5.24. The atmospheric decay of carbon dioxide and the carbon storage benefit at year 0 and year 100 for softwood lumber overall management scenarios (BAU-Business as usual, CA – Climate-adapted, Fire – Climate-adapted plus fire, and Econ – Economic intensive)

5.4.7 A1-C4 Life Cycle Impact Assessment Results

The EoL modeling uses the same dynamic LCA modeling as the A1-A3 described in the previous section. The difference is the modeling is extended an additional 100 years to account for product time in the landfill. For EoL processing, a weighted average of the typical waste treatment in the United States for durable wood products is used: 82 percent landfill and 18 percent incineration (EPA 2019). After the product is removed from service, there are several possible outcomes for its fate. The product can be disposed via landfill, incinerated, or reused/recycled (which may or may not require reprocessing). The results presented for this LCA include a 100 percent landfill scenario and a 100 percent incineration scenario and an average of the two EoL treatments based on disposal rates from the EPA (EPA 2019) (82 % landfill and 18% incineration).

Again, OSB is used to explain Figures 5.25 – 5.27. Just like in the A1-A3, OSB is produced at year zero and its service life ends at year 100 (BAU Figure 5.25). The embodied emissions are delayed for the first 100 years while the product is in service. But instead of ending at year 100, the emissions that started at production at year zero now end at year 200 following the decay pattern of the blue bar. Beginning at year 100 and extending to year 200, the added emissions associated with the EoL are shown in the purple bar. Again, the yellow bar represents the benefit of delayed emissions, it applies the delayed decay emissions of the product (while in use) and subtracts this from the embodied carbon as shown by the yellow bar in Figure 5.25 as a negative decay curve. The green bar reflects the next phase of benefit of delayed emissions by incorporating the delayed decay from landfilling together with the embodied carbon from the landfill activities. The "blip" in the green bar beginning at year 100 and goes for ~12 years is the continuous release of methane. Also, there is no storage benefit after 100 years in the incineration scenario because all the biogenic carbon is released instantly back into the atmosphere and is also reflected in the "larger area" under the purple curve. Figures 5.25– 5.27 are for the three products under the BAU management scenario.

The Climate-adapted plus fire management scenario is worth noting (Figures 5.28 – 5.30). In this scenario the embodied carbon emission that occurred at year zero is so much higher that the carbon storage benefit that the decay emission curves are greater than the storage curve almost making the EoL impacts negligible. This is made clear in Figure 5.31 where for OSB and softwood lumber the carbon emission exceeded the storage over a 200 year decay profile. Hardwood had a net carbon storage under landfill EoL scenario and subsequently the Average scenario also. The other management scenarios (Climate-adapted and Economic intensive) for each product can be found in the Appendix Figures 9.6-9.11)

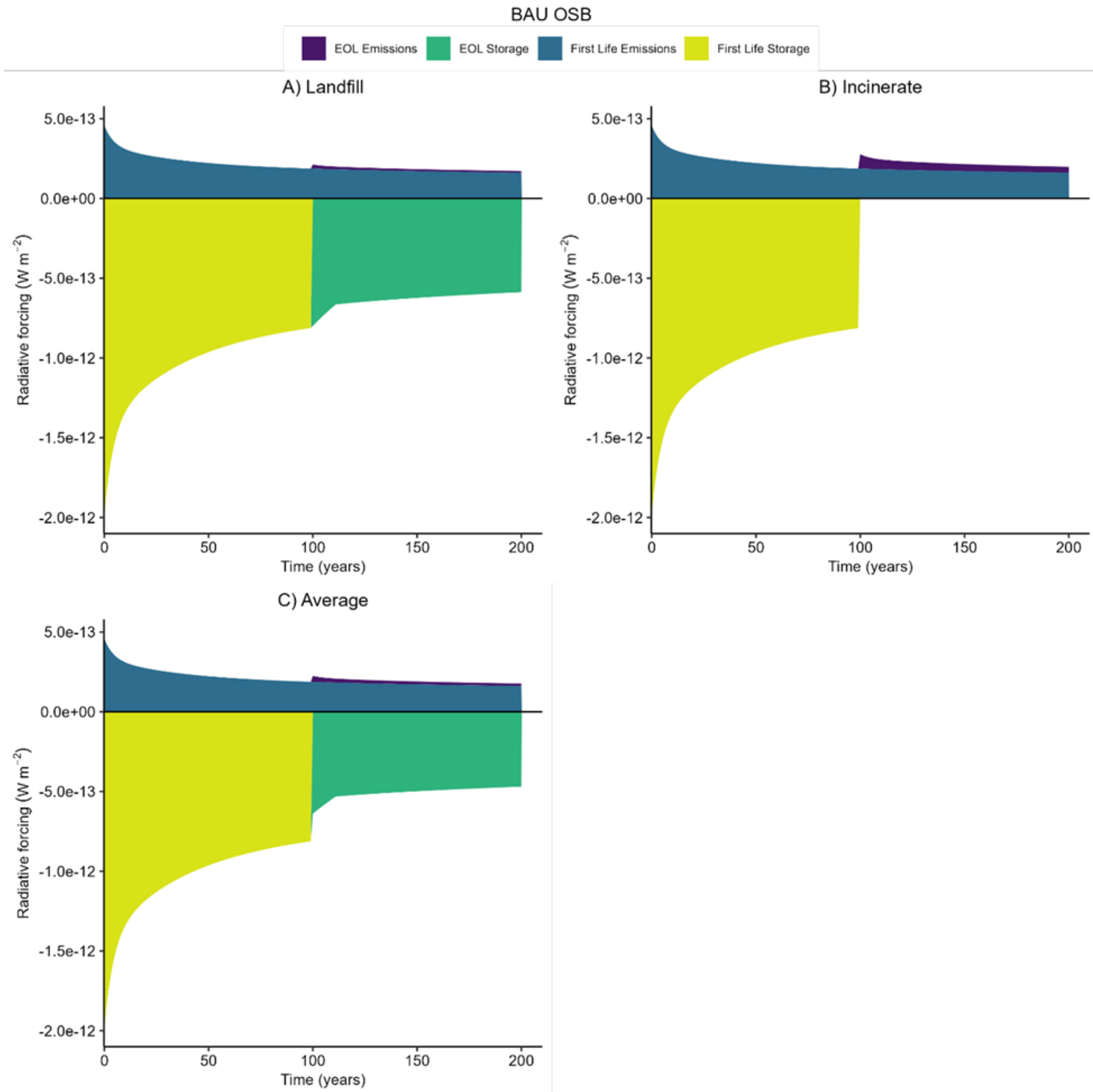

Figure 5.25. The atmospheric decay of carbon dioxide and the carbon storage benefit at year 0 to year 200 for oriented strandboard (OSB) for the BAU-Business as usual management scenario for three EoL of scenarios. (A) Landfill, (B) Incineration, and (C) Average.

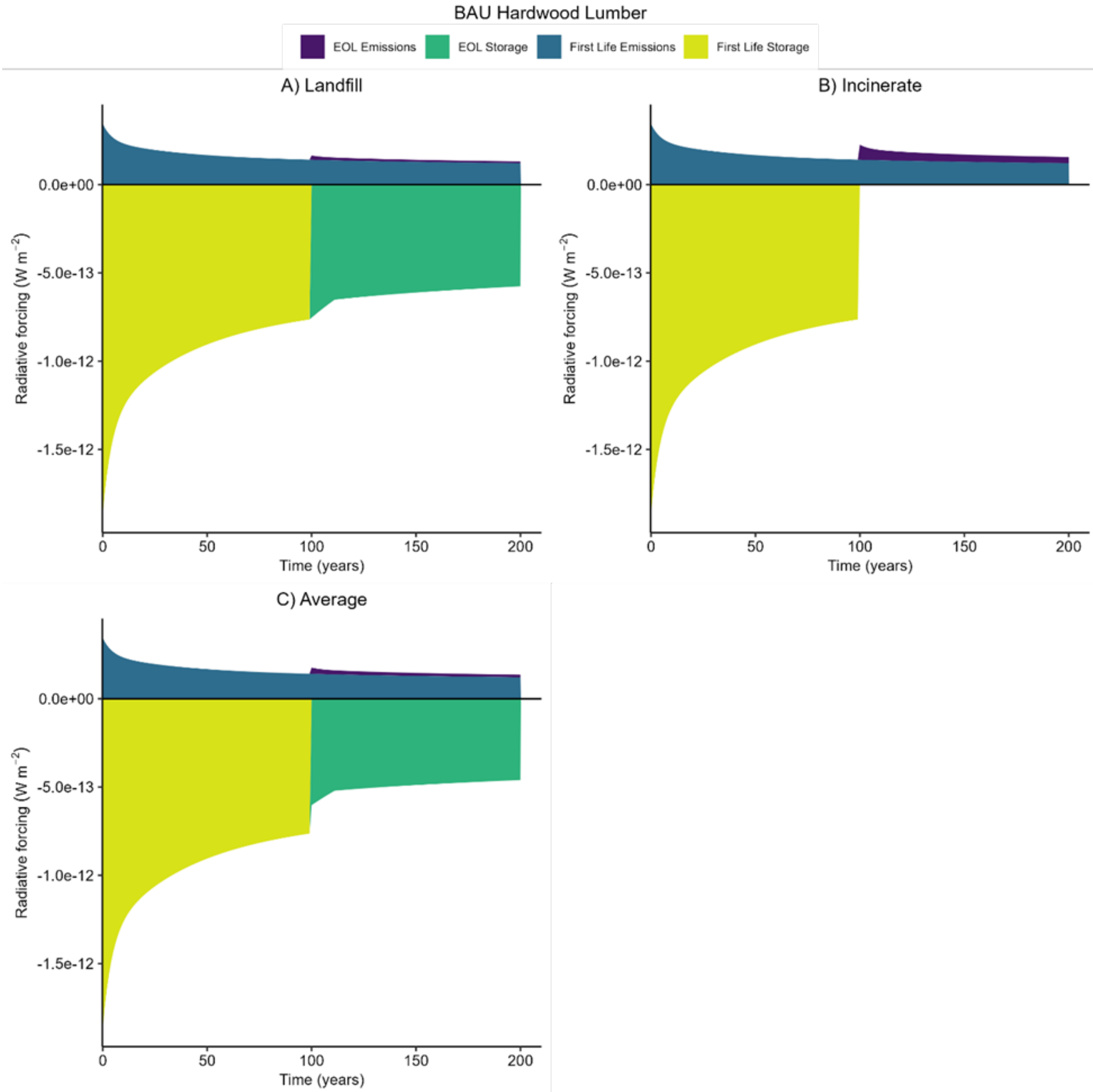

Figure 5.26. The atmospheric decay of carbon dioxide and the carbon storage benefit at year 0 to year 200 for hardwood lumber for the BAU-Business as usual management scenario for three EoL of scenarios. (A) Landfill, (B) Incineration, and (C) Average.

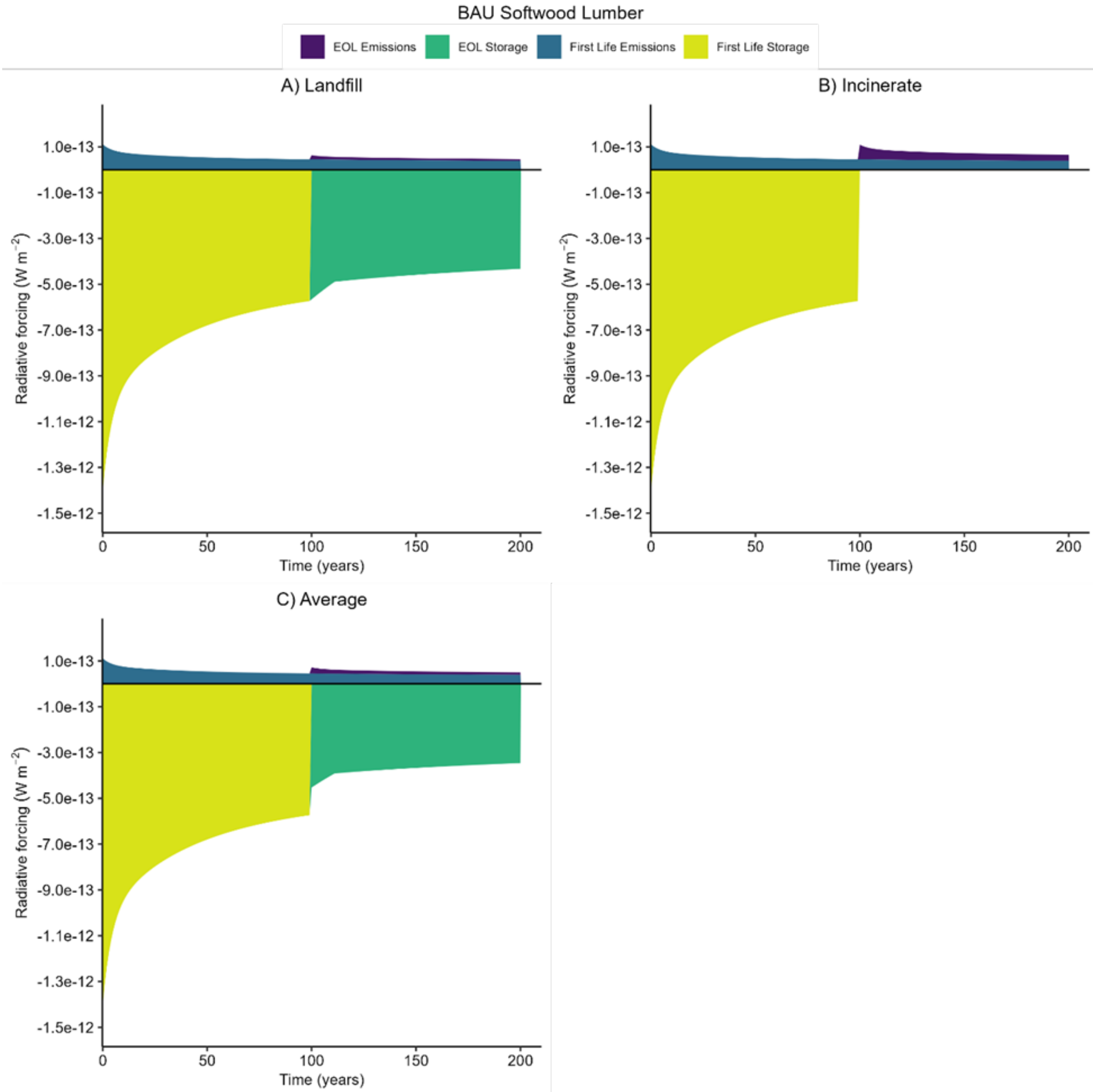

Figure 5.27. The atmospheric decay of carbon dioxide and the carbon storage benefit at year 0 to year 200 for softwood lumber for the BAU-Business as usual management scenario for three EoL of scenarios. (A) Landfill, (B) Incineration, and (C) Average.

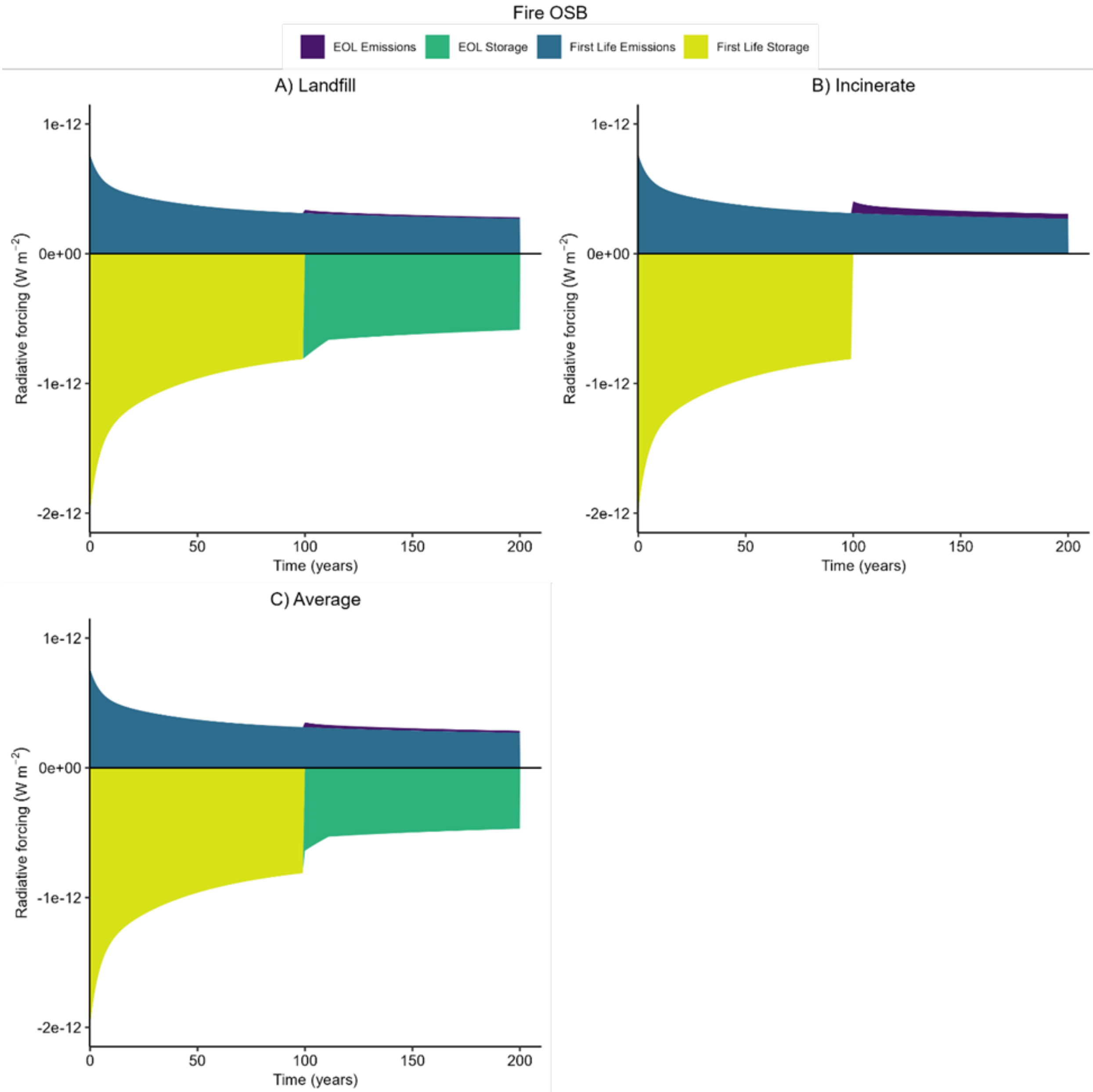

Figure 5.28. The atmospheric decay of carbon dioxide and the carbon storage benefit at year 0 to year 200 for oriented strandboard (OSB) for the Climate-adapted plus fire management scenario for three EoL of scenarios. (A) Landfill, (B) Incineration, and (C) Average.

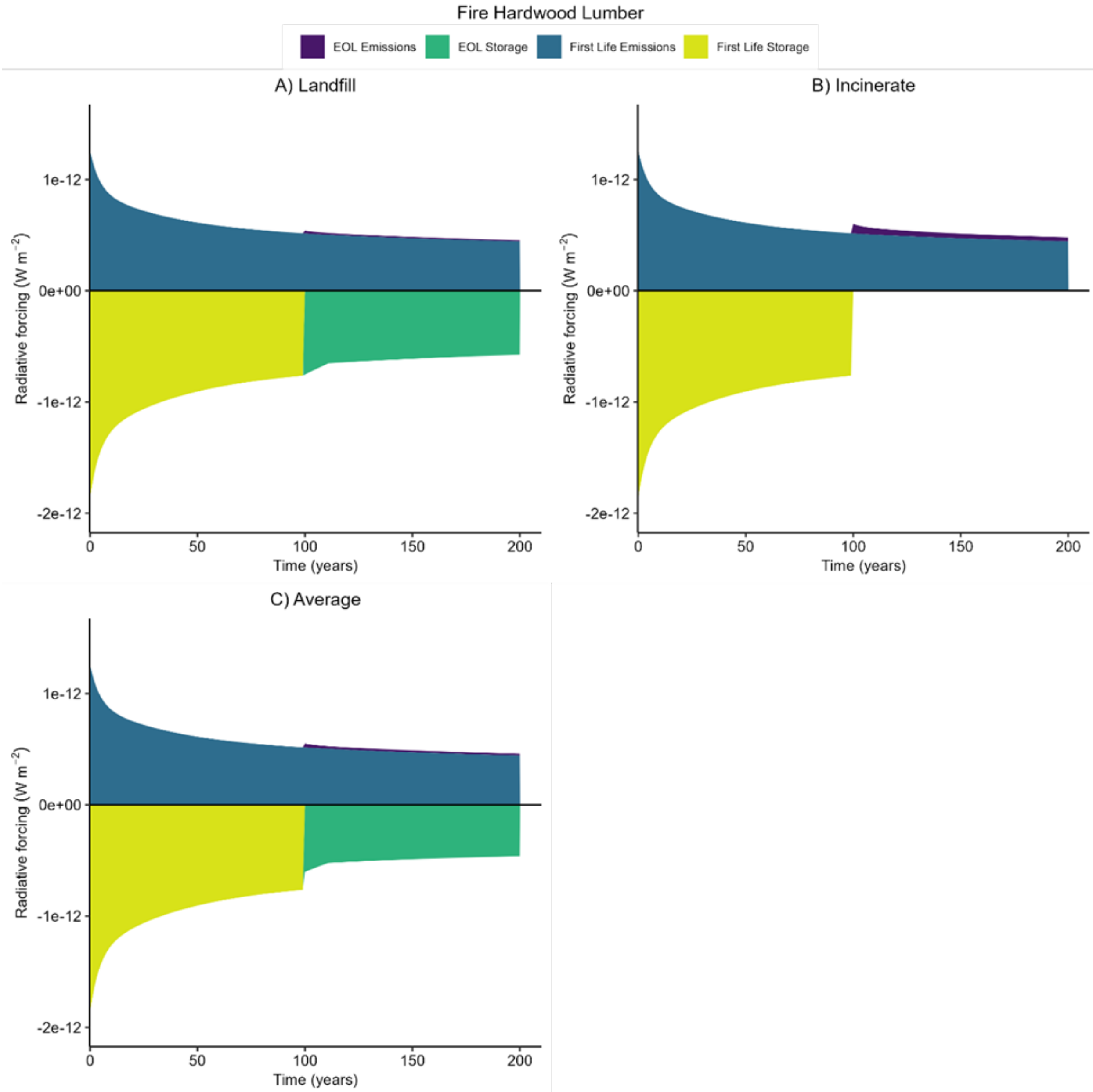

Figure 5.29. The atmospheric decay of carbon dioxide and the carbon storage benefit at year 0 to year 200 for hardwood lumber for the Climate-adapted plus fire management scenario for three EoL of scenarios. (A) Landfill, (B) Incineration, and (C) Average.

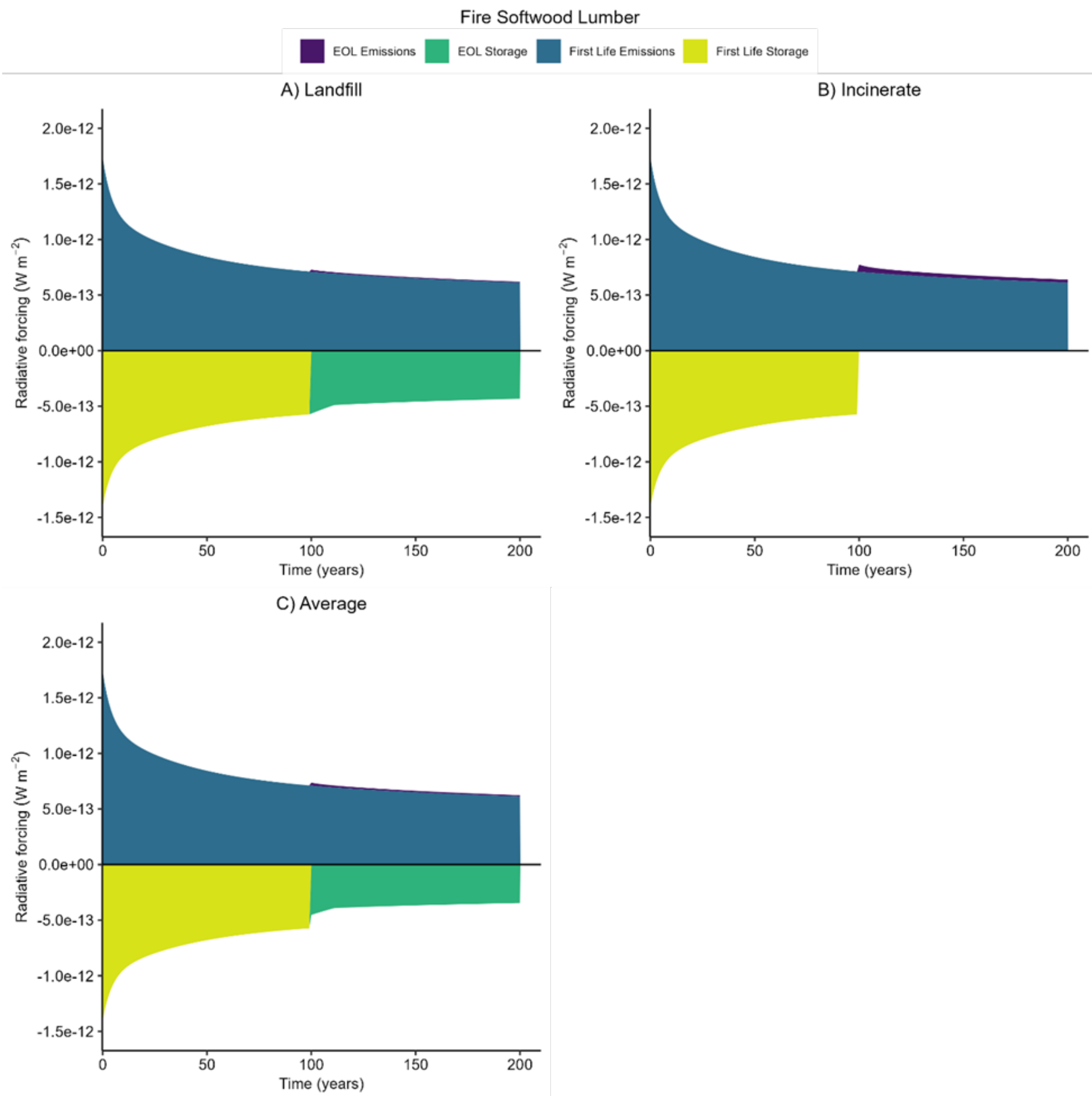

Figure 5.30. The atmospheric decay of carbon dioxide and the carbon storage benefit at year 0 to year 200 for softwood lumber for the Climate-adapted plus fire management scenario for three EoL of scenarios. (A) Landfill, (B) Incineration, and (C) Average.

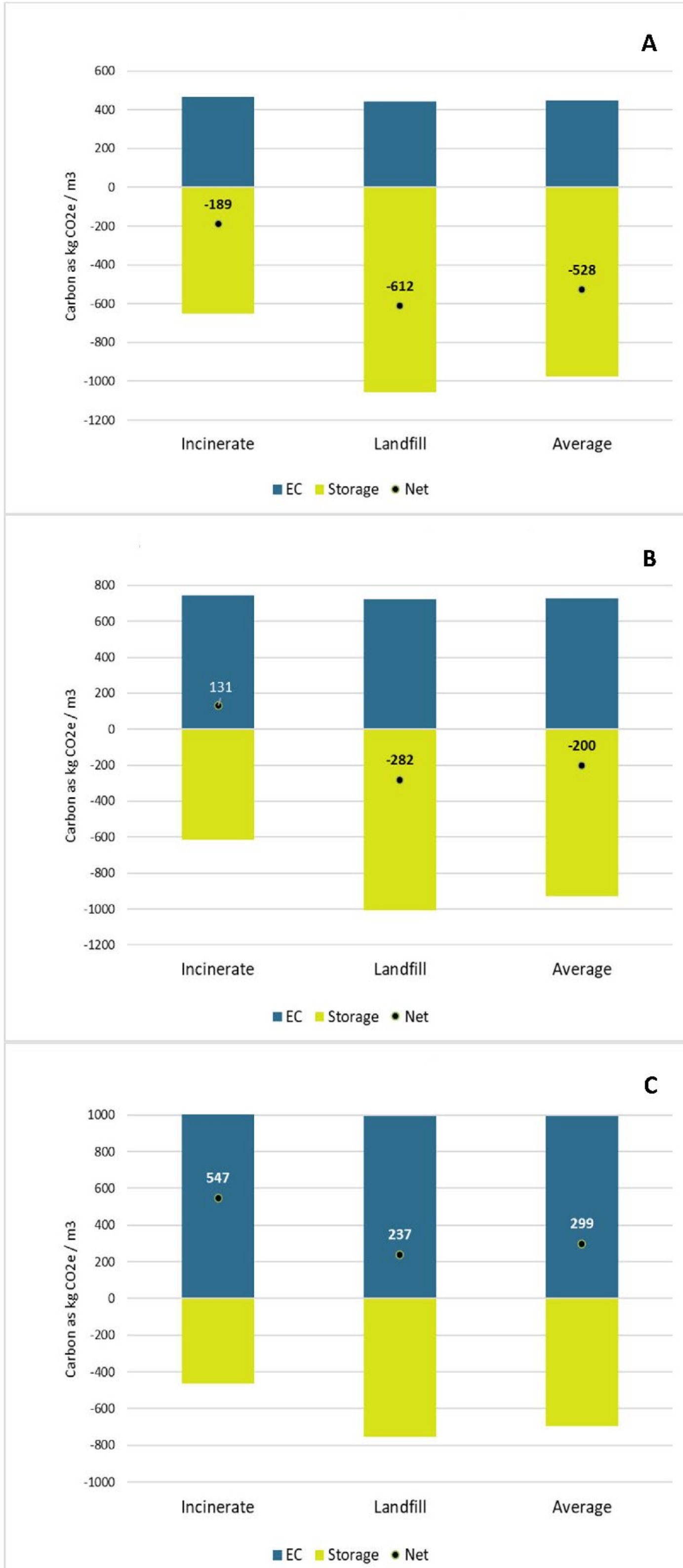

Figure 5.31. 200-year net impacts for cradle-to-grave (A1-C4) carbon accounting for 1 cubic meter of (A) oriented strandboard (OSB), (B) hardwood lumber, and (C) softwood lumber for the Climate-adapted plus fire management scenarios and EoL waste scenarios.

5.4.8 Substitution Impacts

Every product and use have a different carbon impact. Wood growth, harvest, and manufacturing generates less carbon emissions than most other non-biobased materials which usually emit substantially more fossil fuel emissions during production. These differences for functionally equivalent materials (e.g., steel stud vs wood stud) are what translates into climate benefits measured in carbon equivalents. They are reported as a substitution value or substitution pool. Wood is 50 percent carbon by dry weight. That carbon remains in the product for its lifetime. Combining the substitution factor with the carbon stored in wood products generates carbon displacement values as shown in Table 5.16 and Table 5.17 for wood versus steel studs and solid wood cabinet doors versus one made of medium density fiberboard, respectively. Table 5.16 includes the comparison of wood versus steel studs showing the embodied carbon of a wood stud is 1.32 kg CO_2-eq /m^2, while for the steel is 18 kg CO_2-eq /m^2.

Most wood products have a net carbon storage, the product stores more carbon than it releases during manufacturing (A1-A3), therefore the comparison between two wood products seldom indicates a preferable product (e.g., plywood versus OSB). Expansion of the system boundary such as including product transport, use, and end of life scenarios might alter differences. In this LCA, we compared two cabinet doors using hardwood lumber and medium density fiberboard (MDF) as the materials. The embodied carbon for hardwood lumber was 196 kg CO_2-eq/m^3 and 469 kg CO_2-eq/m^3 for MDF. When these values are converted to equivalent functional units, e.g., the quantity of material needed for a cabinet door, the solid hardwood door embodied carbon is 1.65 kg CO_2-eq /door, while the MDF door embodied carbon is 3.91 kg CO_2-eq/door (Table 5.17). The carbon content of a product has significance when comparing two materials has we saw in comparing a wood stud to a steel stud. In the case of a cabinet door, both materials store carbon. The MDF door actually stores more carbon than the hardwood door at 11.10 kg of CO_2-eq/door and the solid hardwood door stores 8.95 kg CO_2-eq/door. The difference between the embodied carbon and the carbon storage gives the net carbon stored or emitted of a product (Equation 5.1). As a result of Equations 5.1 and 5.2, the difference between two carbon containing materials is small.

Equation 5.1:

$$\textbf{Embodied carbon}\ (GWP_{FOSSIL}) - \textbf{Carbon stored in product} = \textbf{Net carbon storage}\ (-)\textbf{or emission}\ (+)$$

In the case of the wood stud versus a steel stud, the comparison is easy because the steel stud stores zero carbon. The result is a net carbon storage for the wood stud and a net emission for the steel stud (Table 5.16). Table 5.17 has both the solid hardwood and the MDF cabinet doors with a very similar net carbon storage (7.30 and 7.19 kg CO_2-eq/door for hardwood and MDF, respectively). The reason for the very similar net values is in the carbon storage of the product. The MDF door contains more wood material per unit than the solid hardwood door therefore storing more carbon.

Substitution benefits have been expressed using many terms such as avoided emissions, displaced emissions, and displacement factor. Table 5.16, Table 5.17, Figure 5.32, and Figure 5.33 show carbon (as CO_2-eq/equivalent unit) displacement or avoided emission because a wood product was used over an alternative material. Again, this is obvious for a wood stud versus a steel stud, where 33 kg CO_2-eq/m^2 were *not emitted* into the atmosphere (Equation 5.2) when the wood product was used over the steel product. For this calculation, we consider the value in the net carbon storage of a wood product (difference in emission and storage) to the net carbon emission or storage of the alternative (Equation 5.3). In the examples in Figure 5.32, and Figure 5.33, we switch the signs to the avoided emissions show as positive benefit (net wood becomes positive, net steel is negative, the difference is a positive benefit).

Equation 5.2:

$$\boldsymbol{Carbon\ stored\ in\ product\ of\ the\ wood\ product - net\ emission\ of\ steel = Avoided\ emission}$$

Equation 5.3:

$$\boldsymbol{-15.38\ kg\ CO2eq. -17.97\ kg\ CO2eq = -33.35}$$

The avoided emission for using a solid hardwood door versus and MDF door is negligible (0.10 kg CO_2-eq/door), again emphasizing that it is uncommon to see a benefit of one wood product over the other.

Table 5.16. Substitution impacts for a wood stud versus a steel stud used in one square meter (m2) of wall area.

	Unit / m^3	**Value**
Product mass, softwood lumber	kg	434.00
Embodied carbon	kg CO_2-eq	63.08
Carbon storage	kg CO_2-eq	795.67
Net - carbon emissions	kg CO_2-eq	(728.69)
Substitution Wall Components	**m^2**	**1**
Softwood studs vs. Steel studs	**m^2**	**1**
	Unit / m^2	**Value**
Wood stud walls, mass	kg	9.11
Steel studs wall, mass	kg	4.15
Embodied carbon, wood wall	kg CO_2-eq	1.32
Embodied carbon, steel wall	kg CO_2-eq	17.97
Carbon storage, wood wall	kg CO_2-eq	(16.70)
Carbon storage, steel wall	kg CO_2-eq	-
Net carbon wood wall	kg CO_2-eq	(15.38)
Net carbon steel wall	kg CO_2-eq	17.97
Avoided emission by using wood wall over a steel wall	kg CO_2-eq	(33.35)

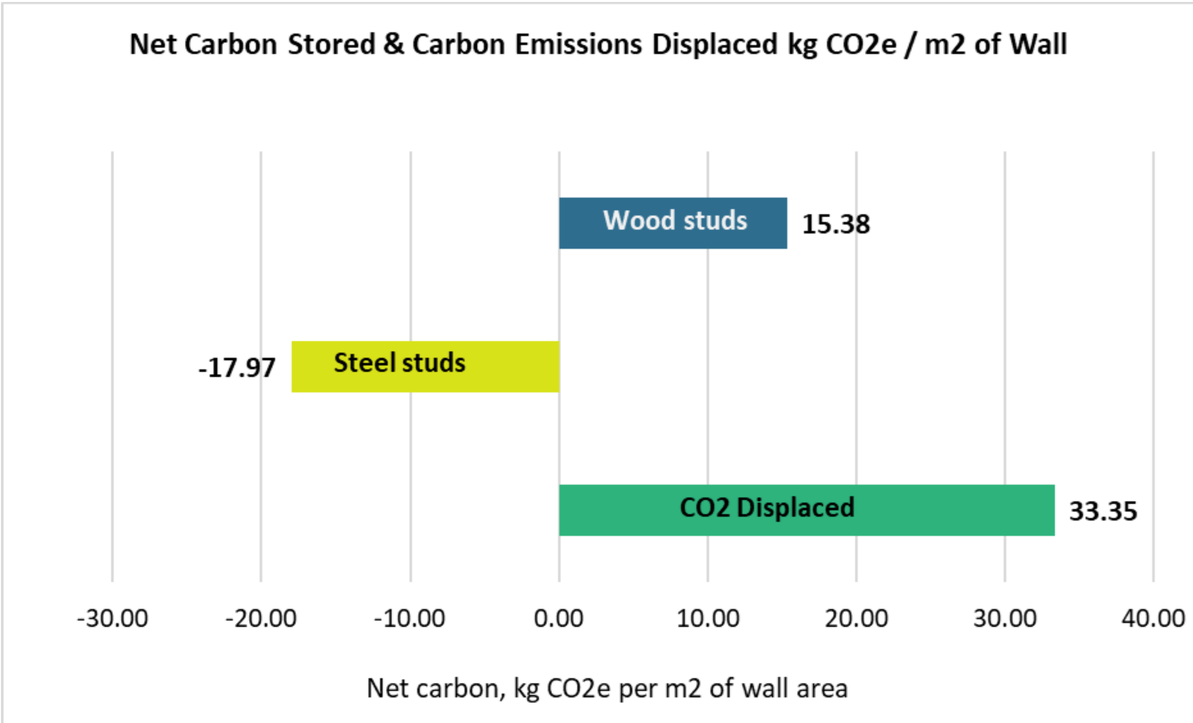

Figure 5.32. Comparison of the net carbon stored, emissions and carbon displaced for a wood stud versus a steel stud in one square meter of wall area.

Table 5.17. Substitution impacts for a solid hardwood cabinet door versus a medium density fiberboard (MDF) cabinet door.

Hardwood Lumber	**Unit / m^3**	**Value**
Product mass	kg	578.00
Embodied carbon	kg CO_2-eq	195.54
Carbon storage	kg CO_2-eq	1,059.67
Net - carbon emissions	kg CO_2-eq	(866.44)
Medium Density Fiberboard (MDF)	**Unit / m^3**	**Value**
Product mass	kg	727.01
Embodied carbon	kg CO_2-eq	469.36
Carbon storage	kg CO_2-eq	1,332.85
Net - carbon emissions	kg CO_2-eq	(863.49)
Substitution Cabinet Door		
Hardwood cabinet door vs MDF cabinet door	**Cabinet door**	**1**
Solid hardwood wood cabinet door(s)	**qty**	**1**
MDF wood cabinet door(s)	**qty**	**1**
	Unit per door	**Value**
Input material hardwood dried sanded	kg	4.88
Input material MDF finish, wood only	kg	6.06
Embodied carbon, hardwood	kg CO_2-eq	1.65
Embodied carbon, MDF	kg CO_2-eq	3.91
1 door Carbon storage, hardwood	kg CO_2-eq	8.95
1 door Carbon storage, MDF	kg CO_2-eq	11.10
Net - Carbon emissions hardwood	kg CO_2-eq	(7.30)
Net - Carbon emissions MDF	kg CO_2-eq	(7.19)
Avoided emission by using hardwood lumber over MDF	kg CO_2-eq	(0.11)

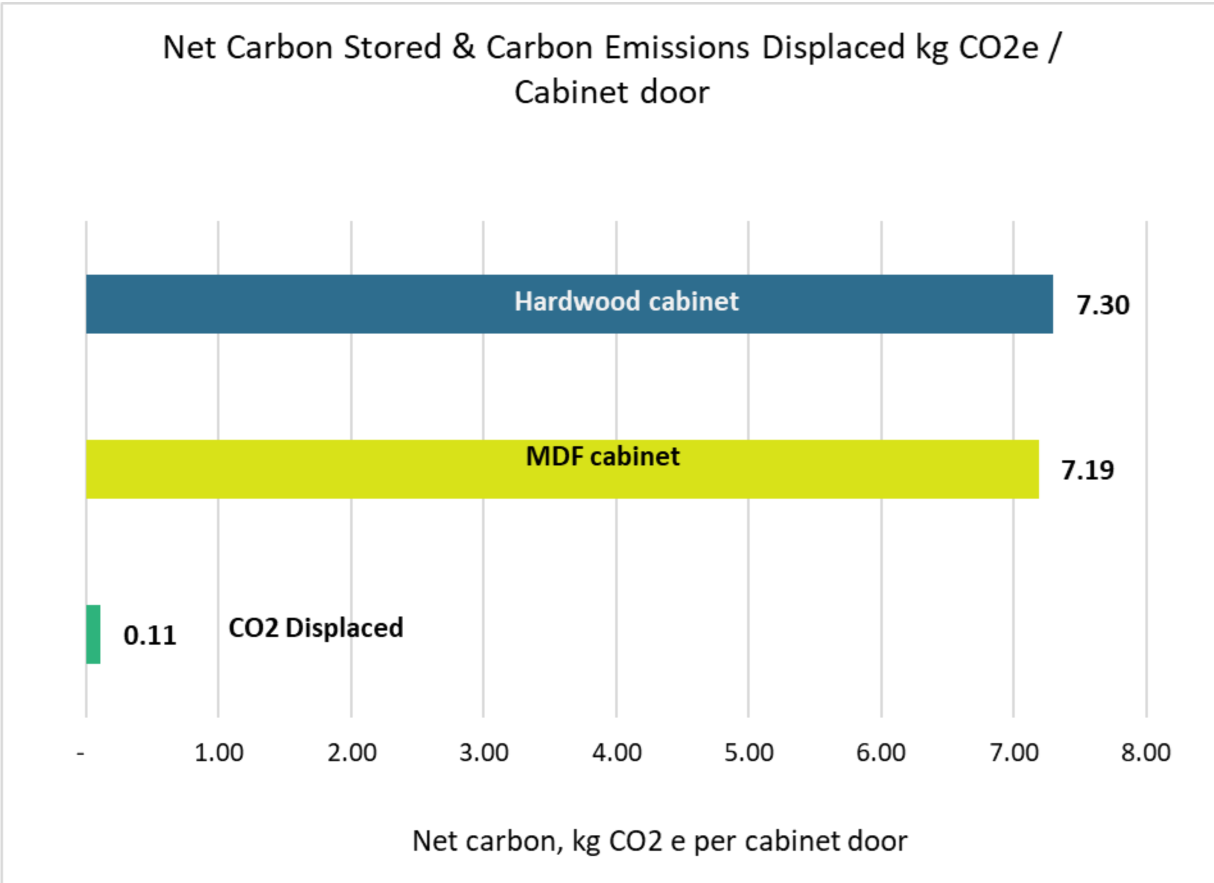

Figure 5.33. Comparison of the net carbon stored, emissions and carbon displaced for a solid hardwood cabinet door versus a medium density fiberboard cabinet door.

5.4.8.1 Case Study – Cotton-based vs. Viscose-based textiles

The life cycle of apparel products is complex that includes raw material extraction, fabric and cloth manufacturing, retailing, use, and disposal (Figure 5.34).

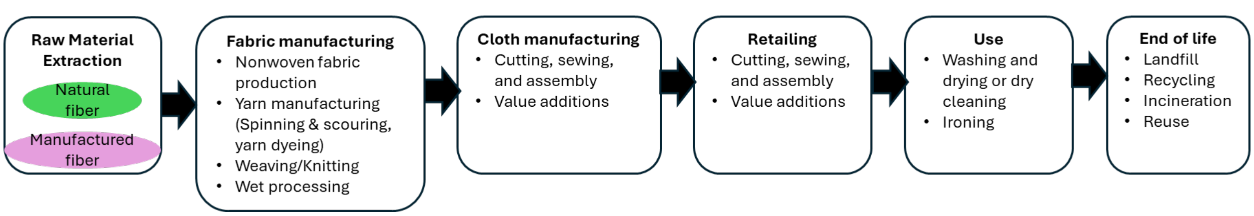

Figure 5.34. Cradle-to-grave life cycle of apparel products (Munasinghe et al. 2021)

Textile fibers can be categorized into natural and manufactured fibers. Cotton, flax, hemp, bamboo, wool, and silk are natural in origin. However, manufactured fibers include synthetic, regenerative cellulose (i.e., Viscose, lyocell, and modal), biobased fiber (polylactic acid-based), and recycled fibers. In this study, we developed a cradle-to-gate LCA model for viscose-based fiber production (Section 5.4.2). We also created an end-of-life viscose fiber LCA model, including landfill, recycling, and incineration.

Per request from the MFRC, we explored the difference between cotton-based textiles and viscose-based textiles. For the cotton-based textiles, we were only able to collect data on fiber manufacturing, cloth manufacturing, retailing, and textile from various literature sources (Chen et al., 2021; Henry et al., 2015; Khan and Shaker, 2023; Roy Choudhury, 2014; Strandberg, 2022). For the cradle to grave analysis, we assumed the same fate and carbon data as used in the viscose-based textile (Section 5.4.6) (Gonzalez et al., 2023; Shen and Kumar Patel 2010). Except for fiber production (cotton- and viscose-based fiber), the rest of the unit operations, such as yarn production, weaving, retailing, use, and end of life, were assumed to be the same.

The results for the comparative study are shown in Figures 5.35 for cradle-to-gate and Figure 5.36 for cradle-to-grave. Both cotton-based textiles and wood-based (viscose fiber) textiles have similar cradle-to-gate carbon footprints. Fiber production contributes only 5 percent of textiles' total cradle-to-grave carbon footprint. Yarn production and weaving contribute around 33-37 percent of the total cradle-to-grave carbon footprint. Around 50 percent of total impacts are contributed by the use of phase due to the high use of electricity for washing and ironing. The yarn production process required was very specific to cotton-based fiber.

Note: The literature did not provide details on the requirement of yarn production for viscose-based fiber. It is the opinion of the authors that the exclusion of this process for viscose-based textiles could have an improved cradle-to-grave carbon footprint over the cotton-based textile due to the likely significant variations in various unit operations and the actual life of the products between cotton- and viscose-based textiles. Figures 5.35 and 5.36 should be considered a preliminary comparison between these types of textile products where further research is needed to fully understand the carbon footprints over their entire lifecycle.

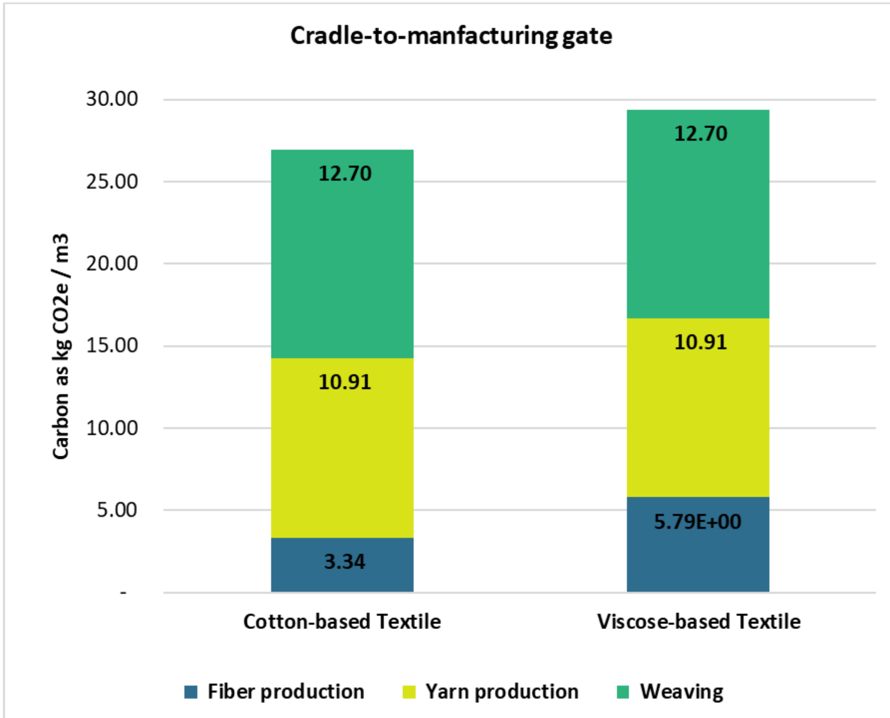

Figure 5.35. Cradle-to-gate (textile manufacturing) carbon footprint of textiles from cotton fiber and viscose fiber.

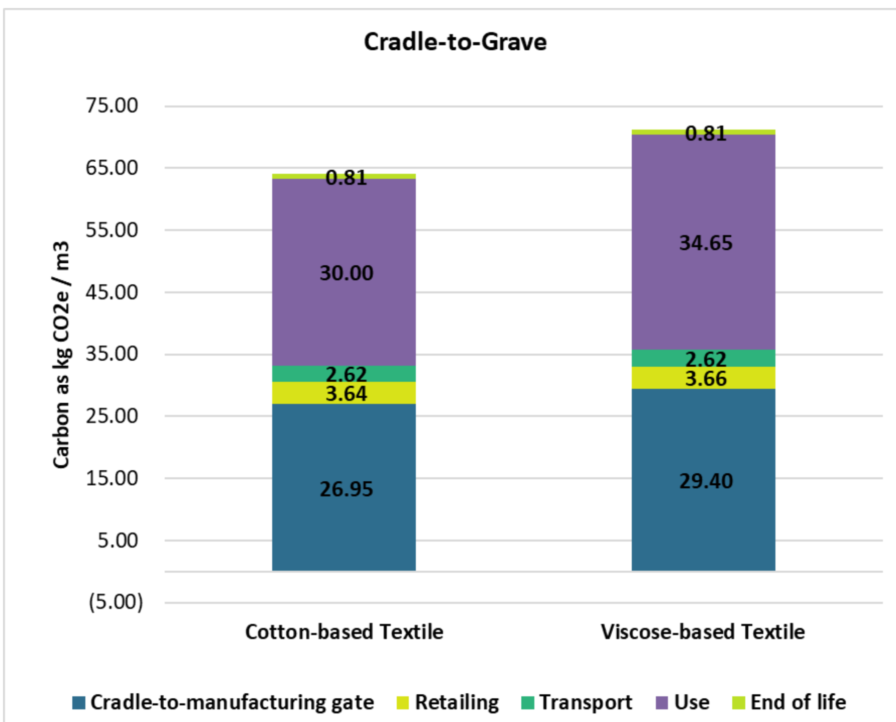

Figure 5.36. Cradle-to-grave (textile manufacturing) carbon footprint of textiles from cotton fiber and viscose fiber

5.4.8.2 Substitution Benefits of Using Wood

Because of lack of LCA data available on alternative products as well as the small number of products produced in Minnesota, the substitution analysis was limited to construction lumber and hardwood lumber. An alternative to OSB is plywood, but as shown in the comparison between MDF and hardwood lumber, whenever a wood product is compared to another wood product the substitution benefits are very small. This study, specifically to Minnesota products, did not fully capture all the substitution benefits of using wood over all possible alternatives because of available data. There is a plethora of information regarding the benefits of using wood over alternatives that can be made applicable to Minnesota and the climate benefits of using wood. In addition, the substitution analysis that was presented in the previous section only considered the BAU management scenario using an average allocation of forest types for each product. The analysis performed also does not include future substitution benefits of using wood products. It does however provide valuable insights into the potential carbon benefits of using wood and the possibility of increasing carbon emissions in the building sector if the use non wood products increased in construction practices.

In Figures 5.32-5.33, the climate benefits are measured in carbon benefits and are reported as substitution benefit or carbon displacement. Wood contains about 50 percent carbon and remains in the product for its lifetime. Service lives vary by product and have been reported from 25-100 years for wood products in general (https://www.nachi.org/life-expectancy.htm)(Hafezi et al. 2021, O'Connor 2004). Longer service lives can have a significant effect on delayed emission of carbon and as we saw in the dynamic carbon modeling (section 5.4.6), are important to carbon emissions calculations.

Previous work by Lippke et al. (2021) have shown that managing forests and harvesting wood for long lived wood products which can substitute for fossil intensive materials can have a significant carbon benefit. (Figure 5.37). Allocating embodied carbon, stored carbon, and substitution to a sustainably managed forest shows their relative contributions through time. Embodied carbon for growing and harvesting plus manufacturing emissions (grey bar) are permanent emissions that accumulate with each subsequent harvest . Through forest growth carbon storage in the forest increases between harvests (dark green). During harvest, some carbon remains in the forest with the remainder allocated to short-(yellow) and long-term (blue) products. Short-lived products decay before the next harvest (45 years later). If a 90-year service life is assumed for long-lived products can result in a constant wood product storage per hectare after the first 90 years. In Figure 5.37, substitution comes from using biofuels (orange) instead of fossil fuels and using wood studs instead of steel studs (light green) based on their embodied carbon relative to functional equivalents uses. Since fossil fuel carbon comes from fossil fuel reserves that will not be replenished in any meaningful time frame, permanence of substitution benefits and manufacturing emissions cannot be dismissed. Wood studs will eventually decay, returning some of their carbon to the atmosphere (here after 90 years), manufacturing emissions and substitution are permanent emissions and therefore accumulate at each harvest.

In summary, forests accumulate carbon in trees (sequestration). Harvesting trees transfers stored carbon from the forest to wood products. In a sustainably managed forest, this cycle can repeat itself in perpetuity. Substitution matters and provides permanent leverage for mitigating climate change. As we have seen in previous sections, how wood is used and how long it remains service are significant drivers in carbon emission calculations over time.

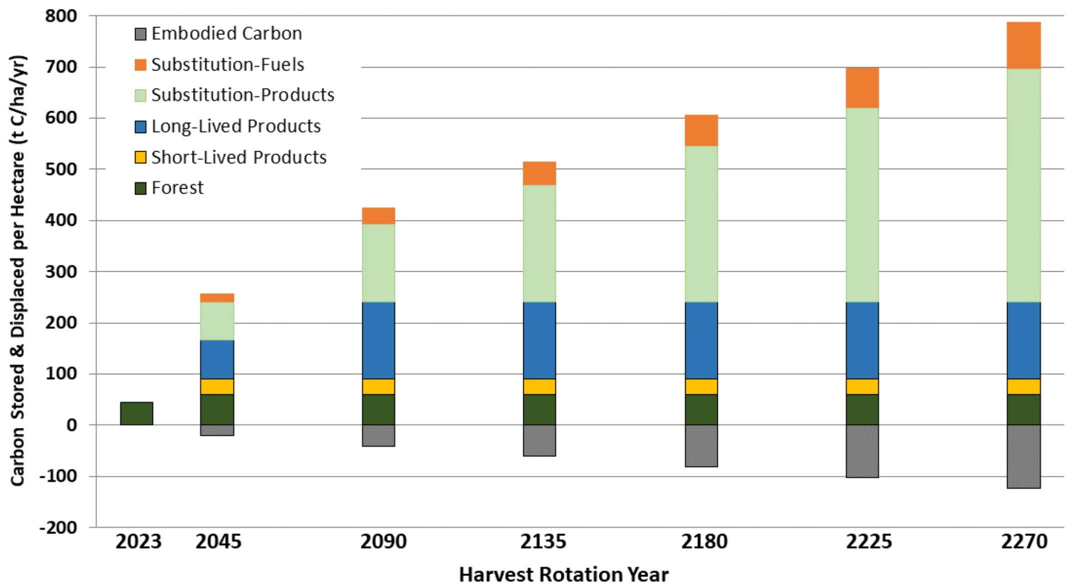

Figure 5.37. Carbon pools in a wall assembly – wood stud vs. steel stud.

6 SYNTHESIS OF RESULTS

A principal objective of this study was to develop a more complete baseline of information related to forest carbon and harvested wood products in Minnesota. Over the last 32 years (1990-2022), total carbon stocks associated with all forest biomass "pools" in Minnesota have increased from 4,150 million metric tonnes of CO_2-equivalent (MMT CO_2-eq) in 1990 to 4,506 MMT CO_2-eq in 2022, an increase of 8.6% (Figure 6.1). Across all component pools, the largest increase has occurred in the aboveground biomass pool, where carbon stocks have increased from 741 MMT CO_2-eq in 1990 to 974 MMT CO_2-eq in 2022, an increase of 31.5%. In relative terms, the largest percent increase in carbon stocks has been in dead wood pools (+37.0%). Carbon stocks have also increased in belowground biomass (+32.5%), litter (+2.6%), and mineral soil (+0.62%), with a slight decrease in organic soil (- 0.02%). In 2022, carbon stocks in belowground biomass represented 19.6% of the aboveground component. Carbon stocks in mineral and organic soil represented 63.6% of total forest ecosystem carbon in 2022 (Walters et al. 2023).

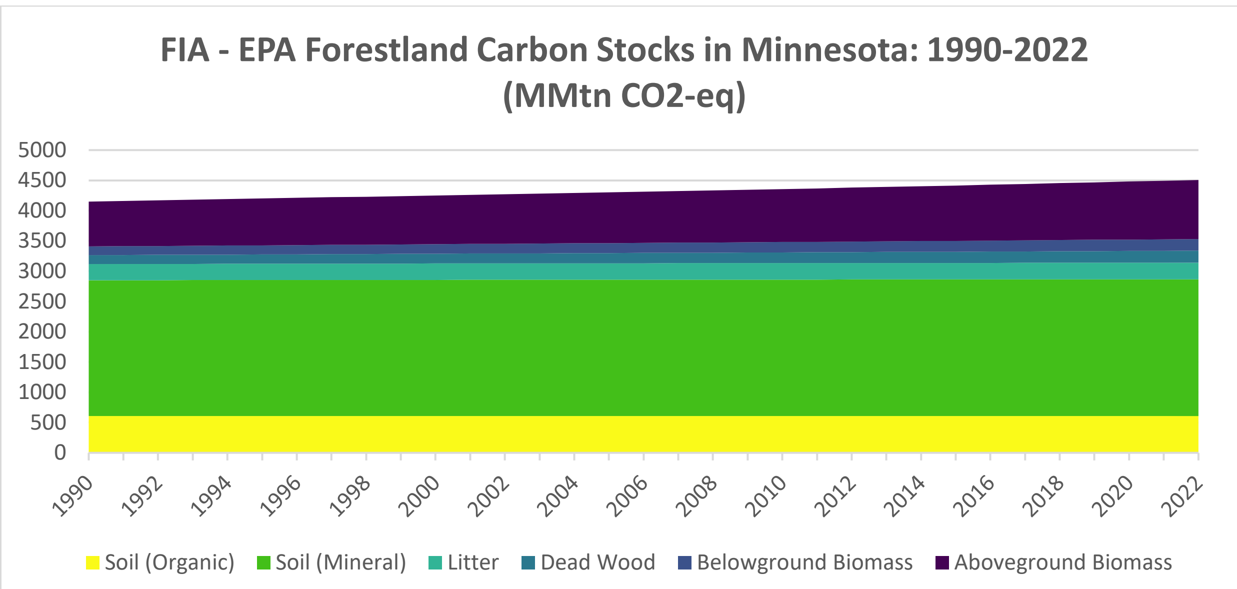

Figure 6.1. Carbon (MMT-CO_2-eq) is distributed across several storage pools in Minnesota's forests. FIA and EPA report the total carbon stocks in these pools on an annual basis from 1990-2022.

Additional analysis of historic timber product output from Minnesota's forests was conducted to better understand the relationship of harvested wood and in-service wood products with total storage and emissions for the forestry sector. Annual contributions of carbon to the (harvested wood products) HWP pool were tracked and can be displayed with annual storage in recycled and solid waste disposal site (SWDS) pools as well as end-of-life emissions (Figure 6.2). Tracking annual storage and emissions for all carbon pools also enables the display of cumulative carbon remaining in HWP in-service, recycled HWP, and SWDS storage along with total emissions over time (Figure 6.3). While cumulative HWP end-of-life emissions are substantial (~700 MMT CO_2-eq since 1821), remaining in-service HWP also stores approximately 100 MMT CO_2-eq as of 2020.

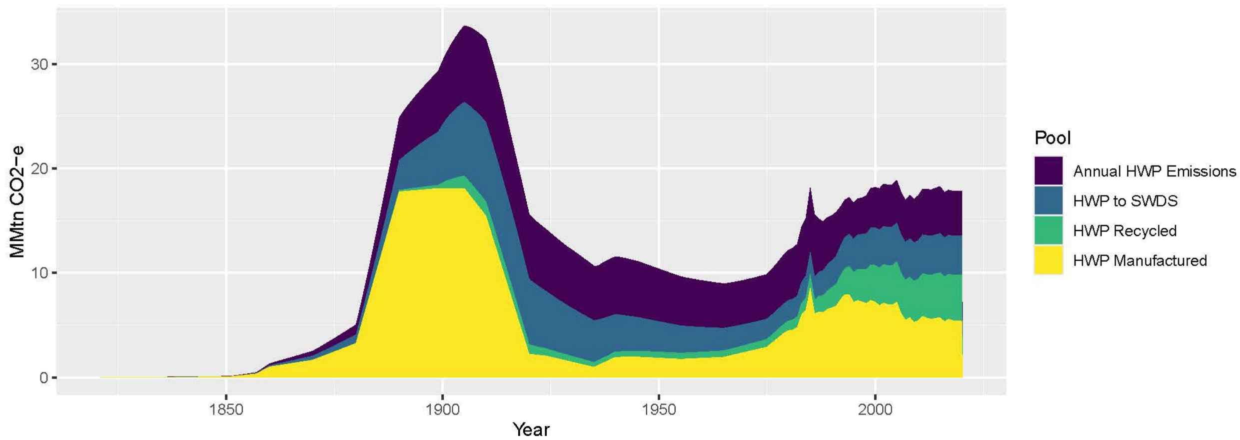

Figure 6.2. Annual harvested wood product production, emissions, and transfer to recycled and solid waste disposal site (SWDS) storage pools (1821-2020). Note: This figure does not include harvesting and manufacturing emissions.

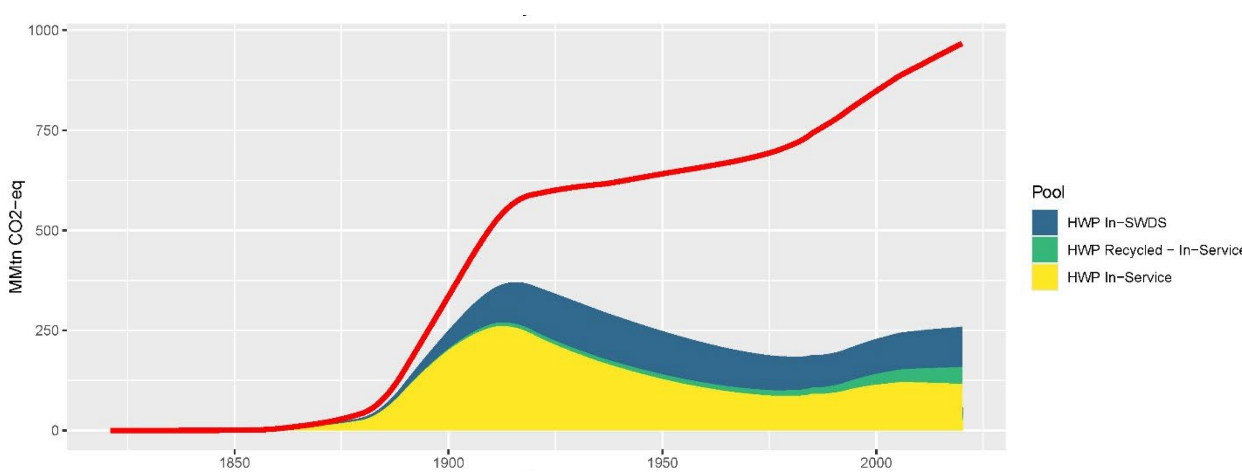

Figure 6.3. Cumulative harvested wood products produced (red line) in-service and stored in recycled products and solid waste disposal sites (1821-2020). Note: This figure depicts the carbon storage pool in which HWPs reside over time as well as storage levels within those pools.

This study also investigated the effect of four silvicultural scenarios (No management, Business as usual (BAU), Climate-adapted, Economic intensive) for all Minnesota forest types on forest sector carbon storage, sequestration, and emissions. Additional scenarios evaluated included prescribed burning for red pine and oak (Climate-adapted plus fire) and increased mortality due to emerald ash borer for black ash (BAU/Climate-adapted plus EAB). Simulations of forest stand development spanned 100 years, while life cycle assessments (LCAs) of harvested wood products covered up to 200 years. Considering the breadth of results from this study, we summarize the key findings and implications below.

Simulation results over 100 years show divergent trends when investigating carbon storage and carbon stock change across forest types and management scenarios across Minnesota. When interpreting modeling results from simulation experiments such as conducted here, it is essential to discuss carbon storage and sequestration as separate entities. It is the interplay between carbon sequestration and different storage pools existing at a landscape level that determines standing stocks and rates of change for the forest as a whole.

The statewide carbon storage estimates were expanded from average per acre carbon stores included in the above ground portions of live trees and in harvested wood products (HWP) (in-service or in a SWDS) (Figure 6.4). Average per acre carbon is calculated as the mean of the per acre values for live and removed trees simulated on FIA plots in FVS. This includes all forest types and conditions found on whole condition plots in the FIA database. Per acre carbon storage values projected over time were expanded to the full 15,799,295 acres of productive timberland in Minnesota to allow comparison of different broad management choices to the Business as usual scenario. This statewide expansion assumes the exclusion of non-productive and reserved forested acres. Initial FIA inventory estimates of in-forest carbon stores on timberland were adjusted with the addition of cumulative carbon stored in HWPs over time (Figure 6.4 black line), along with a decay factor assuming a 25-year average half-life for HWPs in-service or stored in SWDS. After the staggered initial projection period (2017-2023), the 100-year projections to 2123 were evaluated for key differences.

For all scenarios, in-forest and HWP carbon storage increases across the projection period, although at different rates due to differences in management paradigms (Figure 6.4). This increase in storage results at least in part from current harvest rates being approximately half of the maximum sustainable level (MN DNR 2024, GEIS 1994), resulting in continued carbon accumulation regardless of scenario. Other factors may include the lack of simulated large-scale disturbances and increased mortality due to changing climate conditions. The Business as usual scenario (dark blue line in Figure 6.4) depicts the result of average current management prescriptions and harvest levels simulated through time. This line serves as an important reference when comparing the carbon outcomes of alternative scenarios. The concept of additionality is always used with reference to the change nothing, or BAU, scenario.

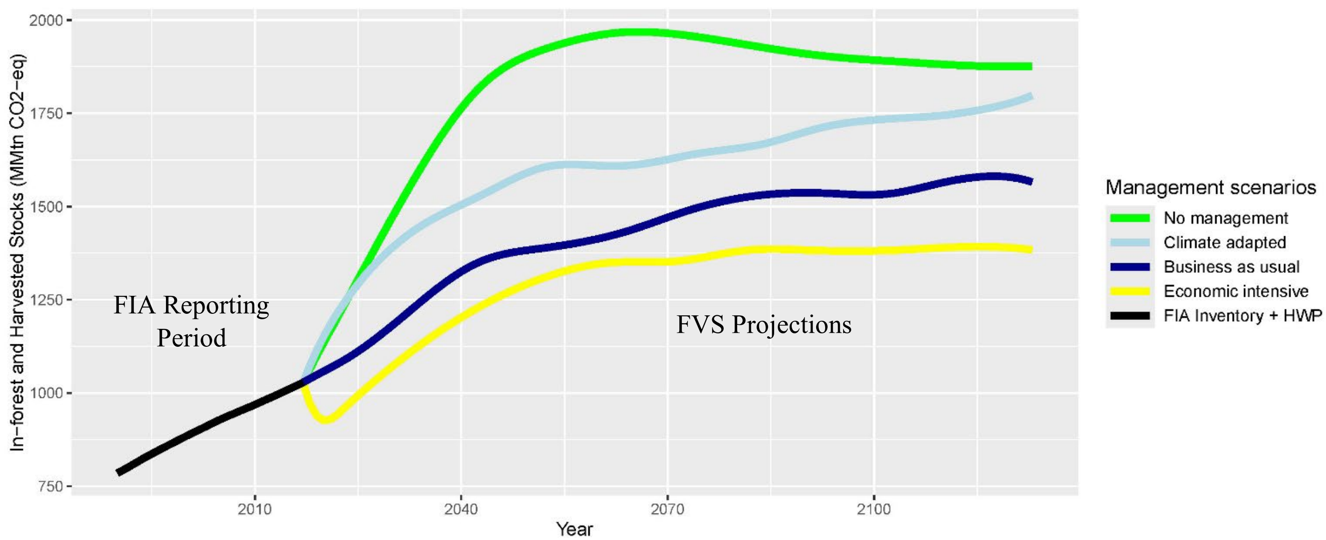

Figure 6.4. FIA inventory and cumulative harvested wood products (HWPs; 1990-2017) are depicted by the black line. FVS projected (2017-2021 to 2123) HWPs and in-forest above ground carbon stocks (MMT CO2-eq) under the four management scenarios illustrate the effect of management on carbon storage. The highest carbon storage is found under the No management scenario (green). The Business as usual scenario (dark blue) maintains its rate of stock growth (in-forest + stored HWP) over time, but removals lower in-forest stocks while recycling and SWDS storage tend to hold stocks for a longer period. The Climate-adapted (light blue) scenario resulted in increased in-forest stocks over time. Economic intensive (yellow) resulted in the lowest in-forest stocks over time due to increased removals. Note: This figure does include carbon stored in in-service HWPs and SWDS.

The Economic intensive scenario (yellow line in Figure 6.4), defined broadly by a shortening of the rotation interval while managing the same total acres over time, shows lower total carbon storage than the other management scenarios, a trend that appears early in the simulation and continues until its end in 2123. This likely results from less carbon being stored in the forest due to removals and the effect of embodied carbon during production of HWP, although overall carbon storage increased across the projection period.

The light blue Climate-adapted scenario depicted in Figure 6.4 shows expanded average per acre carbon stores included in the above ground portions of live trees and in HWP (in-service or in a SWDS) over time. Assumptions underlying this scenario include using a series of partial harvest entries at 20-year intervals (for most forest types) to increase resilience to changing climatic conditions. Although this scenario results in higher overall treatment rates, the many individual entries have smaller volume removals and thus store more carbon in live trees and timber products than either the BAU or Economic intensive scenarios. However, the multiple entries may present additional challenges to landowners and loggers trying to balance the cost of management with revenues generated by the sale of timber.

The No management scenario (green line) in Figure 6.4 depicts the average above ground live carbon stored in trees between 2023 and 2123. This No management line can be considered an average trendline for expected growth of carbon stocks on un-managed stands in Minnesota, barring large changes in mortality or reproduction due to climate driven disturbance. Carbon quickly accumulates on the landscape in the absence of harvest through 2060, then begins to decline due to naturally increased mortality. While evaluating landscape scale risks associated with retaining large stocks of fuel in the forest is beyond the scope of this study, the risks of wildfire should be considered in a full evaluation of likely climate outcomes associated with forest management (or lack thereof). Here, we do explore the likely carbon outcomes of making the choice to reduce or eliminate management from Minnesota's forests by considering carbon outcomes related to choosing more carbon intensive alternatives than wood (e.g., steel or concrete) and the likelihood of harvest simply being shifted to another region to meet timber demand. These phenomena are known as substitution and leakage, respectively, and are explored further below.

Substitution impacts are expected to reduce net CO2 storage from the No management scenario. An example of this can be found in Figure 6.5 in which the green No management line has been adjusted according to the product substitution equation for steel vs. lumber (Equation 6.1). This substitution assumes that all lumber (11.45% of total HWP production) that would have been used in construction is replaced by steel beams.

Equation 6.1: Relative kg/kg substitution effect for embodied and stored carbon in lumber vs. steel construction materials. (Equation 5.3 is re-written here in terms of the substitution impact of using steel in place of 1 MT CO_2-eq contained in the harvested wood product.)

$$\boldsymbol{-1\ Mtn\ CO2eq. -1.17\ Mtn\ CO2eq = -2.17\ Mtn\ CO2eq\ per\ Mtn\ material\ substituted}$$

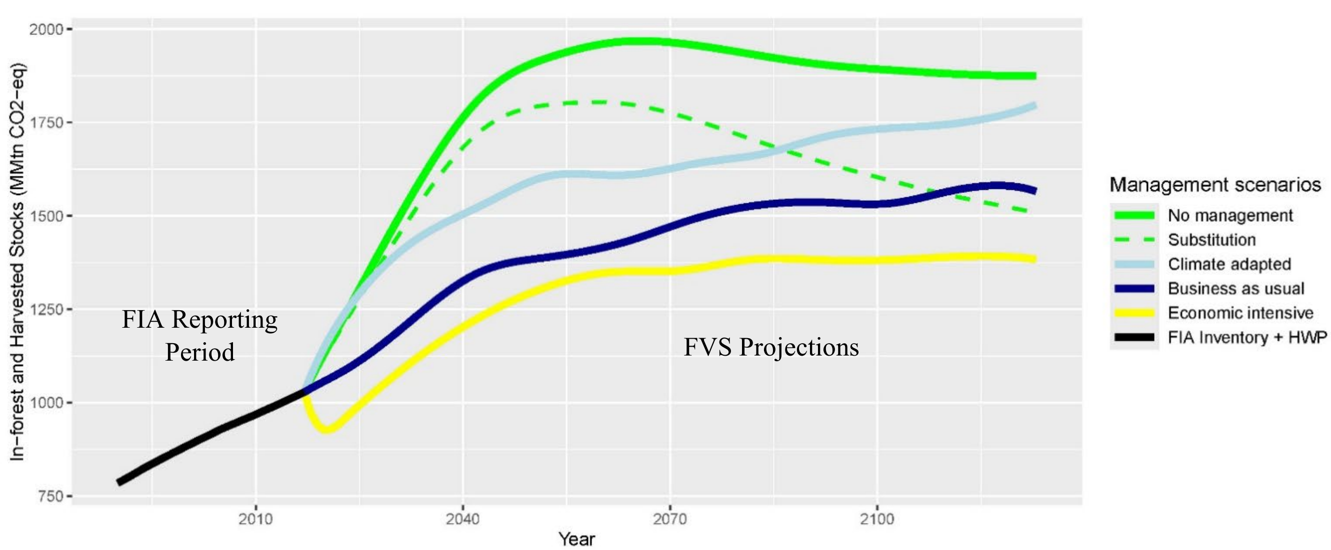

Figure 6.5. FVS projected (2017-2021 to 2123) HWP and in-forest above ground carbon stocks (MMT CO2-eq) under the four management scenarios illustrate the effect of management on carbon storage. In this figure, the No management scenario (green) has been adjusted to account for the relative substitution effect (dashed line) of using steel instead of lumber as produced by the BAU scenario. Note: This figure does include carbon stored in in-service HWPs and SWDS.

Timber harvest leakage can be assumed to reduce the expected benefits of avoided HWP production in the No management scenario over time. Leakage occurs when a reduction in timber harvesting in one region causes an increase in timber harvesting elsewhere to meet timber demand. True leakage rates for the Northeastern United States are often in excess of 80% of expected emissions reductions (Gan & McCarl 2007, Wear & Murray 2004, Nepal et al. 2013). However, harvest leakage and carbon leakage are not always comparable (Daigneault et al., 2023), as some harvest may shift to more productive forested acres in another region, thereby improving the efficiency of harvest and resulting in increased growth on highly productive acres outside of Minnesota. Assumptions related to leakage depend on forest type, rotation length (and nature of changes), assumed implementation rates (for No management), permanency of harvest reductions, and market response via product substitution and other factors. Nevertheless, it is likely that harvest leakage from a No management scenario in Minnesota would be in the 50-80+% range (Figure 6.6). The reduction in carbon storage is even more pronounced when combined with the substitution effect (Figure 6.7).

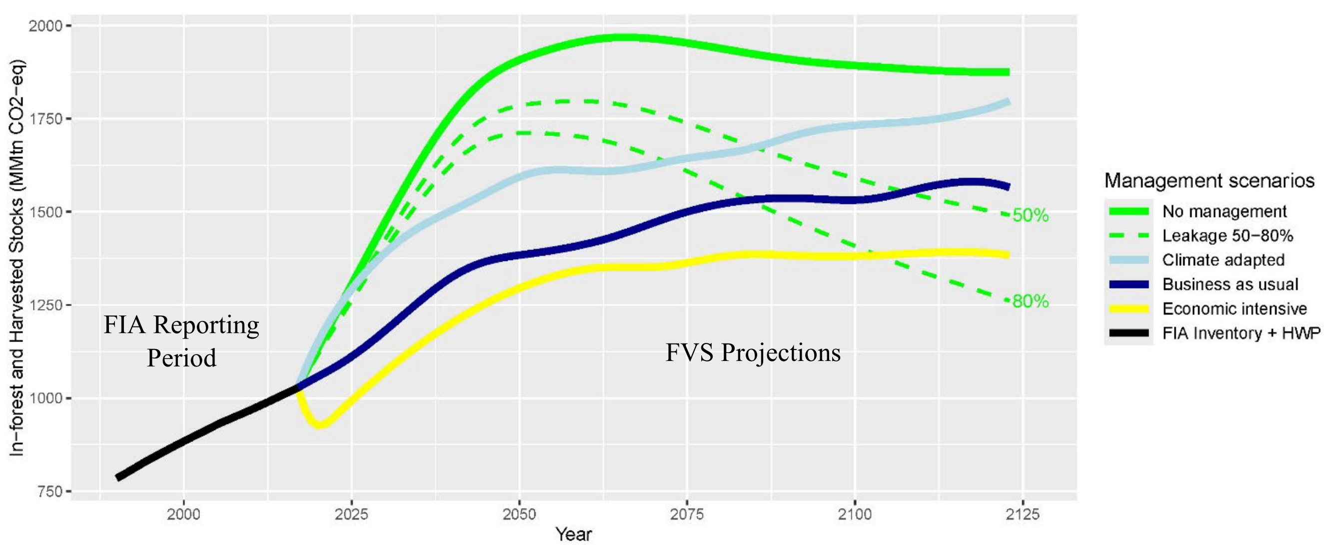

Figure 6.6. FVS projected (2017-2021 to 2123) HWP and in-forest above ground carbon stocks (MMT CO2-eq) under the four management scenarios illustrate the effect of management on carbon storage. In this figure, the No management scenario (green) has been adjusted to account for the effects of leakage (dashed lines). Leakage of overall BAU harvest is assumed to vary between 50% (upper dashed line) and 80% (lower dashed line). Note: This figure does include carbon stored in in-service HWPs and SWDS.

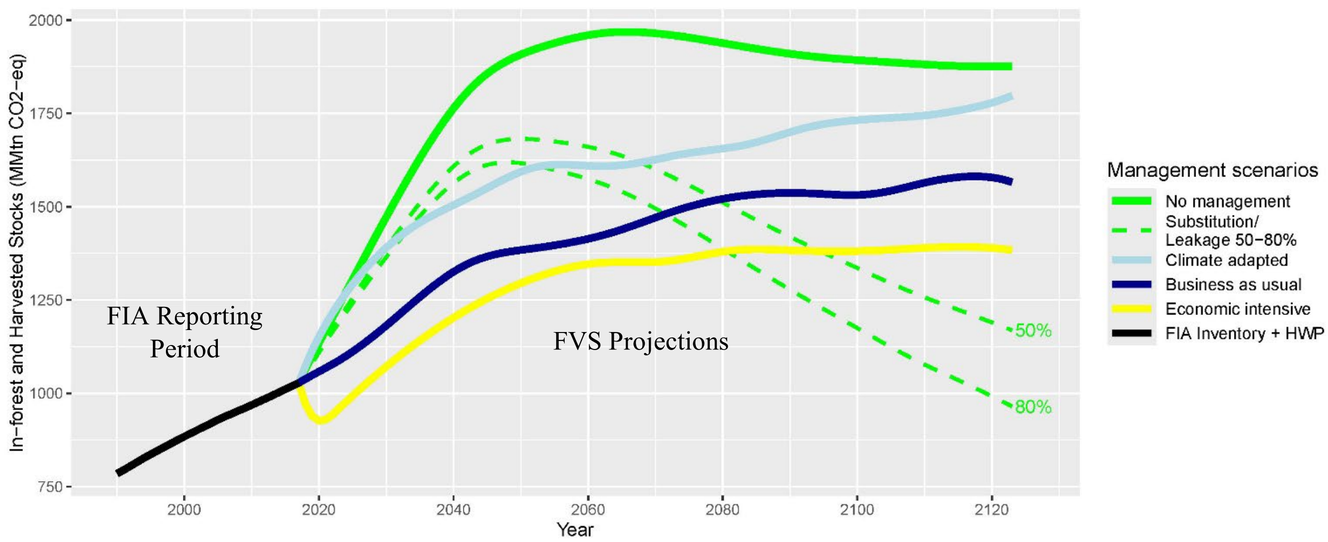

Figure 6.7. FVS projected (2017-2021 to 2123) HWP and in-forest above ground carbon stocks (MMT CO2-eq) under the four management scenarios illustrate the effect of management on carbon storage. In this figure, the No management scenario (green) has been adjusted to account for the effects of substitution and leakage (dashed lines). Leakage of overall BAU harvest is assumed to vary between 50% (upper dashed line) and 80% (lower dashed line), while steel use is substituted for lumber. Note: This figure does include carbon stored in in-service HWPs and SWDS.

To further illustrate how HWPs store and release carbon over time, the Business as usual FVS estimates of harvested wood were used to forecast likely storage and emissions for HWPs produced between 2023 and 2123 (Figure FVS BAU). These estimates were fused with the historic estimates described above to create a carbon timeline for HWPs from Minnesota's forests spanning 300 years (Figure 6.8).

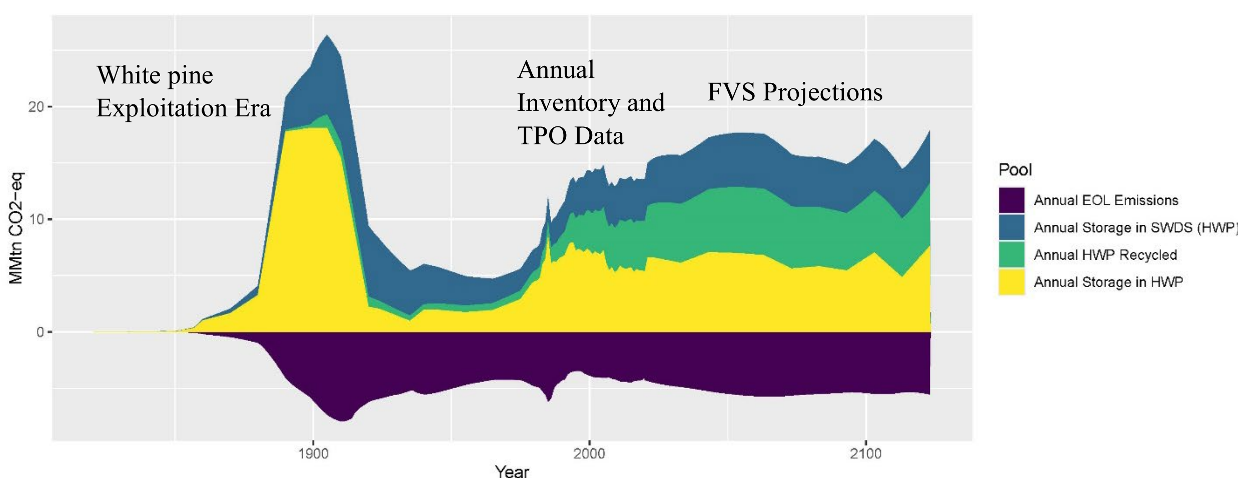

Figure 6.8. Historic harvested wood product production and carbon flow for Minnesota with projections for 2021-2123. Note: This figure does include HWP end-of-life (EOL) emissions, but does not include harvesting, transportation and manufacturing emissions as determined by the LCA component of this study.

Cumulative storage and emissions related to HWPs produced from Minnesota's forests are shown in Figure 6.9. Because current HWP production is nearly balanced by HWP end-of-life emissions and decay from service, the BAU scenario projects relatively level continued HWP storage in in-service products (~6 MMT CO_2-eq annually). The in-service HWP and recycled HWP storage pools continue to grow at a modest rate (~10 MMT CO_2-eq annually combined). Carbon storage in the secondary recycled HWP and SWDS pool is expected to continue increasing as a proportion of total storage.

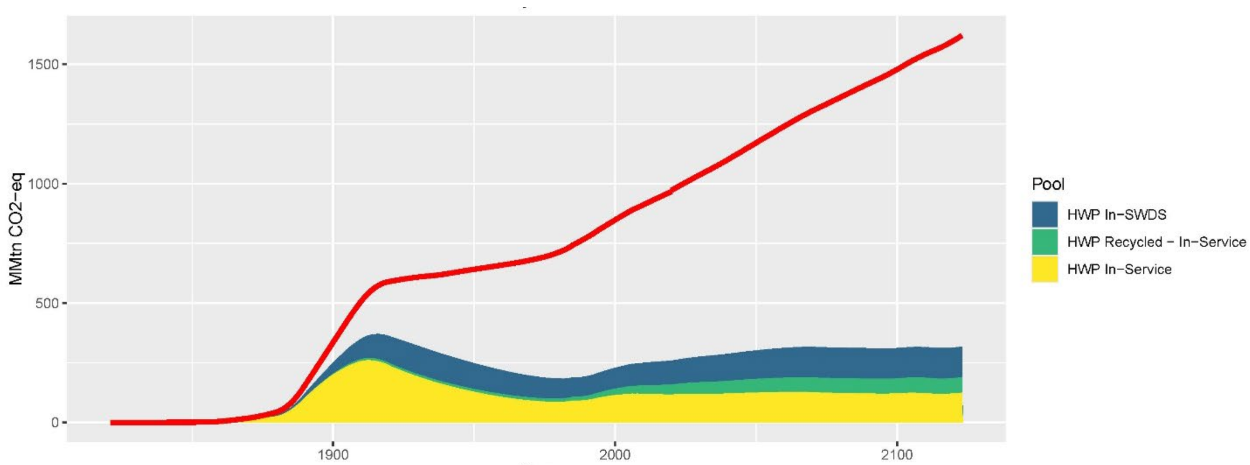

Figure 6.9. Estimated cumulative harvested wood products produced (red line), in-service (yellow), recycled (blue green), and in a SWDS (blue) with projections for 2021-2123 (BAU).

Because calibrated FVS projections were run under different management scenarios and paired with a full life-cycle-assessment, we can now integrate the historic and projected HWP information with our understanding of current in-forest carbon flux and processing and manufacturing emissions (Figure 6.10).

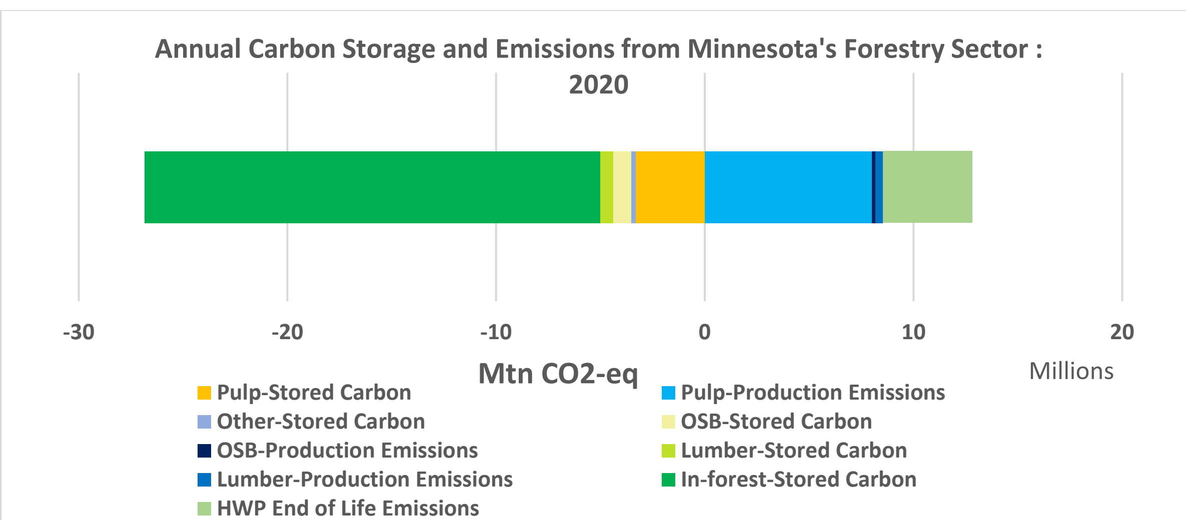

Figure 6.10. Expanded life cycle assessment emissions, end of life emissions, and harvested wood product and in-forest carbon storage for Minnesota (2020).

When compiled with EPA and USDA-FIA reporting on Minnesota's in-forest carbon flux for the 1990-2022 period, an estimate of the trend in total forestry sector carbon flux can be generated (Figure 6.11). When balanced by emissions related to forestry and HWP manufacturing and end of life, the net annual storage in Minnesota's forests is approximately 10.7 MMT CO_2-eq in 2022 (26.96 MMT CO_2-eq storage – 16.24 MMT CO_2-eq emissions = 10.7 MMT CO_2-eq net storage). HWP harvesting, transport, and manufacturing emissions, on average, exceed storage of carbon in those products. This outcome is largely related to the substantial energy and industrial chemical footprint associated with pulp production for kraft pulp and viscose fiber-based industries. However, it is important to acknowledge that current management levels (including harvest) support the overall health and vigor of the forest in Minnesota as it continues to strengthen as a carbon sink.

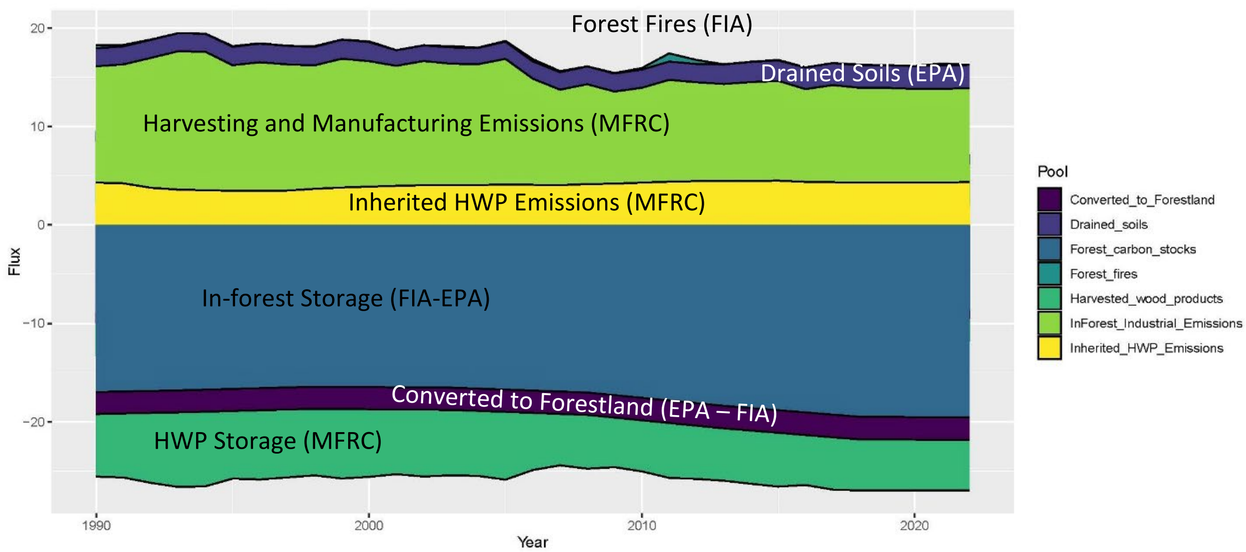

Figure 6.11. From 1990 to 2022, increasing in-forest carbon storage more than offset end of life and manufacturing emissions for Minnesota's harvested wood products. HWP storage and conversion to forested land use add to this effect.

As more wood fiber enters the pool of in-service HWPs each year, the annual end-of-life (EOL) calculation is based on an ever-growing quantity of carbon. This tends to increase annual EOL emissions to the extent that HWP production exceeds the rate of decay for in-service HWPs. Secondary storage of carbon in recycled and SWDS pools tends to further delay the eventual emission of carbon stored in those pools, especially for paper and other short-lived HWPs. This slow release of stored carbon can be seen in the graph of HWP emissions associated with the No management scenario (Figure 6.12). Cumulative total emissions continue to grow (height of the purple area in Figure 6.12), even if the harvesting and manufacturing of HWPs ceases.

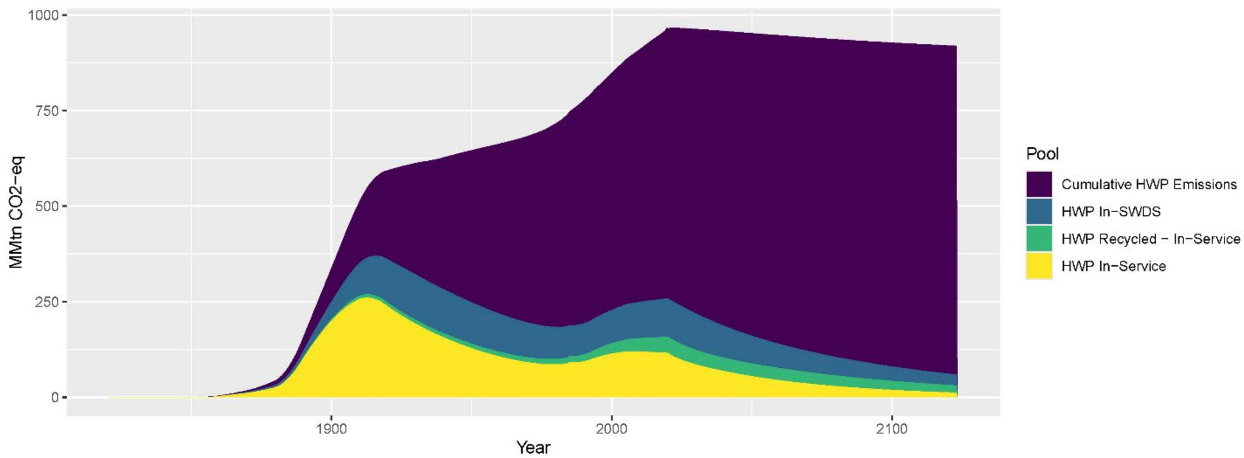

Figure 6.12. Historic cumulative harvested wood products in-service (yellow), recycled (blue-green), in a SWDS (blue), and emitted (dark purple) with projections for 2021-2123 (No management). For this non-managed forest scenario, HWP production drops to zero in 2023. Remaining stocks of in-service HWP slowly reach their end-of-life and are emitted through combustion or transitioned through the recycled and SWDS carbon storage pools prior to emission. Note the continued growth in the size of the purple cumulative emissions and that this figure does not include harvesting and manufacturing emissions.

Important differences in total emissions and in the rates of carbon storage in HWP, recycled HWP, and SWDS pools can be seen by comparing the cumulative outcomes of HWP production in the FVS management scenarios for Economic intensive and Climate-adapted projections (Figures 6.13 and 6.14, respectively) with the BAU (Figure 6.9) and No management (Figure 6.12) scenarios. Importantly, both the Economic intensive and Climate-adapted management scenarios resulted in increased HWP production, although through different harvesting regimes. Economic intensive management used clearcut with reserves combined with a shortened rotation length to increase the intensity of harvest on managed acres. Climate-adapted management used a larger number of more frequent entries with scattered removals to guide development of the forest towards greater resilience to changing climate conditions, resulting in increased carbon storage over time.

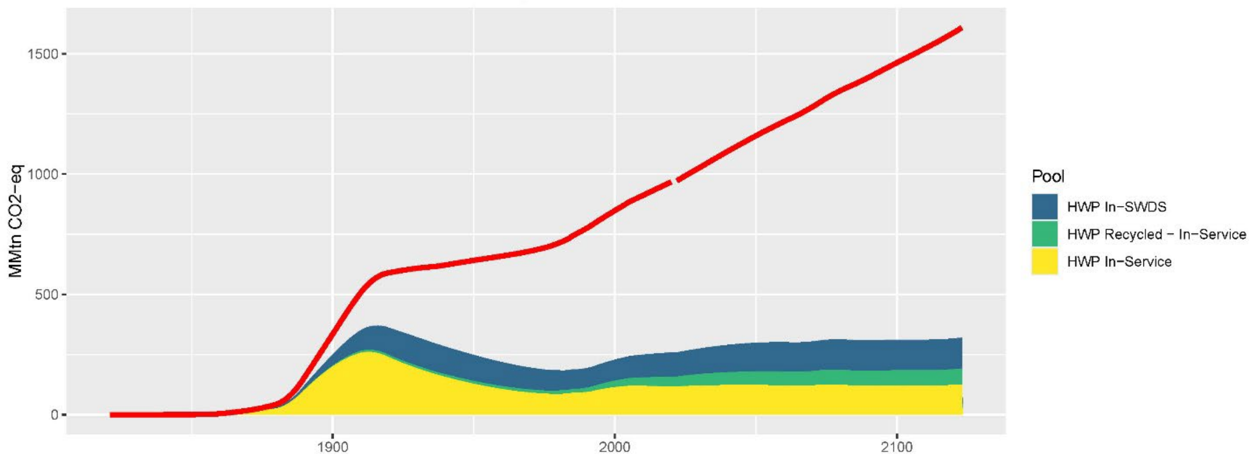

Figure 6.13. Historic cumulative harvested wood products produced (red line) in-service (yellow), recycled (blue-green), and in a SWDS (blue) with projections for 2021-2123 (Economic intensive). Note: This figure does not include harvesting and manufacturing emissions.

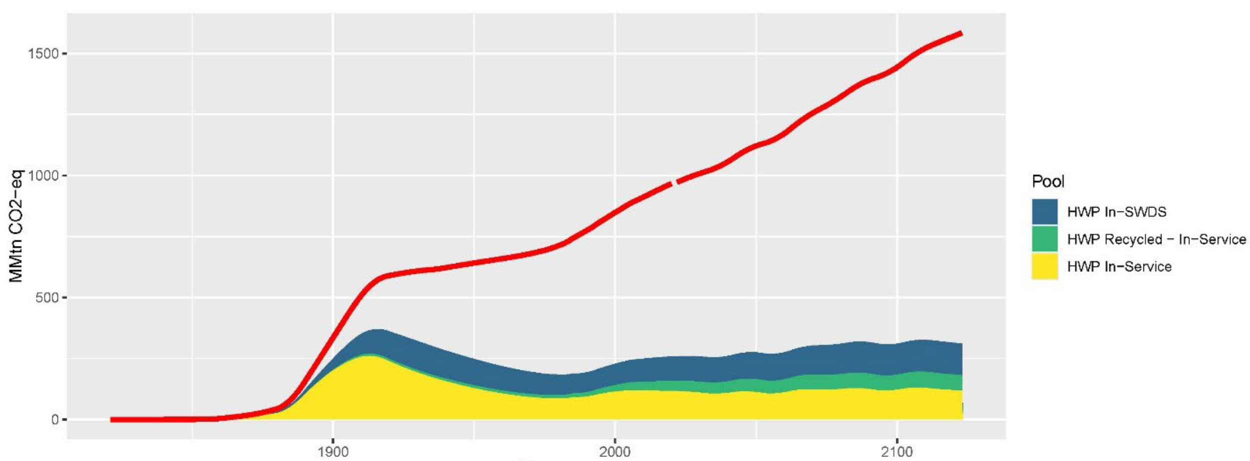

Figure 6.14. Cumulative harvested wood products produced (red line), in-service (yellow), recycled (blue green), and in a SWDS (blue) with projections for 2021-2123 (Climate-adapted). Note: This figure does not include harvesting and manufacturing emissions.

Average carbon stocks (including in-service HWP) in the Climate-adapted scenario become equivalent to non-managed stands after year 90 (Figure 6.15), likely because of additional regeneration stimulated by management in the Climate-adapted scenario and diminishing growth and increased mortality that impact non-managed stands. At 100 years, Climate-adapted scenarios resulted in the highest carbon stocks in aspen-birch and oak, likely a result of the extended rotation ages in the Climate-adapted scenarios in these forest types and the increased stand vigor resulting from management. It is also important to note that aspen-birch and oak forest types represent 7.6 million acres of Minnesota's forests (or 43% of the state's forestland), hence, these forest types impact overall trends at the state level (i.e., Figures 4.1 and 6.14).

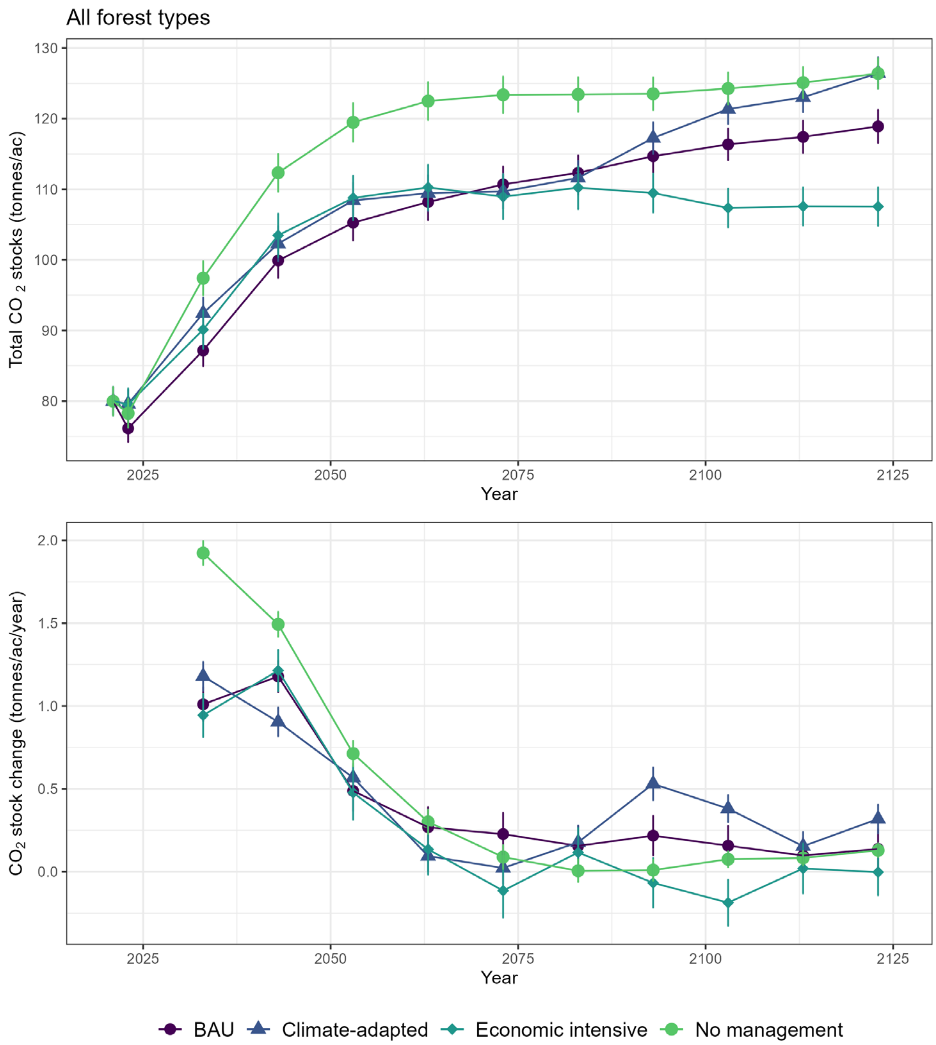

Figure 6.15. Mean forest carbon stocks and stock change (in forest and in harvested wood products) for all forest types across each of the four scenarios. Error bars show ± 2 standard errors. (Reproduction of Figure 4.1).

Even though the Climate-adapted scenario (without fire) had the highest carbon storage at the end of the simulation period, the LCA showed only 72% of Climate-adapted silvicultural actions were likely to generate sufficient volume to warrant economic recovery, contrasted by 87-88% of Economic intensive and BAU scenarios. Economic recovery refers to the likelihood that simulated harvest volume would be removed from the forest and sent into the product stream. Stands with very low merchantable harvest volume per acre (less than a load of logs/acre) were assumed to be uneconomic to recover. For Climate-adapted silvicultural entries, 46% of the entries resulted in almost no recoverable volume/acre (i.e. less than 1/5 load per acre were harvested), whereas only 28% of BAU entries had no commercial value. For EAB scenarios, merchantable volume was available 20% of the time (1 of 5 entries). In such cases the management intervention is treated the same as any other non-commercial entry which carries a carbon footprint but yields no merchantable harvest volume. The LCA showed that the highest predicted recovery volumes are in select scenarios of red pine, oak, and northern hardwood forest types. Higher overall volume is correlated with lower overall carbon footprint per metric ton as emissions are allocated over a larger harvest volume.

It is important to note that regardless of the scenario, more carbon is expected to be stored on a per-acre basis in 100 years compared to current amounts (Figure 6.15). This is likely due to both continued growth of the forest as more acres reach and exceed economic maturity and to the relatively longer rotation ages and low annual harvest rates across the state (Table 4.1). The rotation age and harvest rate within an individual forest type also has an impact on the amount of volume removed from a harvest, an influential value that impacts the LCA and its results. The Climate-adapted and Economic intensive scenarios generally had higher volume removals compared to BAU treatments which continue the trend of management and removals well below the sustainable level (See Table 9.10). More frequent, low volume harvests impact the distribution of volume available to sawlogs and pulpwood, which would influence the amount of carbon processed into different wood product classes that have various lifespans. These differences in annual wood volume converted into HWP have a direct effect on carbon storage and emissions over time. Even when considering embodied carbon associated with processing and manufacturing, storage of carbon in long-lived HWP has a net negative effect on current emissions, with a long tail of emissions stretching into the future. Consequently, it is important to consider both the inherited load of carbon stored in HWP currently in use, and the emissions from this inherited carbon when calculating net emissions. Net emissions must include forest growth, emissions identified from current HWP processing, carbon stored in annually produced HWP, and CO_2-eq emissions from inherited HWP. This study provides the means to incorporate these four pieces of information into a quantifiable unit characterizing net emissions for the forestry sector.

Silvicultural systems that employ selection cuttings have been shown as a silvicultural method that promotes greater carbon storage (Kern et al. 2021), particularly when compared to results from even-aged treatments such as silvicultural clearcutting (Puhlick et al. 2016). Carbon storage in forest types that use selection treatments, namely black ash and northern hardwoods, show carbon stocks that track similarly to other scenarios while also showing consistently high carbon stock change rates. Hardwood species planted as a part of several scenarios across all forest types often include ones that are naturally more carbon-dense, i.e. oaks, maples, basswood. The presence of these species could also play a role in explaining increased carbon stocks in scenarios that plant trees as a part of their forest management strategy.

The majority of flux in carbon stocks can be attributed to changes in the aboveground portion of live trees. Climate-adapted treatments that include a fire treatment results in some of the lowest carbon stocks, likely a result of fires reducing the survival of seedlings and the amount of carbon stored in the litter and duff pools in the forest floor (i.e., Figure 4.3). Multiple understory burns tended to significantly and negatively impact simulated carbon flux and the LCA results in both red pine and oak forests. Natural disturbances have a tremendous impact on the distribution of carbon stored in various pools, as evidenced by the emerald ash borer and its impacts simulated in the black ash forest type (Figure 4.17). Specific disturbances were not simulated in this analysis (other than EAB), and the calibrated mortality parameters were adjusted to include overall levels of disturbance related to mortality prevailing in recent years. Future work could provide greater realism associated with disturbance by applying species-specific mortality parameters at appropriate times and places across the landscape. These methods would more closely simulate both site-specific and landscape-scale impact to carbon stocks and sequestration immediately following disturbances, where large scale disturbances would turn forests into a carbon source rather than a sink for a period. While the No management scenario showed high carbon storage (and low sequestration) for some forest types, there is an extended time of assumed risk of such disturbance effects without storage in harvested wood products (HWP).

The Forest Vegetation Simulator (FVS) model was well-equipped to handle the diverse management scenarios outlined for this study, although it required extensive calibration to achieve realistic results. That is, FVS was able to handle complex forest management treatments like group selection harvests, irregular shelterwoods, and tree planting with different species and a range of densities. Simulated stands in FVS from Minnesota showed similar growth rates when compared to published estimates of carbon stock change rates in the northeastern US using Forest Inventory and Analysis (FIA) data. Across all scenarios, annual carbon stock change in simulated stands ranged from an average of 0.64 to 0.78 tonnes CO_2-eq/ac/year, while the stock change rate for all FIA plots in all Minnesota forests averaged 0.51 tonnes CO_2-eq/ac/year (Hoover and Smith (2023)). Reports from FIA also determined average stock change rates across the Northern Lake States to be between 1.67 and 0.61 tonnes CO_2-eq/ac/year in stands less than 20 years old and older than 121 years, respectively, which generally aligns with FVS simulations (e.g., Figure 4.1). These comparisons indicate lower carbon stock change rates in Minnesota compared to nearby states such as Michigan and Wisconsin. Stock change rates generally declined throughout the 100-year simulation period, a result of increasing stand age in non-managed stands where declining growth and increased mortality likely played a role. The mortality rates were calibrated (i.e., increased) within FVS simulations to account for decreasing growth and vigor in stands that were older than the expected rotation age for a forest type, so this also played a role in results that showed lower stock change through time. However, background regeneration was also added throughout the FVS simulations which helped to increase carbon stock change through the presence of young trees.

Carbon stock change in managed stands tended to be greater than non-managed stands in all forest types (Figure 4.2). Within managed stands, the Climate-adapted scenario showed the greatest average stock change rates. In combination with the results on storage, these findings indicate many Climate-adapted silvicultural treatments that include shelterwood and selection treatments have positive carbon benefits when considering both storage and stock change. Multi-aged management silvicultural systems that maintain or increase carbon stored in large mature trees while using thinning, selection cuttings, or shelterwoods to create gaps can promote the presence and abundance of small, young trees which can boost carbon sequestration rates (D’Amato et al. 2011; Nunnery and Keeton 2010, Kern et al. 2021).

From the LCA, there were little differences when comparing the management scenarios (except for Climate-adapted plus fire) in the cradle-to-gate system boundary. This is driven by the relative allocation of manufacturing versus forest management and transportation impacts: almost universally, manufacturing steps require more energy and materials than forestry activities, resulting in a larger contribution from manufacturing in each impact category. The red pine and northern hardwood forest types contributed to the smog impact indicator as a result of forest silvicultural activities, including frequent underburns coupled with frequent harvest entries (e.g., thinning every 20 years in all scenarios in these forest types). Transportation of the roundwood to facilities was also a significant contributor to the smog impact category.

For OSB and Lumber, in all forest management scenarios (except for Climate-adapted plus fire), the products store more carbon than is released into the atmosphere (Table 6.1, Figure 6.16). Similarly, net carbon emissions of paper and textile products are positive considering the carbon storage in the product at the end of life (Table 6.1). The contribution of the manufacturing life cycle stage is dominant for all products among all impact categories with the exception of smog. The cradle-to-gate environmental impacts of textile is much higher than paper (<1-6 times depending on the impact category). Similarly, the cradle-to-grave environmental impacts of textile is much higher than paper primarily due to more textiles ending up in landfills, lower recycling rates, and higher incineration rates than paper.

Substitution benefits between products is an advantage of managed scenarios versus the No management scenario. Product carbon storage and the embodied emissions to produce the product are both considered in the substitution benefit. The benefit of substituting between two different wood products was found to be insignificant. However, there was a significant amount of avoided emission by using wood over steel when comparing a wood stud versus a steel stud.

Table 6.1. Summary of cradle-to-grave for each product on a per kg basis for management scenarios BAU – Business as usual and Climate-adapted plus fire over all End-of-Life (EoL) scenarios over all forest types.

	Paper	**Textiles**	**OSB**	**Hardwood lumber**	**Softwood lumber**
	(GWP_{TOTAL}) Embodied Carbon kg CO_2-eq / kg of product				
	BAU – Business as usual				
A1-A3 - Cradle-to-product gate	1.7669	5.7870	0.4240	0.3383	0.1453
Carbon Storage	1.1733	1.5400	1.8333	1.8333	1.8333
Net Carbon	0.5725	4.2470	(1.4093)	(1.4950)	(1.6880)
Cradle-to-grave					
A1-C4 - Landfill	4.5627	5.1352	(0.8462)	(0.9140)	(1.1249)
A1-C4 - Incineration	1.7790	2.8855	0.5080	0.4223	0.2294
A1-C4 - Recycle	1.7535	2.8267			
A1-C4 - Average	2.9444	3.8571	(0.5997)	(0.6708)	(0.8784)
	Climate-adapted plus fire				
A1-A3 - Cradle-to-product gate	1.8703	6.0446	0.6725	1.2409	2.2752
Carbon Storage	1.1733	1.5400	1.8333	1.8333	1.8333
Net Carbon	0.6970	4.5046	(1.1608)	(0.5924)	0.4418
Cradle-to-grave					
A1-C4 - Landfill	4.6926	6.9745	(0.5977)	(0.0113)	1.0050
A1-C4 - Incineration	1.9089	6.2090	0.7565	1.3250	2.3592
A1-C4 - Recycle	1.8834	6.0576			
A1-C4 - Average	3.0743	6.6419	(0.3512)	0.2319	1.2514

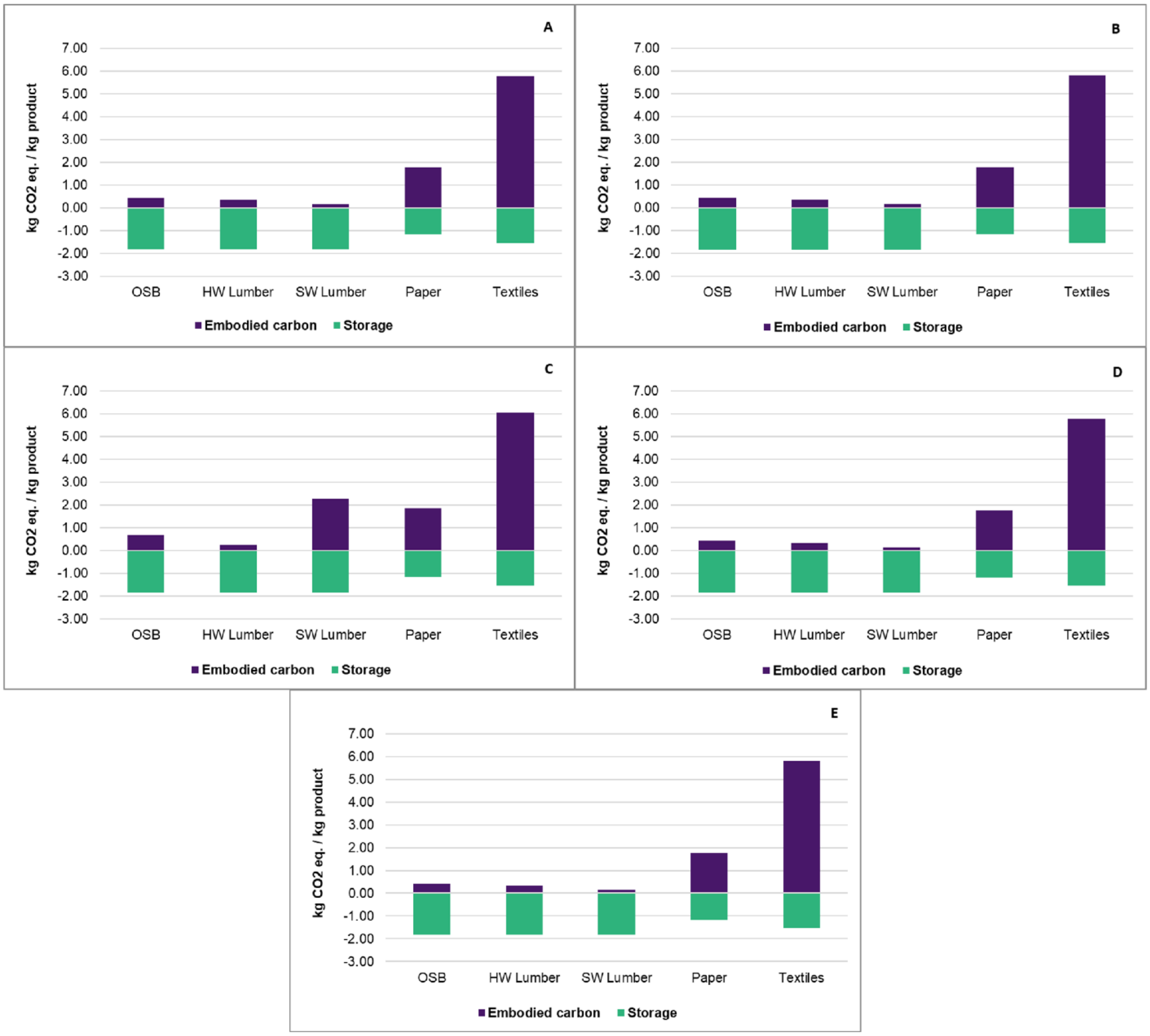

Figure 6.16. Summary of cradle-to-gate embodied carbon and carbon stored, in kg CO_2-eq/kg of product for each product and management scenarios over all forest types in (A) BAU, (B) Climate-adapted, (C) Climate-adapted plus fire, (D) BAU/Climate-adapted plus EAB, and (E) Economic intensive. Note that for the fire scenario, the results shown include all forest types, but prescribed fire was only applied to the red pine and oak forest types, while the others were managed under Climate-adapted prescriptions. For the EAB scenario, again the results shown include all forest types, but EAB mortality was only applied to the black ash forest type, while the others were managed under BAU prescriptions. BAU = Business as Usual, EAB = Emerald Ash Borer.

7 CONCLUSIONS AND TAKEAWAYS

In summary, these results indicate that forest management activities within Minnesota's diverse forest types contribute to long-term carbon storage both within forests and in harvested wood products. By combining forest dynamics in response to different forest management scenarios (i.e., forest simulations) with an assessment of the environmental impacts associated with them (i.e., the LCA analysis), this study reveals that regardless of forest management scenario, forest carbon stocks will continue to increase with few differences from a life cycle perspective. The quantification of the substitution benefit of harvested wood reveals an important consideration of the benefits of managed forests. This report quantifies the nuances of forest carbon outcomes from Minnesota forests that can be weighed with other management approaches that seek to balance the ecological, wildlife, and economic benefits forests provide.

In closing, several key takeaways from this study include the following:

1. Minnesota's forests are a carbon sink (i.e., they absorb more carbon dioxide from the atmosphere than they release) that offsets 15±3% of total statewide greenhouse gas emissions each year.
2. The amount of CO_2 sequestration and carbon storage that is occurring in MN forests and harvested wood products (Total Storage = 26.96 MMtn CO_2-eq per year) is very significant and exceed rates previously assumed for purposes of the Minnesota's Climate Action Framework.
3. Detailed calibration of the FVS model was needed to get accurate results.
4. Forest management activities within Minnesota's diverse forest types contribute to long-term carbon storage both within forests and in harvested wood products.
5. Differences in average growth rates resulting under various management scenarios contribute substantially differences in annual net carbon flux.
6. Regardless of forest management scenario, forest carbon stocks will continue to increase through 2050 with few emissions differences from a life cycle perspective.
7. Harvested wood and wood products emissions are more than offset by in-forest and HWP carbon storage (Net annual stock change = 10.7 MMtn CO_2-eq per year).
8. All forest management scenarios result in increased CO_2 sequestration and carbon storage over baseline conditions up to 2050 (+35% to 45% for AGB).
9. Long-term storage of sequestered carbon in harvested wood offsets carbon emissions associated with logging, hauling, and manufacturing of forest products and supports management for continued health and vigor (growth) of the forest.
10. Changes in net annual flux in above ground biomass pools account for most differences among scenarios.

11. In addition to maintaining health and vigor of the forest, management helps to reduce the risk of carbon stock loss to natural, and increasingly climate-driven, disturbances causing damage and mortality to trees, although this benefit was not modeled here.
12. Substitution of more carbon intensive materials for wood (i.e., steel beams instead of lumber used in structures) and leakage of deferred harvests to another region will dramatically reduce the perceived carbon benefits of the No management scenario over time. Beyond 2070, the managed scenarios including harvested wood products exceed the greenhouse gas benefits expected for No management.
13. After 2100, annual carbon sequestration and storage by Minnesota's forests slows (managed scenarios) or declines (unmanaged). Increasing total acreage of active forest management is needed to further increase carbon sequestration and storage beyond this period.
14. The quantification of the carbon storage and substitution benefit of harvested wood reveals that managed forests store slightly less carbon (due to removals) but accumulate carbon at a faster rate (increased growth).
15. Beyond 2050, annual CO_2 sequestration and carbon storage rates of the different management scenarios slow, stabilize or start to decrease. Lesser management resulted in a sharper decrease in storage rates over time.
16. The nuances of the forest carbon cycle can be evaluated in the context of the many and varied management approaches that seek to balance the climate, ecological, wildlife, social, and economic benefits forests provide; carbon is only one consideration.
17. The implications of large-scale disturbance and changing growth and mortality due to changing climate conditions should be considered when interpreting results, as these may significantly influence future forest conditions and trajectories.
18. The models and methodology developed for this project can be used or expanded to assess CO_2 storage and emission consequences of other forestry sector scenarios. Examples include:
    a. Increasing or reducing harvest intensity or acres managed.
    b. Expanding forest acreage by tree planting or reducing forest acreage through land conversion.
    c. Utilization of different carbon pools (e.g., harvesting logging slash).
    d. Producing different forest products (e.g., biofuel) that directly offset fossil carbon emissions.
    e. Assessing the risk of increased forest disturbance or increased wildfire risk conditions resulting from climate change.
    f. Comparing results associated with different types of land ownership (e.g., public vs. private).
    g. Comparing results associated with different forest regions (e.g., Northeast MN vs. Southeast MN).

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9 APPENDICES

9.1 ABBREVIATIONS

AP	Acidification Potential of Soil and Water Sources
BAU	Business as usual
CA	Climate-adapted
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
CO_2-$eq_{BIOMASS}$	Carbon dioxide emissions from biomass combustion or decay emissions
CO_2-eq_{FOSSIL}	Carbon dioxide emissions from fossil sources
CO_2-eq_{TOTAL}	Sum of $CO2e_{BIOMASS}$ and $CO2e_{FOSSIL}$
CED	Cumulative Energy Demand
CFCs	Chlorofluorocarbons
CFC-11	Trichlorofluoromethane
Econ	Economic intensive
EOL	End-of-Life
EP	Eutrophication Potential
EPD	Environmental Product Declaration
FIA	Forest Inventory and Analysis
FW	Consumption of Freshwater Resources
GWP	Global Warming Potential
GWP_{FOSSIL}	Global Warming Potential as an output from the TRACI impact methods. Does not include carbon dioxide released from biogenic sources, unit is $CO2e_{FOSSIL}$
$GWP_{BIOGENIC}$	Global Warming Potential released from the combustion of biogenic materials (e.g., wood) unit is CO_2-$eq_{BIOGENIC}$
HLRW	High-level Radioactive Waste, Conditioned, to Final Repository
HW	Hardwood
HWD	Hazardous waste disposed
HWP	Harvested wood product
ILLRW	Intermediate- and Low-Level Radioactive Waste, Conditioned, to Final Repository
ISO	International Organization for Standardization
kg	Kilogram
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
m^3	Cubic Meters
MC	Moisture Content
MJ	Megajoule
NCV	Net Caloric Value
MMT	million metric tons
MMtn	million metric tons
Mt	metric tons
NHWD	Non-Hazardous Waste Disposed

NRPRE	Non-Renewable Primary Energy Carrier Used as Energy
NRPRM	Non-Renewable Primary Energy Carrier Used as Material
O_3	Ozone
ODP	Depletion potential of the stratospheric ozone layer
OD	Oven dry
OSB	Oriented Strandboard
RPRE	Renewable Primary Energy Carrier Used as Energy
RPRM	Renewable Primary Energy Carrier Used as Material
SFP	Formation Potential of Tropospheric Ozone
SW	Softwood
SWDS	Solid waste disposal sites
Tkm	Metric-Tonne – Kilometers
Tonne	metric ton
TPO	Timber Product Output
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts

9.2 GLOSSARY

Aboveground biomass. All living biomass above the soil including stems, stumps, branches, bark, seeds, and foliage (Domke et al. 2023).

Allocation. Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems (14040:2006/Amd1:2020)

Belowground biomass. All living biomass of coarse living roots with diameters greater than 2 millimeters (Domke et al. 2023).

Biogenic carbon. Carbon derived from biomass ($CO_{2BIOGENIC}$) (ISO 21930:2017)

Biomass. Organic material, living or dead, such as trees, crops, grasses, tree litter, and roots (Russell et al. 2022).

Carbon flux. The measurement of change in forest carbon stock between two time periods. Also called "net carbon flux" (Minnesota DNR 2023).

Carbon pool. A part of a system that can store, accumulate, or release carbon. Five carbon pools are commonly used to describe forest carbon pools: aboveground biomass, belowground biomass, soil, litter, and dead wood (Domke et al. 2023).

Carbon sequestration. The process by which trees and other plants use carbon dioxide and photosynthesis to store carbon as plant biomass.

Carbon storage/stock. The amount of carbon in a tree or forest. Reflects a physical amount of carbon that is the result of sequestration.

CO_2-eq/Carbon dioxide equivalent/CO2 equivalent. Unit for comparing the radiative forcing of a greenhouse gas to that of carbon dioxide (ISO 14067)

Co-product. Any of two or more products coming from the same unit process or product system (ISO 14040:2006/Amd1:2020)

Cradle-to-gate. Covers the mandatory production stage that includes the following information modules: extraction and upstream production (raw material supply), transport to factory and manufacturing (ISO 21930:2017)

Declared unit. Quantity of a construction product for use as a reference unit in an EPD based on LCA, for the expression of environmental information needed in information modules. When the precise function of the product or scenarios at the construction works level is not stated, or is unknown, a declared unit may be used instead of the functional unit (ISO 21930:2017)

Embodied carbon. The global warming impact of all the greenhouse gas emissions through production of the product. Usually displayed in mass of CO_2 equivalents (e.g., kg CO_2-eq.)

Emission. Release of carbon into the atmosphere.

Global Warming Potential. Refers to a measure of how much a greenhouse gas contributes to global warming compared to carbon dioxide over a set period of time (e.g., 100 years). GWP allows comparison of the global warming impacts of different gases. Specifically, it is a measure of how much energy the emission of 1 ton of gas will absorb over a given period of time, relative to the emission of 1 ton of carbon dioxide (CO_2). In this report, GWP is referred to as CO_2-eq and embodied carbon.

Life cycle assessment (LCA). Compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle (14040:2006/Amd1:2020)

Life cycle inventory (LCI). Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle (14040:2006/Amd1:2020)

Life cycle impact assessment (LCIA). Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product (14040:2006/Amd1:2020)

Soil carbon. All organic material in soil to a depth of 1 meter but excluding the coarse roots of the belowground pools.

Substitution. The difference between functionally equivalent materials (e.g., steel stud vs wood stud) measured in carbon equivalents.

System boundary. A set of criteria that specifies which unit processes are part of a product system (ISO 14044/Amd1:2017/Amd2:2020)

9.3 FVS MORTALITY PARAMETERS

Table 9.1. Mortality parameters used in each forest type within FVS simulations, identified through a calibration exercise comparing FVS predictions with up to 18 years of FIA remeasurement data.[1]

Forest type	**Minimum stand age to apply mortality (rotation age; years)**	**Proportion of the tree record that will be killed**	**Smallest DBH to which mortality rate will be applied (inches**	**Largest DBH to which mortality rate will be applied (inches)**
Aspen/birch	50	0.20	5	999
Red pine	90	0.05	15	999
Upland spruce/fir	60	0.05	0	999
Oak	90	0.20	10	999
Northern hardwoods	85	0.20	10	999
Lowland conifers	75	0.05	5	999
Black ash	120	0.10	5	999
Other forest types	80	0.10	5	999

[1] In FVS, (1) defined proportion was added to the mortality rate calculated in the model and (2) mortality was concentrated by size, from largest- to smallest-sized trees.

9.4 FVS Regeneration Inputs

Figure 9.1. Average ingrowth (number of trees growing into 1.0-inch diameter class) applied to FVS models runs within each forest type according to stand age class and rotation age, identified using FIA data. See Table 4.1 for rotation age.

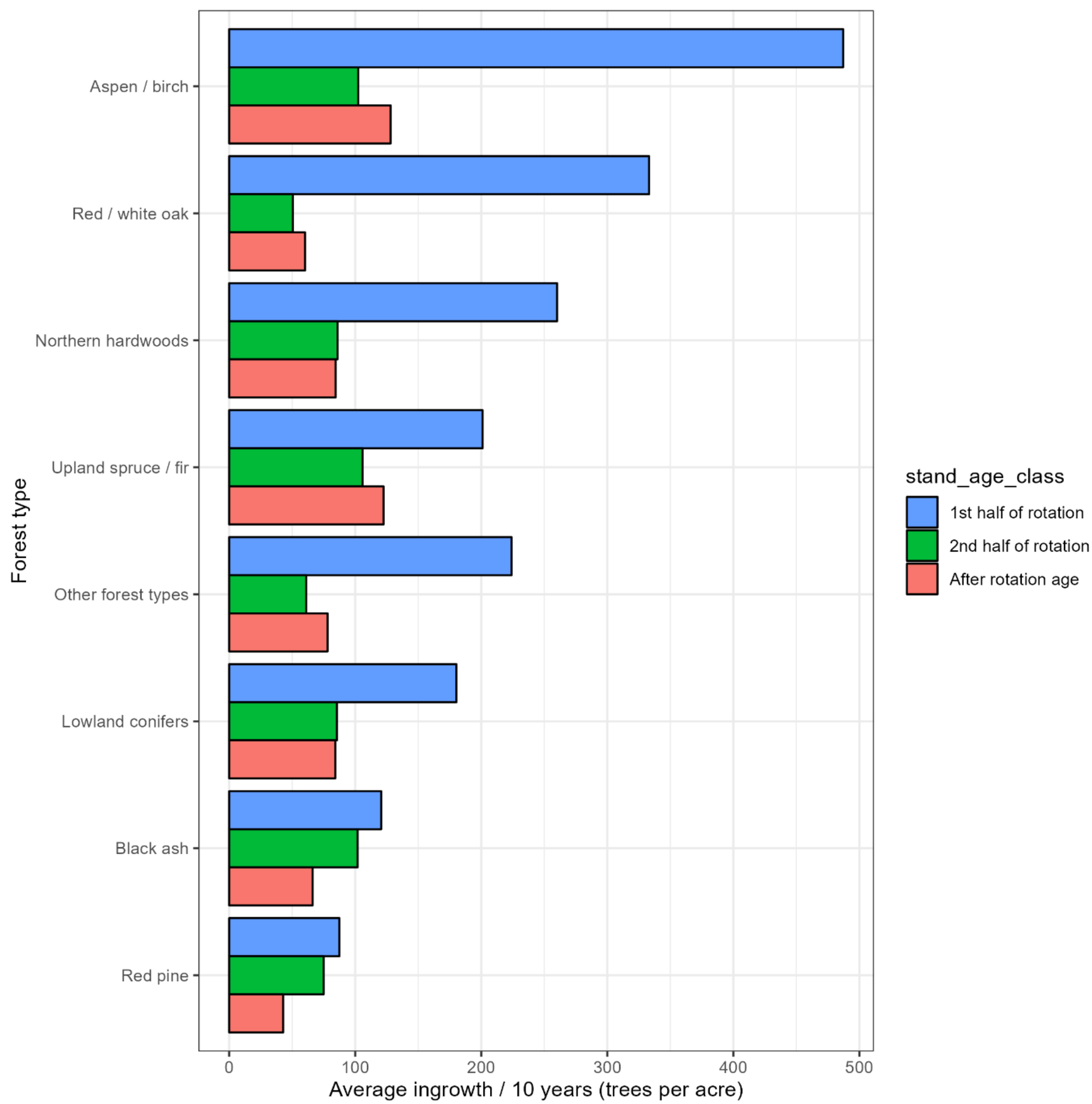

Figure 9.2. Average ingrowth (number of trees growing into 1.0-inch diameter class) applied to FVS models runs within each forest type according to stand age class. Species are the most common ones identified using FIA data. See Table 4.1 for rotation age.

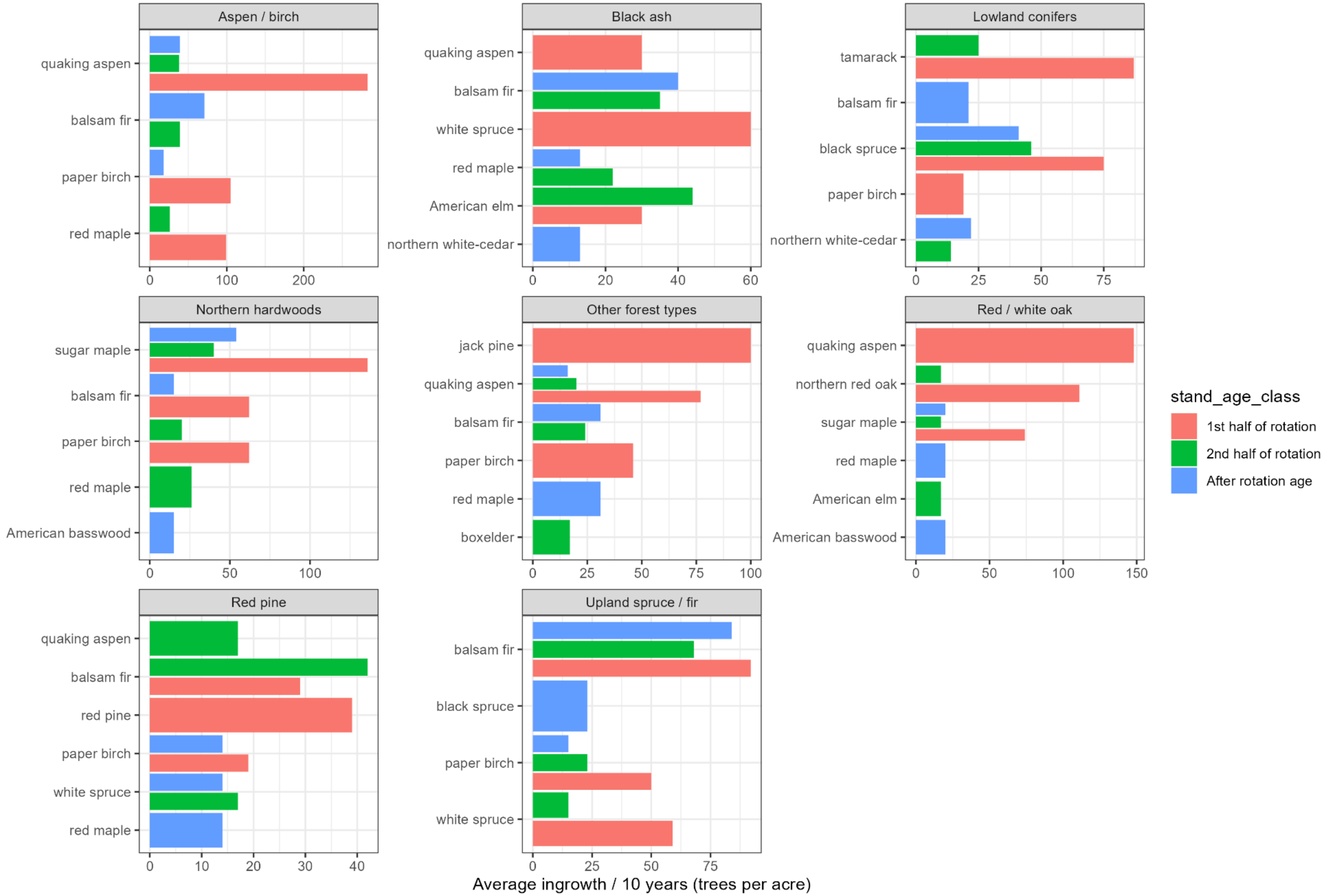

Table 9.1. Regeneration inputs to FVS model simulations for the aspen-birch forest type (trees per acre). Note: Regeneration is natural unless noted.

Scenario	quaking aspen	paper birch	red maple	balsam poplar	balsam fir	northern red oak (natural)	northern red oak (planted)	white spruce (planted)	eastern white pine (planted)	**TOTAL**
Regeneration added following harvest										
Business as usual	2,500	200	200	200	-	200	-	-	-	3,300
Economic intensive	2,500	200	200	200	-	200	-	-	-	3,300
Climate-adapted	2,500	-	-	-	-	-	150	500	150	3,300
Background regeneration (added to all scenarios every 10 years)										
Stand age 10 - 25 years	283	105	99	-	-	-	-	-	-	487
Stand age 25 - 50 years	77	-	26	-	-	-	-	-	-	103
Stand age >= 50 years	-	42	42	-	42	-	-	-	-	126

Table 9.2. Regeneration inputs to FVS model simulations for the red pine forest type (trees per acre). Note: Regeneration is natural unless noted.

Scenario	red pine (natural)	red pine (planted)	balsam fir	paper birch	white spruce	quaking aspen	red maple	eastern white pine (natural)	eastern white pine (planted)	northern red oak (planted)	bur oak (planted)	red maple (planted)	**TOTAL**
Regeneration added following harvest													
Business as usual	500	-	75	75	75	-	-	75	-	-	-	-	800
Economic intensive	-	600	-	-	-	-	-	-	-	-	-	-	600
Climate-adapted	-	500	-	-	-	-	-	-	75	75	75	75	800
Climate-adapted + fire	-	500	-	-	-	-	-	-	75	75	75	75	800
Background regeneration (added to all scenarios every 10 years)[1]													
Stand age 10 - 38 years	39	-	29	19		-	-	-	-	-	-	-	87
Stand age 38 - 75 years	-	-	42	-	17	17	-	-	-	-	-	-	76
Stand age >= 75 years	-	-	-	14	14	-	14	-	-	-	-	-	42

[1] No background regeneration added to red pine economic intensive treatment

Table 9.3. Regeneration inputs to FVS model simulations for the upland spruce/fir forest type (trees per acre). Note: Regeneration is natural unless noted.

Scenario	balsam fir	white spruce (natural)	white spruce (planted)	quaking aspen	paper birch	black spruce	**TOTAL**
Regeneration added following harvest							
Business as usual	667	667	-	666	-	-	2,000
Economic intensive	300	700	-	1,000	-	-	2,000
Climate-adapted	-	-	500	1,500	-	-	2,000
Background regeneration (added to all scenarios every 10 years)							
Stand age 10 - 30 years	92	59	-	-	50	-	201
Stand age 30 - 60 years	68	15	-	-	23	-	106
Stand age >= 60 years	84	-	-	-	15	23	122

Table 9.4. Regeneration inputs to FVS model simulations for the oak forest type (trees per acre). Note: Regeneration is natural unless noted.

Scenario	quaking aspen	northern red oak	white oak	bur oak (planted)	American elm	sugar maple	basswood (natural)	basswood (planted)	black cherry (planted)	**TOTAL**
Regeneration added following harvest										
Business as usual	-	600	100	-	-	100	100	-	-	900
Economic intensive	-	600	100	-	-	100	100	-	-	900
Climate-adapted	-	250	150	116	-	150	-	117	117	900
Climate-adapted + fire	-	250	150	350	-	150	-	-	-	900
Background regeneration (added to all scenarios every 10 years)										
Stand age 10 - 45 years	119	95	-	-	-	48	-	-	-	150
Stand age 45 - 90 years	22	-	-	-	17	16	-	-	-	51
Stand age >= 90 years	16	-	-	-	-	22	22	-	-	60

Table 9.5. Regeneration inputs to FVS model simulations for the northern hardwoods forest type (trees per acre). Note: Regeneration is natural unless noted.

Scenario	**Sub-scenario**	balsam fir	northern red oak	paper birch	yellow birch	sugar maple	red maple	basswood	**TOTAL**
Regeneration added following harvest									
Business as usual	-	-	-	-	-	134	133	133	400
Economic intensive	Following thinning	-	-	-	-	134	133	133	400
	Following shelterwood	-	300	-	300	-	-	300	900
Climate-adapted	-	-	200	-	200	200	-	200	800
Background regeneration (added to all scenarios every 10 years)									
Stand age < 42 years	-	62	-	62	-	136	-	-	260
Stand age 42 - 85 years	-	-	-	20	-	40	26	-	86
Stand age >= 85 years	-	15	-	-	-	54	-	15	84

Table 9.6. Regeneration inputs to FVS model simulations for the lowland conifers forest type (trees per acre). Note: Regeneration is natural unless noted.

Scenario	black spruce	tamarack	northern white-cedar	quaking aspen	eastern white pine	paper birch	balsam fir	**TOTAL**
Regeneration added following harvest								
Business as usual	600	600	200	-	-	-	-	1,400
Economic intensive	600	600	200	-	-	-	-	1,400
Climate-adapted	234	234	233	233	233	233	-	1,400
Background regeneration (added to all scenarios every 10 years)								
Stand age < 40 years	75	87	-	-	-	19	-	181
Stand age 40 - 80 years	46	25	14	-	-	-	-	85
Stand age >= 80 years	41	-	22	-	-	-	21	84

Table 9.7. Regeneration inputs to FVS model simulations for the black ash forest type (trees per acre). Note: Regeneration is natural unless noted.

Scenario	balsam fir	quaking aspen	balsam poplar	paper birch	swamp white oak (planted)	balsam poplar (planted)	sycamore (planted)	river birch[1] (planted)	white spruce	American elm	red maple	northern white-cedar	**TOTAL**
Regeneration added following harvest													
Business as usual	150	150	150	150	150	150	150	150	-	-	-	-	1,200
Economic intensive	225	225	225	225	-	-	-	-	-	-	-	-	900
Climate-adapted	150	150	150	150	150	150	150	150	-	-	-	-	1,200
Background regeneration (added to all scenarios every 10 years)													
Stand age < 60 years	-	30	-	-	-	-	-	-	60	30	-	-	120
Stand age 60 - 120 years	35	-	-	-	-	-	-	-	-	44	22	-	101
Stand age >= 120 years	40	-	-	-	-	-	-	-	-	-	13	13	66

[1] No species growth equations are available for river birch in FVS-Lake States, so yellow birch was used.

Table 9.8. Regeneration inputs to FVS model simulations for other forest types (trees per acre). Note: Regeneration is natural unless noted.

Scenario	quaking aspen	paper birch	red maple	eastern white pine	jack pine	quaking aspen	balsam fir	boxelder	**TOTAL**
Regeneration added following harvest									
Business as usual	500	500	500	500	-	-	-	-	2,000
Economic intensive	500	500	500	500	-	-	-	-	2,000
Climate-adapted	300	300	300	300	-	-	-	-	1,200
Background regeneration (added to all scenarios every 10 years)									
Stand age < 40 years	-	46	-	-	100	77	-	-	223
Stand age 40 - 81 years	-	-	-	-	-	20	24	17	61
Stand age >= 81 years	-	-	31	-	-	16	31	-	78

9.5 GROWTH CALIBRATIONS IN FVS

Table 9.9. Estimates of total timberland acres and volume harvested to calibrate FVS growth simulations.

Forest type	**Timberland area (acres)**	**Annual harvest rate (%)**	**Annual timberland harvest (acres)**	**Total volume harvested (2020, cords)[1]**	**Volume harvested per acre (cords)**
Aspen/birch	5,855,639	1.27	74,367	1,537,658	20.7
Red pine	524,286	2.51	13,160	300,744	22.9
Upland spruce/fir	509,976	1.40	7,140	105,197	14.7
Oak	1,096,519	0.65	7,127	139,152	19.5
Northern hardwoods	1,403,510	0.68	9,544	187,245	19.6
Lowland conifers	3,162,574	0.43	13,599	264,831	19.5
Black ash	962,243	0.56	5,389	84,060	15.6
Other forest types	2,284,548	0.93	21,246	152,685	7.2
All forest types	**15,799,295**	**0.92**	**145,354**	**2,771,572**	**19.1**

[1] Values from MN DNR Forest Resources Report (MN DNR 2024, their Table 2-1).

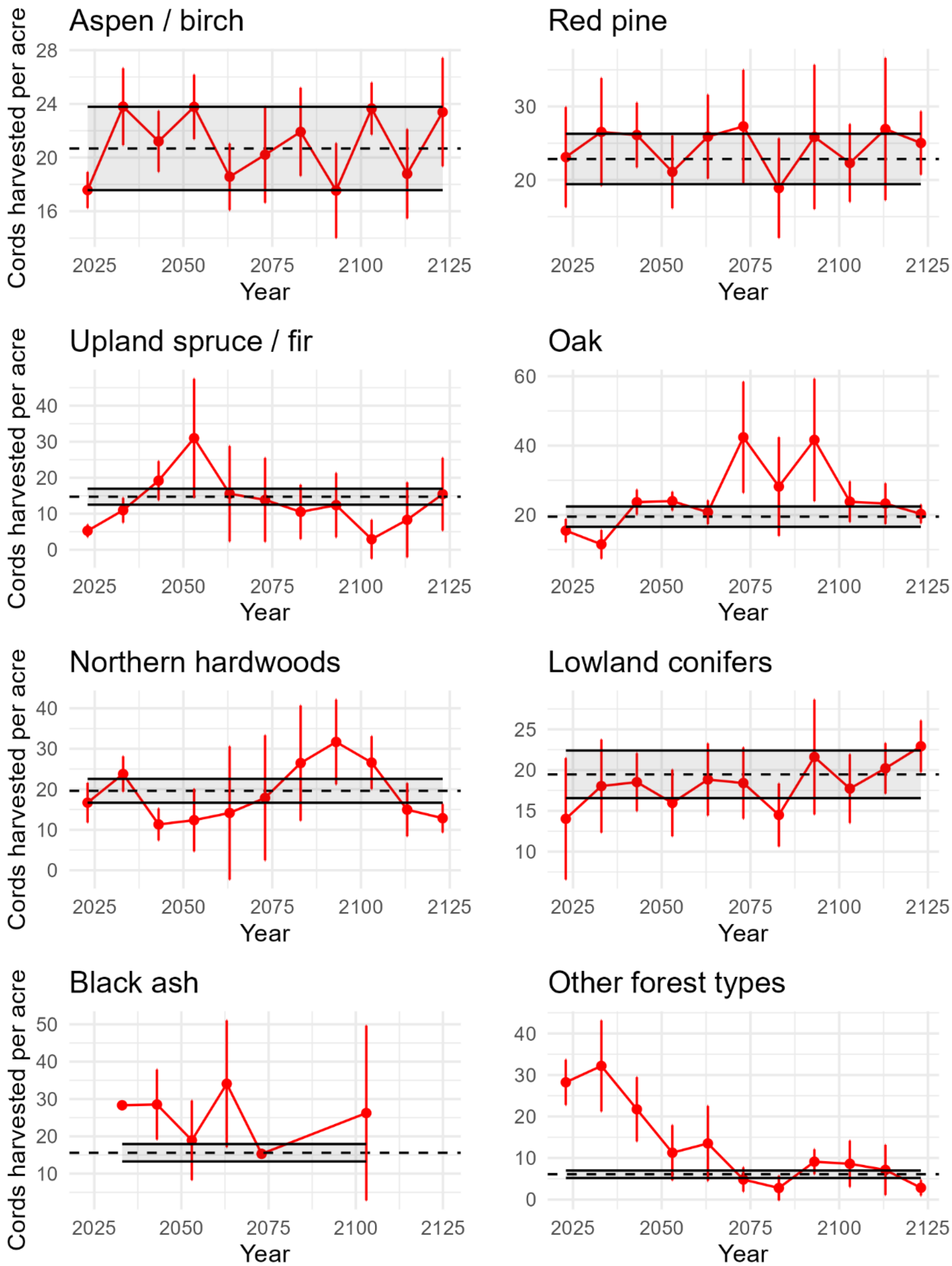

Figure 9.3. Projected volume removals assuming business as usual scenario after calibrating diameter and height growth in FVS growth simulations. Red lines show mean removals (± two standard errors); dashed line shows average volume removal determined from MN DNR report; grey regions show ± 15% of average volume removed from MN DNR report. Note scale differences in y-axis.

9.6 LCA – MINNESOTA FOREST GROWTH AND YIELD DATA AND SIMULATIONS

Growth and yield modeling estimates of the four silvicultural pathways across eight distinct forest types were conducted by Arbor Custom Analytics (see section 4). Yield by treatment entry type (e.g. first thinning, second thinning, final harvest) is shown in Table 9.10. These data were supplied to CORRIM as expected yield per entry for each combination of scenario and forest type. Silviculture, harvesting, and hauling activities were modeled on sixty-nine (69) different stand entries across all pathways and forest types (Table 9.10) to derive an expected life cycle inventory and assessment (LCIA) and LCA for all combinations provided (Table 9.11). Data were aggregated by scenario and allocated to downstream processes based on the reported TPO allocations for each forest type within the study (see findings in section 5)

Table 9.10. Simulated Yield (cubic feet) by forest type, scenario, and treatment entry.

				Yield per Acre in Cubic Feet (cf)					
Forest Type	**Simulation Scenario**	**Stand age**	**# entries over 100 year simulation**	**Total cf (mean)**	**Total cf (sd)**	**Sawlog cf (mean)**	**Sawlog cf (sd)**	**pulpwood cf (mean)**	**pulpwood cf (sd)**
Aspen / birch	BAU	50	1371	1663	1300	144	338	1519	1228
Aspen / birch	Climate-adapted - 1st thinning	40	1017	278	414	10	51	268	402
Aspen / birch	Climate-adapted - Final harvest	75	744	1386	922	55	194	1331	882
Aspen / birch	Economic intensive	40	1707	940	1038	82	244	857	944
Northern hardwoods	BAU - 1st thinning	50	27	2479	810	1774	844	704	394
Northern hardwoods	BAU - 2nd thinning	70	31	1621	1272	1084	871	537	591
Northern hardwoods	BAU - 3rd thinning	90	24	1320	969	984	858	336	318
Northern hardwoods	BAU - 4th thinning	110	26	1120	754	658	539	463	321
Northern hardwoods	BAU - 5th thinning	130	34	821	519	479	363	342	272
Northern hardwoods	Climate-adapted - 1st selection	30	1	1193	NA	342	NA	851	NA
Northern hardwoods	Climate-adapted - 2nd selection	50	2	1716	945	655	137	1061	807
Northern hardwoods	Climate-adapted - 3rd selection	70	4	2322	790	1440	228	883	618
Northern hardwoods	Climate-adapted - 4th selection	90	13	1901	866	1439	791	462	302
Northern hardwoods	Climate-adapted - 5th selection	110	30	1867	773	1400	823	467	234
Northern hardwoods	Climate-adapted - 6th selection	130	150	2168	638	1767	600	401	237

				Yield per Acre in Cubic Feet (cf)					
Forest Type	**Simulation Scenario**	**Stand age**	**# entries over 100 year simulation**	**Total cf (mean)**	**Total cf (sd)**	**Sawlog cf (mean)**	**Sawlog cf (sd)**	**pulpwood cf (mean)**	**pulpwood cf (sd)**
Northern hardwoods	Economic intensive - 1st thinning	50	41	2254	886	1250	641	1005	546
Northern hardwoods	Economic intensive - 2nd thinning	70	48	925	795	603	639	322	223
Northern hardwoods	Economic intensive - Shelterwood	75	41	1629	411	778	629	851	339
Oak	BAU - Shelterwood prep	80	56	1780	1122	671	809	1109	775
Oak	BAU - Shelterwood removal	90	118	1741	865	1270	826	471	553
Oak	Climate-adapted + fire - Shelterwood 1 (prep)	70	15	543	662	213	454	331	429
Oak	Climate-adapted + fire - Shelterwood 2 (establishment)	95	59	994	658	759	675	235	208
Oak	Climate-adapted + fire - Shelterwood 3 (removal)	110	28	1446	471	1246	583	200	256
Oak	Climate-adapted - Shelterwood 1 (prep)	70	48	1143	951	413	596	730	746
Oak	Climate-adapted - Shelterwood 2 (establishment)	95	76	1653	726	1181	803	472	410
Oak	Climate-adapted - Shelterwood 3 (removal)	110	28	1862	519	1679	584	183	272
Oak	Economic intensive - 1st thinning	50	87	1035	690	511	579	524	425
Oak	Economic intensive - Shelterwood prep	70	96	1279	882	548	683	731	684

				Yield per Acre in Cubic Feet (cf)					
Forest Type	**Simulation Scenario**	**Stand age**	**# entries over 100 year simulation**	**Total cf (mean)**	**Total cf (sd)**	**Sawlog cf (mean)**	**Sawlog cf (sd)**	**pulpwood cf (mean)**	**pulpwood cf (sd)**
Oak	Economic intensive - Shelterwood removal	80	89	1627	511	1149	696	478	413
Black ash	BAU/Climate-adapted (hydric) - 1st selection	30	9	145	109	61	41	84	81
Black ash	BAU/Climate-adapted (hydric) - 2nd selection	50	14	273	151	107	73	166	105
Black ash	BAU/Climate-adapted (hydric) - 3rd selection	70	25	430	199	184	120	246	142
Black ash	BAU/Climate-adapted (hydric) - 4th selection	90	25	563	274	240	167	323	220
Black ash	BAU/Climate-adapted (mesic) - Clearcut	100	15	2066	867	808	686	1258	666
Black ash	BAU/Climate-adapted + EAB (hydric) - 1st selection	30	8	150	119	58	48	92	83
Black ash	BAU/Climate-adapted + EAB (hydric) - 2nd selection	50	12	269	176	100	83	169	117
Black ash	BAU/Climate-adapted + EAB (hydric) - 3rd selection	70	23	383	264	171	137	213	167
Black ash	BAU/Climate-adapted + EAB (hydric) - 4th selection	90	25	283	280	120	138	163	213

				Yield per Acre in Cubic Feet (cf)					
Forest Type	**Simulation Scenario**	**Stand age**	**# entries over 100 year simulation**	**Total cf (mean)**	**Total cf (sd)**	**Sawlog cf (mean)**	**Sawlog cf (sd)**	**pulpwood cf (mean)**	**pulpwood cf (sd)**
Black ash	BAU/Climate-adapted + EAB (mesic) - Clearcut	100	15	1775	892	746	679	1029	675
Black ash	Economic intensive + EAB - Shelterwood	90	55	902	719	338	389	564	459
Other forest types	BAU - 1st thinning	30	38	64	117	9	36	55	108
Other forest types	BAU - 2nd thinning	50	81	301	407	46	124	255	346
Other forest types	BAU - harvest	70	154	1837	1504	945	1352	892	681
Other forest types	Climate-adapted - shelterwood	70	46	1860	1133	755	1087	1105	570
Other forest types	Economic intensive - 1st thinning	35	46	138	367	42	177	96	208
Other forest types	Economic intensive - harvest	50	231	1182	1463	594	1150	588	708
Red pine	BAU - 1st thinning	30	20	250	364	5	21	246	352
Red pine	BAU - 2nd thinning	45	30	1332	975	205	374	1127	848
Red pine	BAU - 3rd thinning	60	65	1686	1014	830	901	855	747
Red pine	BAU - final harvest	75	145	2564	1348	2306	1324	257	342
Red pine	Climate-adapted + fire - 1st thinning	30	3	451	163	0	0	451	163
Red pine	Climate-adapted + fire - 2nd thinning	50	23	822	729	301	626	521	435

				Yield per Acre in Cubic Feet (cf)					
Forest Type	**Simulation Scenario**	**Stand age**	**# entries over 100 year simulation**	**Total cf (mean)**	**Total cf (sd)**	**Sawlog cf (mean)**	**Sawlog cf (sd)**	**pulpwood cf (mean)**	**pulpwood cf (sd)**
Red pine	Climate-adapted + fire - 3rd thinning	70	48	1219	1116	667	732	552	807
Red pine	Climate-adapted + fire - 4th thinning	90	60	787	549	609	526	178	207
Red pine	Climate-adapted + fire - 5th thinning	110	66	567	421	481	378	86	146
Red pine	Climate-adapted + fire - 6th thinning	130	35	180	213	118	135	62	133
Red pine	Climate-adapted + fire - final harvest	150	40	4264	796	4083	851	182	221
Red pine	Climate-adapted - 1st thinning	30	3	391	116	0	0	391	116
Red pine	Climate-adapted - 2nd thinning	50	22	867	739	258	606	608	498
Red pine	Climate-adapted - 3rd thinning	70	47	1383	1073	765	732	618	799
Red pine	Climate-adapted - 4th thinning	90	60	1098	563	860	570	238	226
Red pine	Climate-adapted - 5th thinning	110	68	858	480	736	455	121	182
Red pine	Climate-adapted - 6th thinning	130	52	260	210	209	184	51	108
Red pine	Climate-adapted - final harvest	150	40	4388	730	4213	794	176	213
Red pine	Economic intensive - 1st thinning	30	103	1239	704	571	640	668	358
Red pine	Economic intensive - 2nd thinning	40	112	2491	1012	2049	1045	443	292

				Yield per Acre in Cubic Feet (cf)					
Forest Type	**Simulation Scenario**	**Stand age**	**# entries over 100 year simulation**	**Total cf (mean)**	**Total cf (sd)**	**Sawlog cf (mean)**	**Sawlog cf (sd)**	**pulpwood cf (mean)**	**pulpwood cf (sd)**
Red pine	Economic intensive - final harvest	60	88	3446	1129	2753	1051	693	557
Red pine	Economic intensive - final harvest	70	71	3828	1138	2850	1304	978	651
Upland spruce / fir	BAU - 1st thinning	35	56	360	579	113	306	247	392
Upland spruce / fir	BAU - final harvest	85	51	1875	1298	402	733	1473	1044
Upland spruce / fir	Climate-adapted - final harvest	100	40	1566	1415	245	445	1321	1310
Upland spruce / fir	Economic intensive - 1st thinning	30	23	111	400	0	0	111	400
Upland spruce / fir	Economic intensive - final harvest	55	64	1909	1277	601	754	1308	970
Lowland conifers	BAU/Economic intensive harvest	80	359	1444	1011	190	433	1254	854
Lowland conifers	Climate-adapted - Shelterwood harvest	100	289	629	726	32	203	597	671

Life cycle assessment results for all forest types and scenarios (A1-A2) are shown in Table 9.11 using a functional unit of 1 metric ton of green logs. Values for the Climate-adapted plus fire scenarios were substantially different than all other scenarios and are therefore identified as outliers in this section.

Table 9.11. LCA metrics by forest type and scenario per 1 metric ton of logs, unallocated.

Impact category	Ozone depletion	Global warming	Smog	Acid-ification	Eutro-phication	Fossil fuel depletion
Unit per metric ton of harvested logs	kg CFC-11 eq	kg CO2 eq	kg O3 eq	kg SO2 eq	kg N eq	MJ surplus
BAU scenarios						
BAU, Aspen/Birch Forestry	1.50E-07	30.93	10.16	0.33	2.21E-02	59.15
BAU, Northern Hardwood Forestry	1.53E-07	30.57	10.21	0.33	2.21E-02	58.96
BAU, Oak Forestry	1.29E-07	29.88	8.84	0.29	2.02E-02	56.34
BAU, Black Ash Forestry	1.53E-07	31.68	9.95	0.32	2.28E-02	61.08
BAU, Other Forest types Forestry	1.55E-07	31.05	10.02	0.32	2.28E-02	61.53
BAU, Red Pine Forestry	1.49E-07	29.31	9.95	0.32	2.15E-02	56.77
BAU, Upland Spruce Forestry	1.57E-07	30.1	10.32	0.33	2.25E-02	59.28
BAU/Economic, Lowland Conifer Forestry	1.59E-07	31.45	10.69	0.34	2.29E-02	60.47
Climate Adapted Scenarios						
Climate Adapted, Aspen/Birch Forestry	1.72E-07	34.72	11.06	0.36	2.53E-02	65.92
Climate Adapted, Northern Hardwood Forestry	1.31E-07	27.33	8.87	0.29	1.94E-02	52.19
Climate Adapted, Oak forestry	1.44E-07	32.15	9.74	0.32	2.20E-02	60.56
Climate Adapted, Black Ash Forestry	1.53E-07	31.68	9.95	0.32	2.28E-02	61.08
Climate Adapted, Other Forest Types forestry	1.34E-07	27.79	9.04	0.29	1.97E-02	53.09
Climate Adapted, Red Pine Forestry	1.48E-07	29.38	9.54	0.31	2.17E-02	57.7
Climate Adapted, Upland Spruce Forestry	1.62E-07	31.11	10.63	0.35	2.30E-02	58.65
Climate Adapted, Lowland Conifer Forestry	1.62E-07	31.81	10.84	0.35	2.32E-02	61.18
Economic Scenarios						
Economic, Aspen/Birch Forestry	1.62E-07	32.67	10.91	0.35	2.36E-02	62.66
Economic, Northern Hardwood Forestry	1.45E-07	29.4	9.67	0.31	2.12E-02	56.79
Economic, Oak Forestry	1.49E-07	32.85	10.12	0.33	2.26E-02	62.29
Economic, Black Ash Forestry	1.63E-07	32.94	10.96	0.35	2.37E-02	63.13
Economic, Other Forest Types Forestry	1.76E-07	34.29	11.51	0.37	2.55E-02	67.57
Economic, Red Pine Forestry	1.26E-07	25.95	8.51	0.27	1.85E-02	49.4
Economic, Upland Spruce Forestry	1.57E-07	30.06	10.31	0.33	2.25E-02	59.18
BAU/Economic, Lowland Conifer Forestry	1.59E-07	31.45	10.69	0.34	2.29E-02	60.47
Climate with Fire and Insect Scenarios						
Climate Adapted with fire, Oak forestry (with biogenic carbon)	1.65E-07	1,049.18	81.18	5.36	3.17E-01	66.11
Climate Adapted with fire, Red Pine forestry (with biogenic carbon)	1.60E-07	1,669.91	99.86	4.93	3.06E-01	58.02
Climate Adapted with fire, Oak forestry (with biogenic carbon)	1.65E-07	83.01	81.18	5.36	3.17E-01	70.29
Climate Adapted with fire, Red Pine forestry (without biogenic carbon)	1.60E-07	95.55	99.86	4.93	3.06E-01	61.69
Climate Impacted, Black Ash Forestry with EAB	1.56E-07	32.17	10.08	0.33	2.32E-02	62.13

Table 9.12. Fuel Loads (tons/acre) by photo series for oak and red pine fuel types.

Fuel loads in tons/acre from Ottmar and Vihanek (1999) ***https://depts.washington.edu/nwfire/dps/***							
fuel type	1 hr	10 hr	100 hr	1000 hr			
size class	<1/4"	<1"	1-3"	3-9"	total understory	>9"	
Red pine fuel types							
MP01	0.3	0.6	0.5	0.2	1.6	0.0	1.6
MP02	0.2	0.3	0.4	0.8	1.7	0.0	1.7
MP03	0.1	0.2	0.1	1.5	1.9	0.0	1.9
MP04	0.2	0.4	0.9	0.9	2.4	0.3	2.7
MP05	0.1	0.2	0.6	0.4	1.3	1.4	2.7
MP06	0.5	0.8	1.3	1.2	3.8	0.0	3.8
MP07	0.3	0.5	1.8	4.0	6.6	0.4	7.0
MP08	0.2	0.3	1.7	3.5	5.7	1.5	7.2
MP09	0.6	1.0	1.9	4.2	7.7	1.5	9.2
MP10	0.4	0.7	1.3	7.2	9.6	3.4	13.0
MP11	0.5	0.9	1.4	4.8	7.6	7.3	14.9
MP12	0.9	1.5	1.9	5.6	9.9	6.5	16.4
MP13	0.7	1.1	1.2	4.3	7.3	28.9	36.2
average (unweighted)	**0.4**	**0.7**	**1.2**	**3.0**	**5.2**	**3.9**	**9.1**
Oak fuel types							
MO01	0.6	1	1.1	0.9	3.6	0	3.6
MO02	0.6	0.9	1.5	1.2	4.2	0.2	4.4
MO03	0.7	1.2	1.1	2.9	5.9	0.3	6.2
MO04	0.4	0.7	1.4	2	4.5	2.2	6.7
MO05	0.5	0.8	1.6	2.5	5.4	2.3	7.7
MO06	1.4	2.3	2.2	1.2	7.1	0.7	7.8
MO07	1	1.6	1.6	8.4	12.6	1.3	13.9
MO08	0.8	1.4	1.5	7.6	11.3	4.4	15.7
MO09	0.6	1.1	2.4	9.3	13.4	5.6	19
MO10	1.5	2.5	3	7.5	14.5	7.7	22.2
MO11	0.5	0.9	2.4	11.9	15.7	12.4	28.1
average (unweighted)	**0.78**	**1.31**	**1.80**	**5.04**	**8.93**	**3.37**	**12.30**

Statewide estimate of A1-A2 weighted by Forest Type and Scenario

Table 9.13. TRACI Impact Indicators allocated across forest types by scenario A1-A2.

Impact category	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Fossil fuel depletion
Unit	**kg CFC-11 eq**	**kg CO2 eq**	**kg O3 eq**	**kg SO2 eq**	**kg N eq**	**MJ surplus**
Business As Usual Scenario allocated by Forest type						
Aspen/Birch	8.11E-08	1.67E+01	5.49E+00	1.76E-01	1.19E-02	3.40E+01
Northern Hardwoods	9.32E-09	1.86E+00	6.23E-01	2.00E-02	1.35E-03	3.82E+00
Black Ash	5.05E-09	1.04E+00	3.28E-01	1.07E-02	7.52E-04	2.14E+00
Oak	6.08E-09	1.40E+00	4.16E-01	1.35E-02	9.47E-04	2.82E+00
Other	6.83E-09	1.36E+00	4.41E-01	1.42E-02	1.00E-03	2.88E+00
Red Pine	1.79E-08	3.51E+00	1.19E+00	3.83E-02	2.57E-03	7.24E+00
Upland Spruce/Fir	2.06E-08	3.94E+00	1.35E+00	4.34E-02	2.95E-03	8.26E+00
Lowland Conifers	3.81E-09	7.54E-01	2.57E-01	8.23E-03	5.49E-04	1.54E+00
BAU Total	**1.51E-07**	**3.06E+01**	**1.01E+01**	**3.25E-01**	**2.20E-02**	**6.27E+01**
Climate adapted scenario allocated by forest type						
Aspen/Birch	8.59E-08	9.26E-08	1.87E+01	5.97E+00	1.96E-01	6.67E+01
Northern Hardwoods	1.02E-08	8.02E-09	1.67E+00	5.41E-01	1.74E-02	5.31E+00
Black Ash	5.56E-09	5.05E-09	1.04E+00	3.28E-01	1.07E-02	3.62E+00
Oak	8.12E-09	6.77E-09	1.51E+00	4.58E-01	1.49E-02	4.99E+00
Other	6.99E-09	5.91E-09	1.22E+00	3.98E-01	1.28E-02	3.89E+00
Red Pine	2.16E-08	1.78E-08	3.52E+00	1.15E+00	3.72E-02	1.23E+01
Upland Spruce/Fir	1.92E-08	2.12E-08	4.07E+00	1.39E+00	4.53E-02	1.35E+01
Lowland Conifers* (used BAU as no climate scenario)	3.78E-09	3.81E-09	7.54E-01	2.57E-01	8.23E-03	2.36E+00
Total	**1.61E-07**	**3.25E+01**	**1.05E+01**	**3.43E-01**	**2.37E-02**	**6.60E+01**
Climate adapted plus fire (oak and red pine only) scenario allocated by forest type						
Aspen/Birch	9.26E-08	1.87E+01	5.97E+00	1.96E-01	1.37E-02	3.78E+01
Northern Hardwoods	8.02E-09	1.67E+00	5.41E-01	1.74E-02	1.18E-03	3.39E+00
Black Ash	5.15E-09	1.06E+00	3.33E-01	1.09E-02	7.66E-04	2.18E+00
Oak	7.77E-09	3.90E+00	3.82E+00	2.52E-01	1.49E-02	3.30E+00
Other	5.91E-09	1.22E+00	3.98E-01	1.28E-02	8.67E-04	2.48E+00
Red Pine	1.92E-08	1.15E+01	1.20E+01	5.91E-01	3.67E-02	7.40E+00
Upland Spruce/Fir	2.12E-08	4.07E+00	1.39E+00	4.53E-02	3.02E-03	8.17E+00
Lowland Conifers* (used	3.81E-09	7.54E-01	2.57E-01	8.23E-03	5.49E-04	1.54E+00

BAU as no climate scenario)						
Total	**1.64E-07**	**4.28E+01**	**2.47E+01**	**1.13E+00**	**7.16E-02**	**6.63E+01**
Economic Scenario allocated by Forest type						
Aspen/Birch	8.76E-08	1.76E+01	5.89E+00	1.89E-01	1.27E-02	3.60E+01
Northern Hardwoods	8.84E-09	1.79E+00	5.90E-01	1.90E-02	1.29E-03	3.68E+00
Black Ash	5.37E-09	1.09E+00	3.62E-01	1.16E-02	7.81E-04	2.21E+00
Oak	7.02E-09	1.54E+00	4.76E-01	1.54E-02	1.06E-03	3.11E+00
Other	7.76E-09	1.51E+00	5.07E-01	1.63E-02	1.12E-03	3.16E+00
Red Pine	1.52E-08	3.11E+00	1.02E+00	3.29E-02	2.22E-03	6.30E+00
Upland Spruce/Fir	2.05E-08	3.93E+00	1.35E+00	4.33E-02	2.94E-03	8.24E+00
Lowland Conifers	3.81E-09	7.54E-01	2.57E-01	8.23E-03	5.49E-04	1.54E+00
Total	**1.56E-07**	**3.13E+01**	**1.05E+01**	**3.36E-01**	**2.27E-02**	**6.42E+01**

Table 9.14. Cumulative Energy Demand Allocated by Forest Type to each Scenario, Statewide Forest Resources A1-A2.

Impact category	Non renewable, fossil	Non-renewable, nuclear	Non-renewable, biomass	Renewable, biomass	Renewable, wind, solar, geothe	Renewable, water
Unit	**MJ**	**MJ**	**MJ**	**MJ**	**MJ**	**MJ**
Business As Usual Scenario allocated by Forest type						
Aspen/Birch	2.27E+02	1.24E+00	1.46E-06	3.23E-02	4.78E-02	1.09E-01
Northern Hardwoods	2.56E+01	1.40E-01	1.68E-07	3.67E-03	5.45E-03	1.23E-02
Black Ash	1.45E+01	1.06E-01	8.87E-08	3.24E-03	7.30E-03	1.14E-02
Oak	1.88E+01	1.33E-01	1.04E-07	3.44E-03	4.99E-03	1.17E-02
Other	1.93E+01	1.50E-01	1.16E-07	3.90E-03	5.70E-03	1.32E-02
Red Pine	4.85E+01	2.59E-01	3.26E-07	6.78E-03	1.01E-02	2.27E-02
Upland Spruce/Fir	5.53E+01	3.37E-01	3.68E-07	8.80E-03	1.30E-02	2.96E-02
Lowland Conifers	1.03E+01	5.05E-02	7.00E-08	1.33E-03	1.98E-03	4.44E-03
BAU Total	**4.19E+02**	**2.41E+00**	**2.70E-06**	**6.34E-02**	**9.64E-02**	**2.14E-01**
Climate adapted scenario allocated by forest type						
Aspen/Birch	2.60E+02	1.74E+00	1.70E-06	6.57E-02	2.03E-01	2.41E-01
Northern Hardwoods	2.26E+01	1.27E-01	1.44E-07	3.32E-03	4.91E-03	1.12E-02
Black Ash	1.45E+01	1.06E-01	8.87E-08	3.24E-03	7.30E-03	1.14E-02
Oak	2.03E+01	1.34E-01	1.18E-07	3.78E-03	7.03E-03	1.31E-02
Other	1.66E+01	9.26E-02	1.06E-07	2.42E-03	3.58E-03	8.15E-03
Red Pine	4.97E+01	3.69E-01	3.11E-07	1.09E-02	2.24E-02	3.79E-02
Upland Spruce/Fir	5.60E+01	2.47E-01	4.09E-07	1.04E-02	3.56E-02	3.84E-02
Lowland Conifers* (used BAU as no climate scenario)	1.03E+01	5.05E-02	7.00E-08	1.33E-03	1.98E-03	4.44E-03
Total	**4.50E+02**	**2.86E+00**	**2.95E-06**	**1.01E-01**	**2.86E-01**	**3.66E-01**
Climate adapted plus fire (oak and red pine only) scenario allocated by forest type						
Aspen/Birch	2.60E+02	1.74E+00	1.70E-06	6.57E-02	2.03E-01	2.41E-01
Northern Hardwoods	2.26E+01	1.27E-01	1.44E-07	3.32E-03	4.91E-03	1.12E-02
Black Ash	1.48E+01	1.11E-01	9.03E-08	3.45E-03	8.03E-03	1.22E-02
Oak	2.23E+01	1.52E-01	1.37E-07	4.51E-03	9.51E-03	1.58E-02
Other	1.66E+01	9.26E-02	1.06E-07	2.42E-03	3.58E-03	8.15E-03
Red Pine	5.00E+01	3.77E-01	3.36E-07	1.11E-02	2.28E-02	3.86E-02
Upland Spruce/Fir	5.60E+01	2.47E-01	4.09E-07	1.04E-02	3.56E-02	3.84E-02
Lowland Conifers* (used BAU as no climate scenario)	1.03E+01	5.05E-02	7.00E-08	1.33E-03	1.98E-03	4.44E-03
Total	**4.53E+02**	**2.90E+00**	**2.99E-06**	**1.02E-01**	**2.89E-01**	**3.70E-01**

Economic Scenario allocated by Forest type						
Aspen/Birch	2.41E+02	1.26E+00	1.59E-06	3.29E-02	4.90E-02	1.11E-01
Northern Hardwoods	2.46E+01	1.47E-01	1.58E-07	3.83E-03	5.66E-03	1.29E-02
Black Ash	1.48E+01	7.84E-02	9.75E-08	2.05E-03	3.05E-03	6.90E-03
Oak	2.08E+01	1.34E-01	1.22E-07	3.48E-03	5.08E-03	1.18E-02
Other	2.12E+01	1.40E-01	1.37E-07	3.65E-03	5.38E-03	1.23E-02
Red Pine	4.24E+01	2.27E-01	2.77E-07	6.56E-03	1.30E-02	2.27E-02
Upland Spruce/Fir	5.52E+01	3.35E-01	3.68E-07	8.75E-03	1.30E-02	2.94E-02
Lowland Conifers	1.03E+01	5.05E-02	7.00E-08	1.33E-03	1.98E-03	4.44E-03
Total	**4.30E+02**	**2.37E+00**	**2.82E-06**	**6.26E-02**	**9.61E-02**	**2.11E-01**

Table 9.15. Fuel and Fire Tools Emission Estimates: Red Pine and Oak Forest Types

Stratum	Red Pine	Oak
	Consumption (Tons/acre)	
Total Consumption	10.34	15.60
Canopy Consumption	0.18	0.21
Shrub Consumption	0.67	0.96
Herb Consumption	0.10	0.01
Wood Consumption	7.42	7.73
LLM Consumption	1.52	3.35
Ground Consumption	0.46	3.35
Pollutant	Emissions (US tons/acre)	
CH4	0.03	0.06
CO	0.91	1.47
CO2	16.77	25.42
NMOC	0.24	0.24
NO	0.02	0.06
NO2	0.02	0.02
SO2	0.00	0.01
PM10	0.12	0.25
PM2.5	0.11	0.22

Table 9.16. Specific gravity, moisture contents, densities used to determine weighted average roundwood weights.

Forest Type	Specific Gravity			Density				weighting calculations					
	Green >30% MC	MC 12%	MC 0%, OD	kg/m3, OD (oven dry)	*average moisture content of green logs	average lbs/cf of green logs	average kg/m3 of green logs	weighting value lbs/cf for green logs	kg/m3 weighting values for OD logs	kg/m3 weighting values for green logs	OD/green comparison	m3/truck (6 axle)	m3/truck (7 axle self loader)
Aspen/Birch	0.36	0.40	0.42	415.68	124.17	50.86	814.99	25.63	209.51	410.77	0.51	30.05	30.33
Red pine	0.41	0.43	0.46	460.00	64.00	41.96	672.40	3.53	38.66	56.51	0.68	36.43	36.76
upland spruce/fir	0.33	0.34	0.35	349.18	87.99	38.71	620.36	2.42	21.86	38.84	0.56	39.48	39.85
Oak	0.58	0.67	0.69	693.61	78.17	64.50	1,033.71	3.64	39.14	58.33	0.67	23.70	23.91
northern hardwoods	0.42	0.46	0.49	489.58	79.66	46.62	747.12	2.93	30.78	46.97	0.66	32.78	33.09
lowland conifers	0.46	0.50	0.53	532.87	61.38	46.04	737.84	4.39	50.75	70.27	0.72	33.20	33.50
Black ash	0.45	0.49	0.51	510.00	85.00	51.95	832.50	1.89	18.54	30.26	0.61	29.42	29.69
Other	0.37	0.40	0.43	427.10	101.58	47.13	755.35	6.28	56.87	100.57	0.57	32.43	32.73
weighted average lbs/cf and kg/m3 based on harvest volume by forest type.													

9.7 LCA – Harvest Wood Products

Table 9.17 Allocation of products assigned to Forest Type using TPO data by species.

	Contribution by Forest Type	Bioenergy Fuelwood	Composite Panel	House Logs	Misc.	Poles, Posts, Pilings	Pulpwood	Saw Logs	Veneer Logs
		Percent Contribution by Product Over All Forest Types							
Aspen/Birch	54.0%	2.00%	14.23%	0.00%	1.23%	0.00%	33.48%	3.07%	0.01%
Black Ash	3.3%	0.96%	0.00%	0.00%	0.07%	0.00%	1.50%	0.81%	0.00%
Lowland Conifers	2.4%	0.52%	0.44%	0.01%	0.14%	0.00%	0.93%	0.31%	0.00%
Northern Hardwoods	6.1%	0.43%	0.19%	0.00%	0.53%	0.00%	3.69%	1.20%	0.03%
Oak	4.7%	0.51%	0.00%	0.00%	0.15%	0.00%	0.02%	4.05%	0.01%
Red Pine	12.0%	0.91%	0.88%	0.02%	1.43%	0.13%	0.82%	7.82%	0.00%
Upland Spruce/Fir	13.1%	0.22%	0.00%	0.00%	0.05%	0.00%	11.18%	1.61%	0.00%
Other	4.4%	0.61%	0.03%	0.00%	0.06%	0.05%	0.98%	2.68%	0.00%
Total	**100%**	**6.16%**	**15.77%**	**0.04%**	**3.65%**	**0.19%**	**52.60%**	**21.54%**	**0.06%**

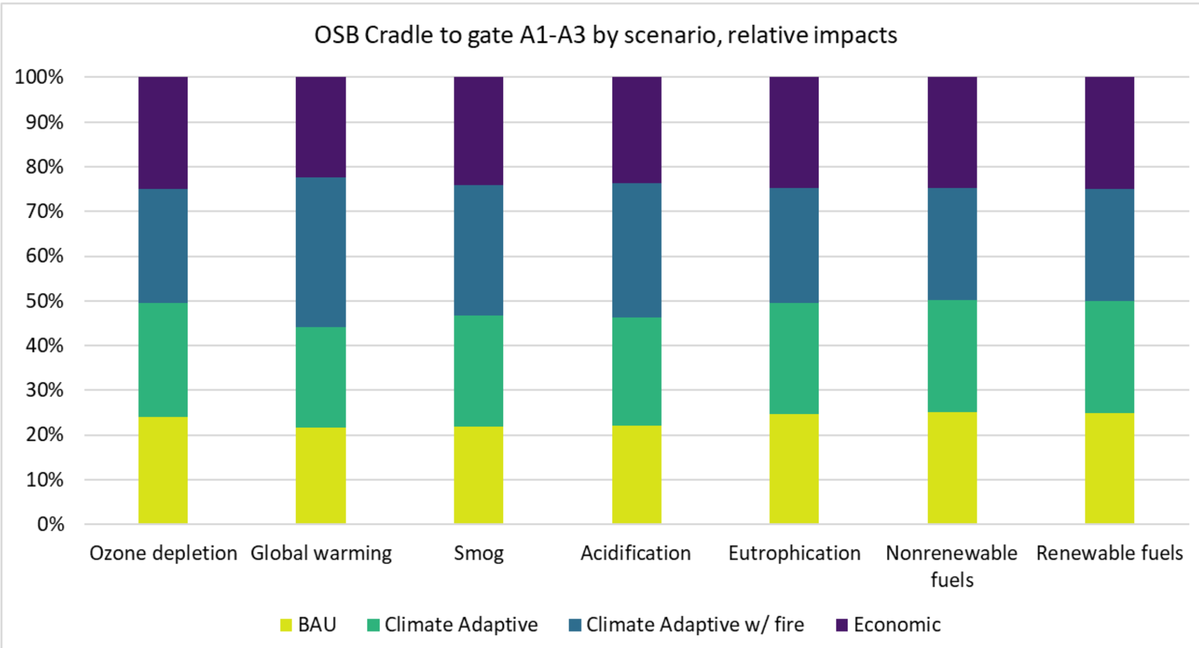

Figure 9.4. Relative comparison between management scenarios for oriented strandboard (OSB) for selected impact categories.

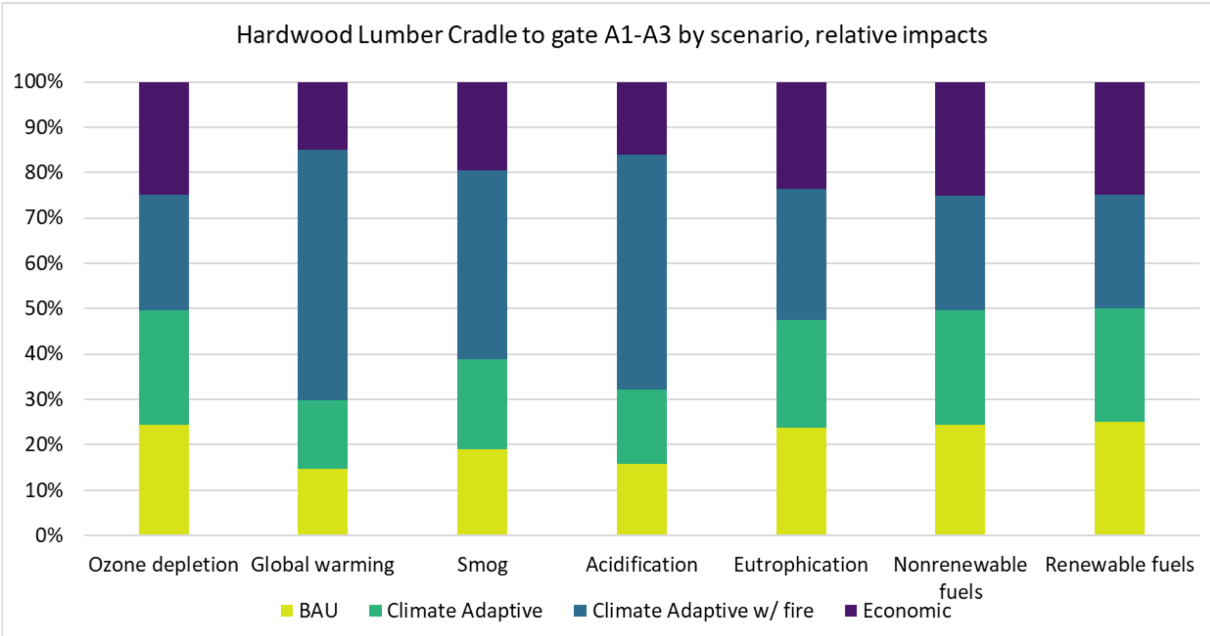

Figure 9.5. Relative comparison between management scenarios for hardwood lumber for selected impact categories.

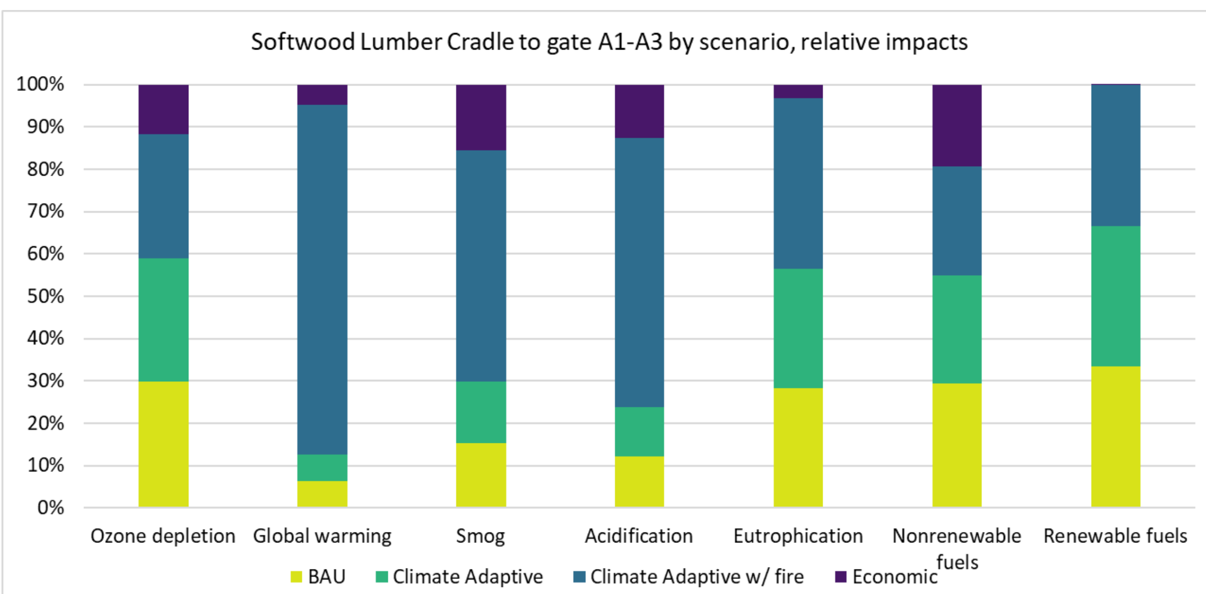

Figure 9.6. Relative comparison between management scenarios for softwood lumber for selected impact categories.

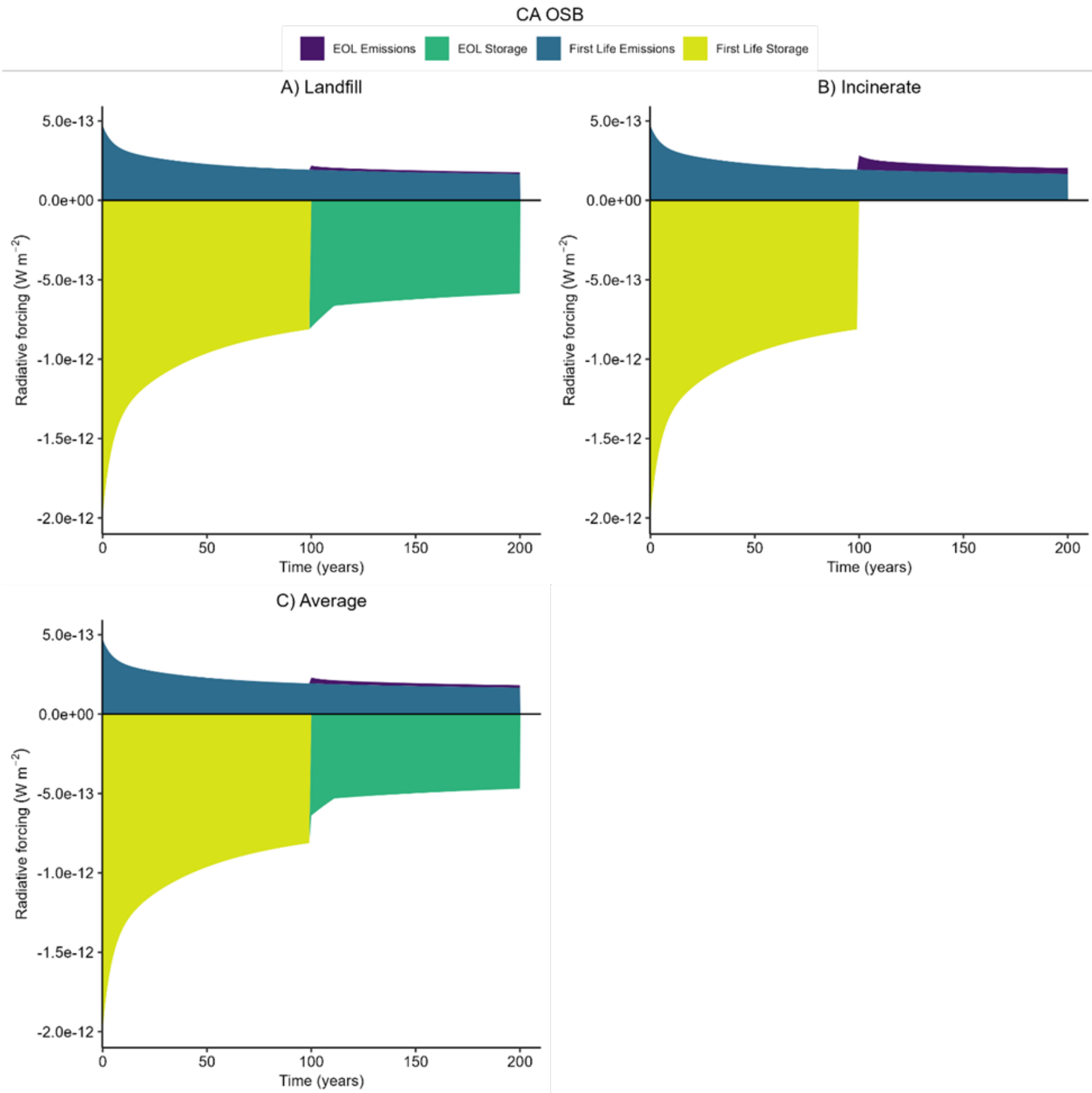

Figure 9.7. The atmospheric decay of carbon dioxide and the carbon storage benefit at year 0 to year 200 for oriented strandboard (OSB) for the Climate-adapted management scenario for three EoL of scenarios.

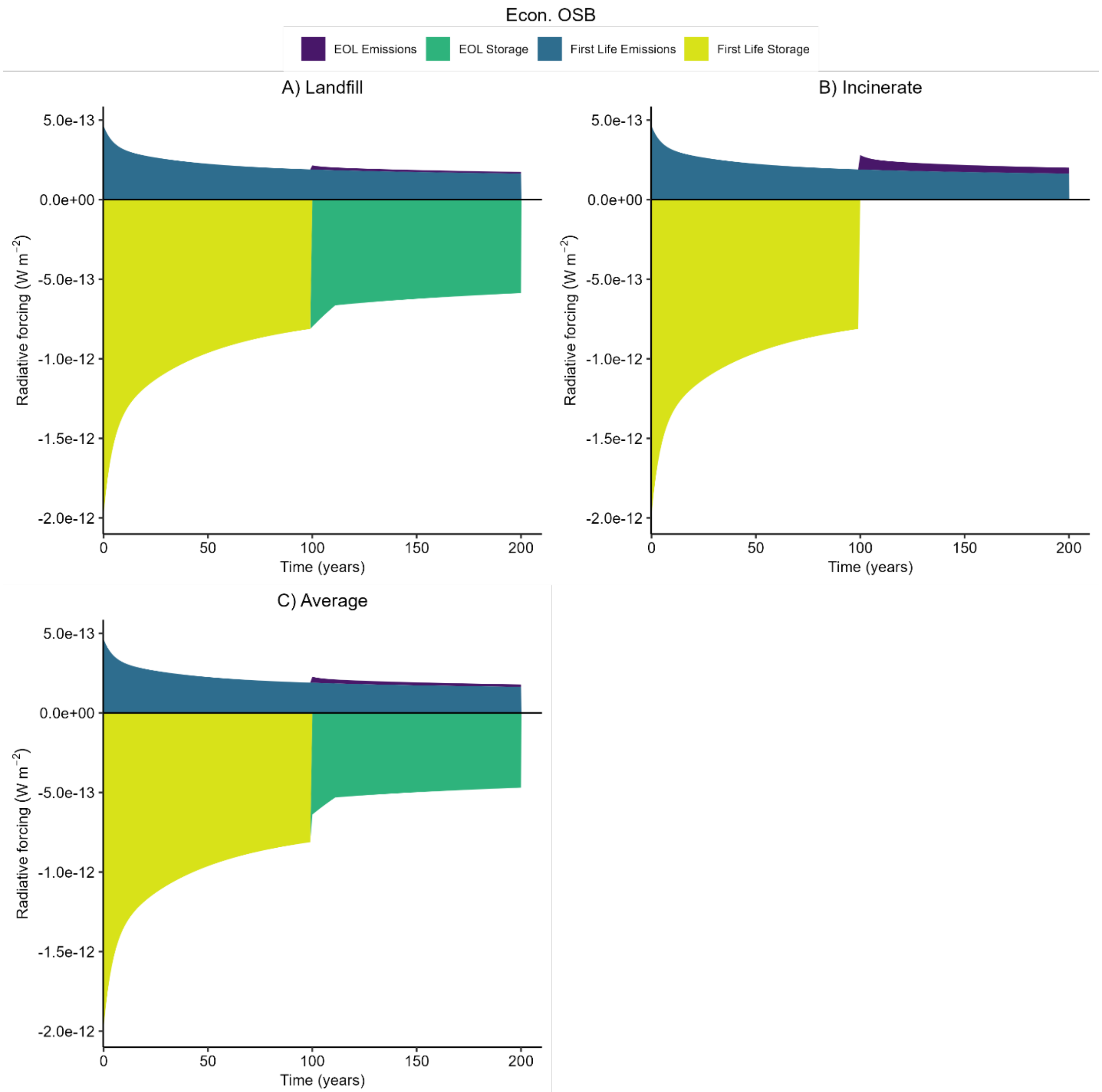

Figure 9.8. The atmospheric decay of carbon dioxide and the carbon storage benefit at year 0 to year 200 for oriented strandboard (OSB) for the Economic intensive management scenario for three EoL of scenarios.

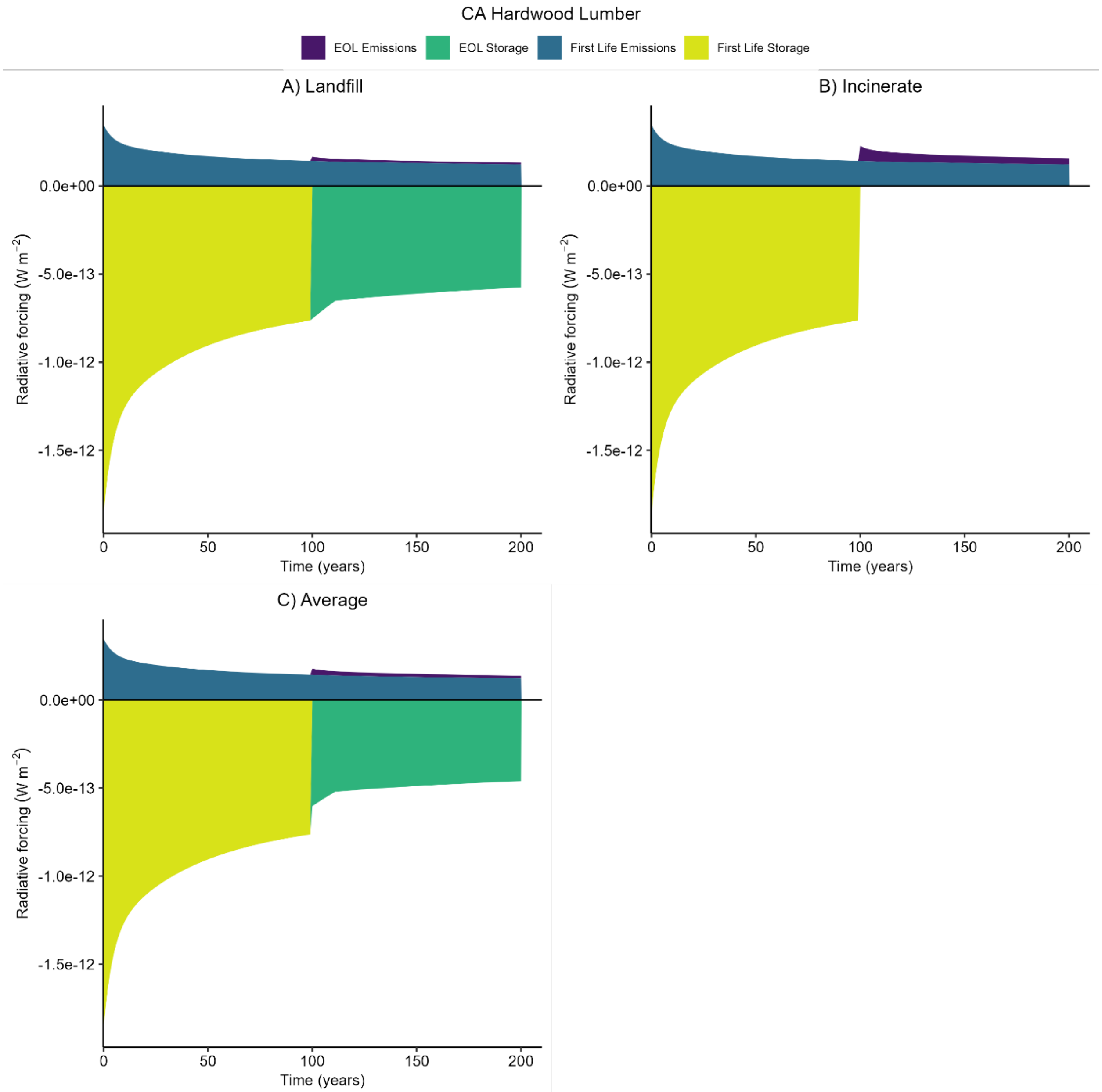

Figure 9.9. The atmospheric decay of carbon dioxide and the carbon storage benefit at year 0 to year 200 for hardwood lumber for the Climate-adapted management scenario for three EoL of scenarios.

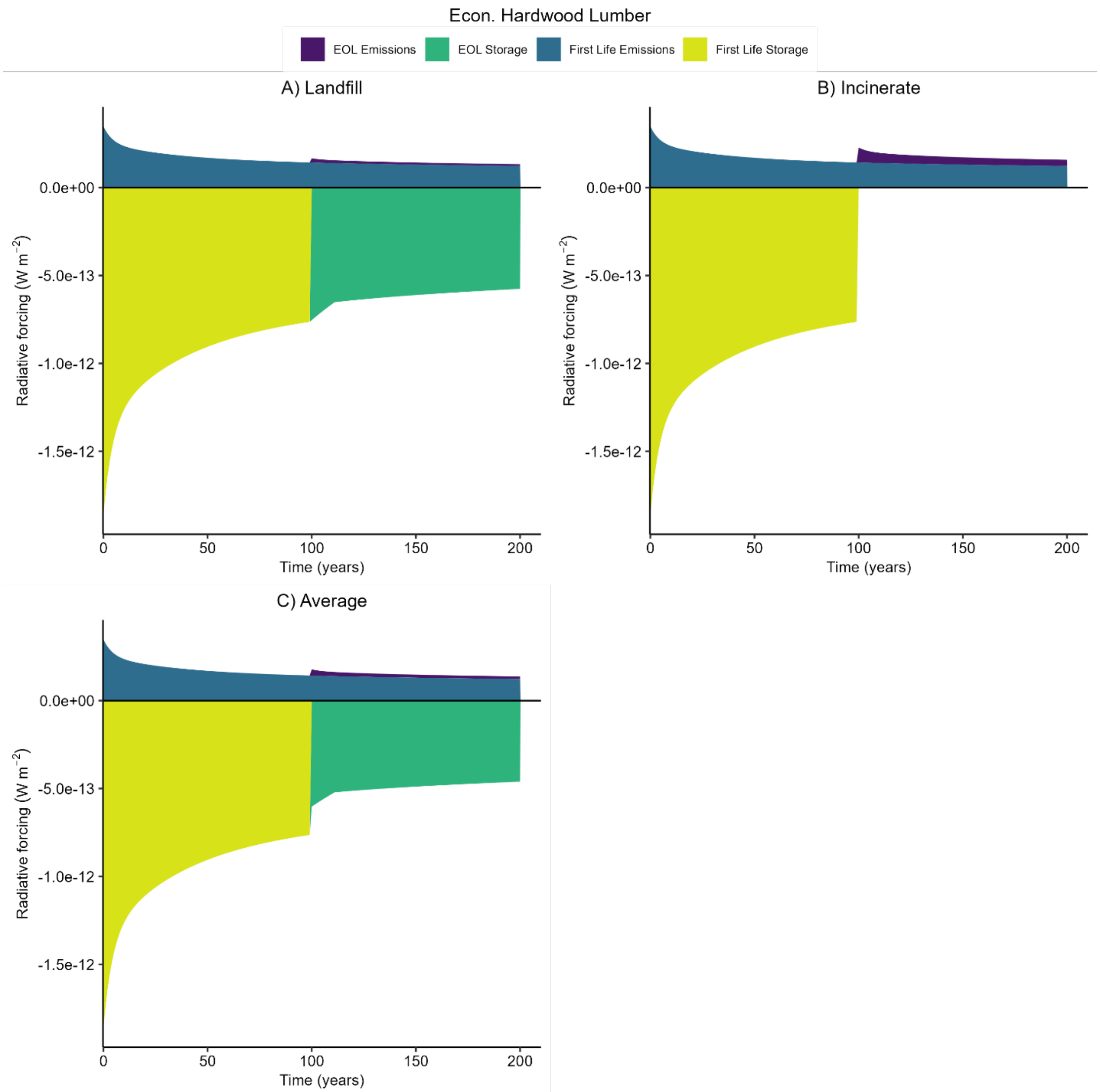

Figure 9.10. The atmospheric decay of carbon dioxide and the carbon storage benefit at year 0 to year 200 for hardwood lumber for the Economic intensive management scenario for three EoL of scenarios.

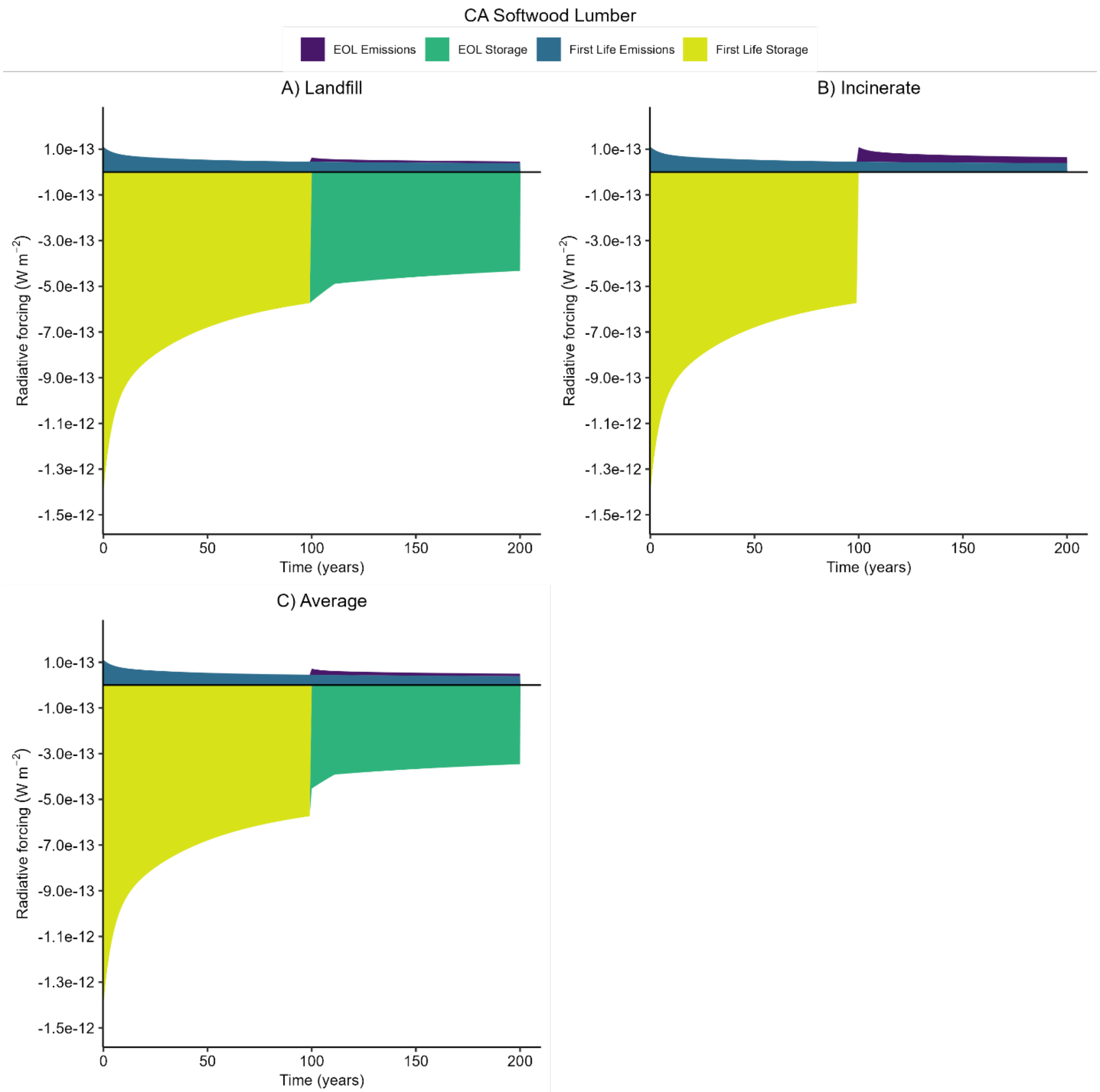

Figure 9.11. The atmospheric decay of carbon dioxide and the carbon storage benefit at year 0 to year 200 for softwood lumber for the Climate-adapted management scenario for three EoL of scenarios.

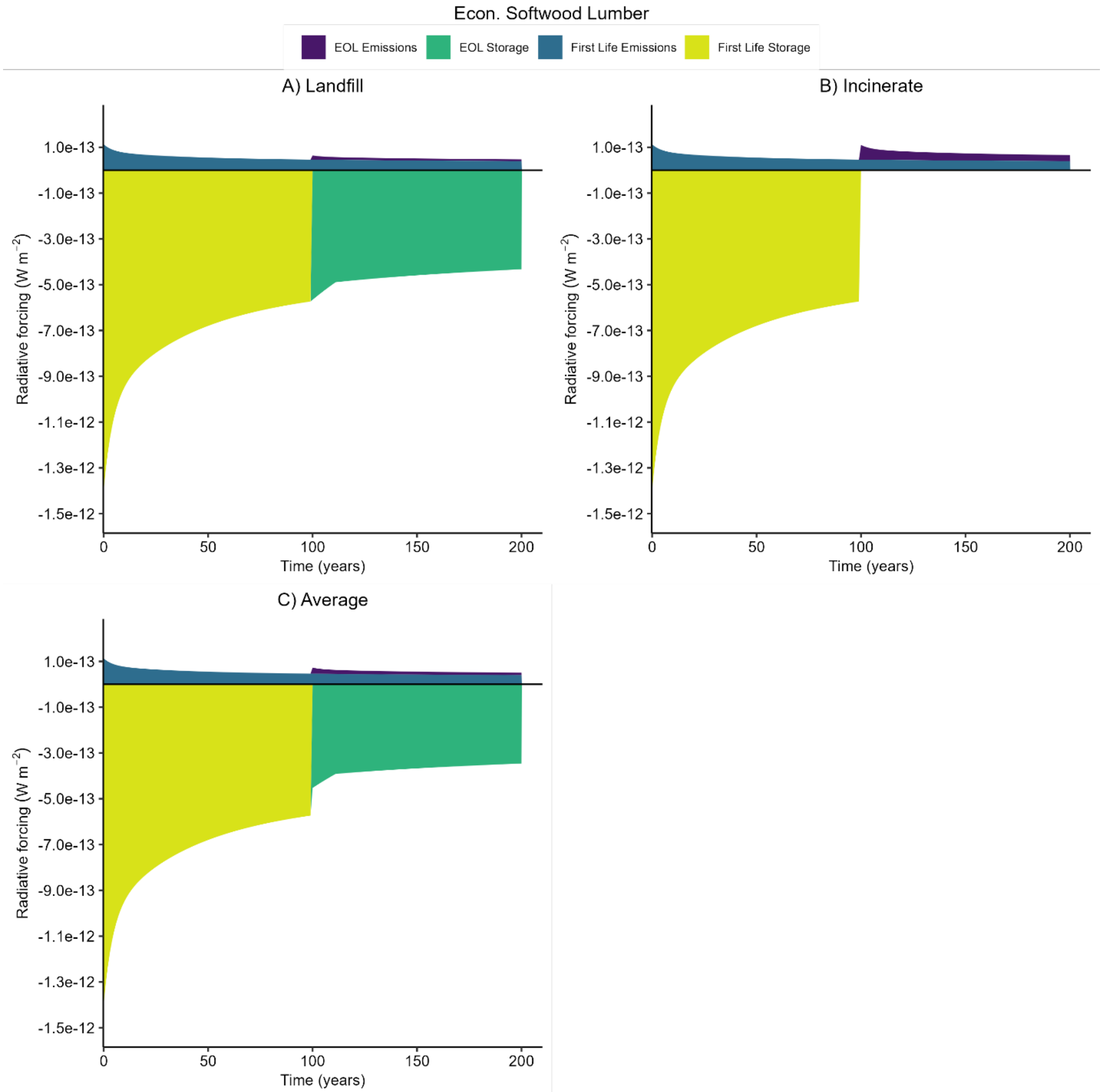

Figure 9.12. The atmospheric decay of carbon dioxide and the carbon storage benefit at year 0 to year 200 for softwood lumber for the Economic intensive management scenario for three EoL of scenarios.

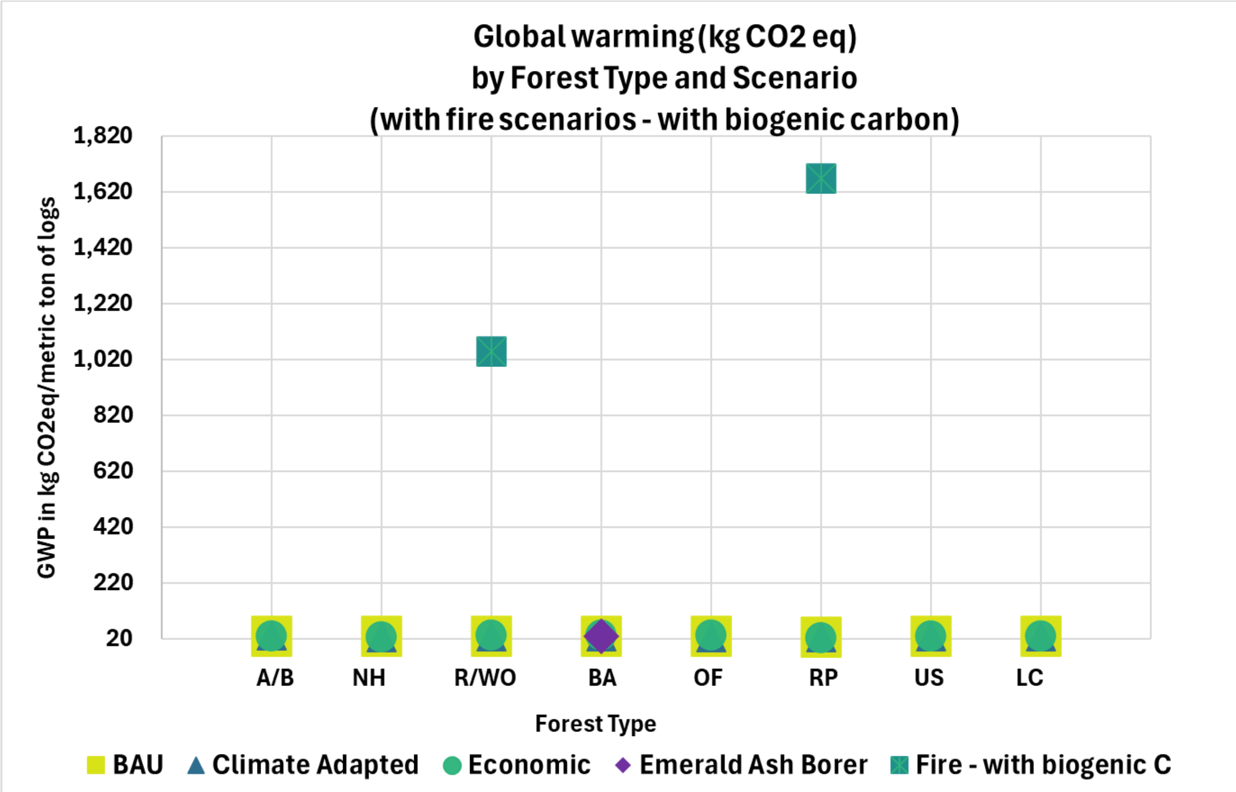

Figure 9.13. Warming Potential (kg CO_2 eq) per metric ton of green logs delivered to the mill. Reported by scenario and forest type. A/B = Aspen/Birch; NH = Northern Hardwoods, R/WO = Oak; BA = Black Ash; OF = Other Forest types; RP = Red Pine; US= Upland Spruce, LC = Lowland Conifer. includes Climate-adapted plus fire scenario, with biogenic carbon. Not shown – Climate-adapted plus fire scenario, excluding biogenic C.

9.8 MEMO – IMPACTS OF CHANGING MERCHANTABILITY LIMITS

To: MFRC members
From: Matt Russell, John Zobel, and UMN modeling team
Date: 3 Oct 2024; Updated 29 Oct 2024
Re: Impacts that changing merchantability limits have on FVS volume removals

There has been interest in understanding the "sensitivity" of volume removal estimates from Forest Vegetation Simulator runs after changing merchantability limits. The economic intensive scenarios were run again using a revised set of merchantability limits for the aspen/birch and red pine forest types. The differences in volume removed from all harvests that occurred in the 100-year simulation (measured in cords) were compared with current FVS estimates that used default merchantability limits.

Aspen/birch

For aspen/birch, the pulpwood top diameter was lowered to 3.0 inches. Here are the merchantability limits that were applied to all quaking aspen, balsam poplar, bigtooth aspen, and paper birch in the forest type:

FVS Version	Sawtimber Minimum DBH	Sawtimber top diameter	Pulpwood Minimum DBH	Pulpwood top diameter
Current FVS (using default merchantability limits)	11.0 in	9.6 in	6.0 in	4.0 in
Revised FVS (using "MN-specific" merchantability limits)	11.0 in	9.6 in	6.0 in	3.0 in

The impact of changing the merchantability limits in aspen/birch results in an increase of 0.7 cords being harvested on average, an increase of 5.8%. The volume harvested in pulpwood increases as a result of the lower merchantability limits, while sawtimber volumes remain the same. The change would annually affect 0.47% of all timberland acres statewide.

Aspen economic intensive scenario	**Volume harvested (cords/acre)***		
	Total	Sawtimber	Pulpwood
Current FVS Final harvest (age 40)	12.0	1.0	10.9
Revised FVS Final harvest (age 40)	12.7	1.0	11.7
Volume difference from current FVS (cords) (*over 40 year rotation*)	+ 0.7	0.0	+ 0.9
Percent difference from current FVS (*over 40 year rotation*)	+ 5.8%	0.0%	+ 7.8%

** Discrepancies in numbers due to rounding*

Red pine

For red pine, the sawtimber and pulpwood top diameters were lowered to 6.0 and 3.0 inches, respectively. Here are the merchantability limits that were applied to all red pine trees:

FVS Version	Sawtimber Minimum DBH	Sawtimber top diameter	Pulpwood Minimum DBH	Pulpwood top diameter
Current FVS (using default merchantability limits)	9.0 in	7.6 in	5.0 in	4.0 in
Revised FVS (using "MN-specific" merchantability limits)	9.0 in	6.0 in	5.0 in	3.0 in

The impact of changing the merchantability limits in red pine results in an increase of 0.7 cords being harvested on average, an increase of 1.1%. The volume harvested in sawtimber and pulpwood products shifts as a result of the lower merchantability limits. The change would annually affect 0.08% of all timberland acres statewide.

Red pine economic intensive scenario	**Volume harvested (cords/acre)**		
	Total	Sawtimber	Pulpwood
Current FVS			
1st thinning (age 30)	7.8	3.6	4.2
2nd thinning (age 40)	15.8	13.0	2.8
3rd thinning (age 60)	21.8	17.4	4.4
Final harvest (age 70)	24.2	18.0	6.2
Cumulative volume harvested	*69.6*	*52.0*	*17.6*
Revised FVS			
1st thinning (age 30)	8.0	4.6	3.4
2nd thinning (age 40)	15.9	14.4	1.4
3rd thinning (age 60)	22.0	19.5	2.5
Final harvest (age 70)	24.3	19.1	5.2
Cumulative volume harvested	*70.4*	*57.8*	*12.6*
Volume difference from current FVS (cords) (*over 70 year rotation*)	+ 0.7	+ 5.7	- 5.0
Percent difference from current FVS (*over 70 year rotation*)	+ 1.1%	+ 10.9%	- 28.3%

Summary: Due to the limited impact at the per acre and statewide levels, and after consultation with MFRC staff, the current FVS analysis was maintained. Revisions to merchantability limits were instead added to the list of possible future project updates.

Date: 3 Nov 2024
Re: Reply to Feedback Questions from Executive Director Eric Schenck
Note: Emails were edit for spelling

From: **John Zobel** <jzobel@umn.edu>
Date: Sun, Nov 3, 2024 at 7:33 PM
Subject: Re: Memo: Merchantability limits sensitivity analysis--please review and respond
To: Schenck, Eric (DNR) Eric.Schenck@state.mn.us\

Hi Eric!

After consulting with some team members on your merch limit questions, answers are embedded in **bold** below. If you have additional questions or need clarity on anything, please feel free to let me know. Thanks!

John Z.

On Wed, Oct 30, 2024 at 3:25 PM Schenck, Eric (DNR) <Eric.Schenck@state.mn.us> wrote:

John,

I greatly appreciate the extra effort that went into this sensitivity analysis.

However, I do ask you to clarify one of your summary sentences: "Due to the limited impact at the per acre and statewide levels, and after consultation with MFRC staff, the current FVS analysis was maintained." Please expand on the "consultation with MFRC staff" portion because I am sure I (we) will be asked.

During a prior meeting with the team (early October), we asked about the status of the merchantability redo. I appreciated David's answer that we were not going to go that route (lack of funding, time limits, further LCA redos, negligible change, etc.), but rather placing that adjustment in the follow-up category. The other team members agreed with this decision, and I think changing the limits falls within the scope of next steps.

Even more important, please help me understand the results/conclusions as they apply <u>specifically to red pine</u>. As you have now determined, the revised FVS showed very little difference on total volume harvest (+1.1%), but significantly more difference on the <u>split of the volume</u> between sawtimber (+10.9%) and pulpwood (-28.3%).

The red pine split is certainly the biggest change from our original runs. However, the +5.7 cords/ac increase in sawtimber and -5.0 cords/ac decrease in pulpwood are cumulative over 70 years. This averages out to annual changes of +0.08 cords/ac sawtimber and -0.07 cords/ac pulpwood. That said, summed over all the acres over the projection period, the numbers get larger. But the effect is a drop in the bucket when we consider the forest as a whole.

Also, you state that changing the FVS merchantability for red pine only affects .08% of the timberland acres statewide. The real question is not so much how this affects the "all cover types" results (I think your answer is negligibly), but how does the sawtimber vs pulp assumptions specifically affect the red pine results?

As far as red pine results specifically, the non-LCA results will change negligibly (see below), and the per unit LCA results also will not change. Once you scale up the per unit to statewide (David's work), you may begin to see noticeable red pine changes. But given only 2.5% of red pine acres are harvested each year, the in-forest carbon component will likely dwarf the changes at the product level. When considering carbon and our different management scenarios as a whole, the effects are miniscule. If we stress red pine results alone, we run the risk of making a large issue out of one that has no practical effect on the objectives of this study.

A few follow-up questions that I ask you to please briefly (best guess) answer. No additional analysis is requested.

1. For red pine acres, would the sawtimber/pulpwood harvested volume differences make any difference in the FVS determined C stocks or net C/CO2 flux? (i.e., no LCA considerations). -- **No, there should be negligible impact on the FVS carbon results.**

2. Similarly, would the results of the economic intensive red pine scenario be any different than the BAU or climate adaptive FVS results for C stocks or C/CO2 flux? -- **Besides the differences already noted in the original runs, no, the merch limit changes should not noticeably impact comparisons across FVS scenario runs.**

3. Now considering the comprehensive red pine model results which includes harvested wood and LCA, can we assume that the LCA results are where the sawtimber vs pulp volume carbon differences are most pronounced? Is there any way that this can be compared/estimated short of completely running more LCA's? (e.g., by comparing the per acre LCA results of the two different products?) -- **Elaine responded that the merch limit changes will not noticeably impact the forestry LCAs and will not impact the manufacturing LCAs either, since the input into the latter is on a per m3 scale. It's the same amount of wood either way. She suggested statewide impact might change a bit, once scaled up. Again, though, we are only considering the 2.5% of red pine acres harvested each year. The cumulative effects of the new product allocations may be slightly noticeable across the 100 year projection, but they may also be swamped by the signal from the unharvested acres. I think the latter is much more likely, leading to essentially the same graphs for red pine regardless of which merch limits were used.**

4. My impression is that overall, the harvested wood portion of the carbon assessment makes relatively small difference to the overall C/CO2 results because the amount of carbon stored in forest products is only slightly more than the emissions. However, I must assume that the difference is most pronounced in red pine because of the difference in longevity between lumber and paper. Again, can you opine on red pine sawtimber vs. pulp specific to the LCA results? -- **We feel that, given the annual amount of acres harvested in red pine is small enough (2.5%), and relative to the full forest carbon system, the product differences will have minimal effect on the results, for both red pine and all cover types.**

5. In your summary section, can we "tweak" the idea of future project updates involving "more red pine scenarios that include, for example, alternative merchantability

assumptions, harvest volumes, and product substitution effects (e.g. mill residuals for biofuel).” -- **I am perfectly fine with tweaks! I tried to keep this 2-pager merch limit specific, as our final report might include a section on future opportunities, but we can include some here too, if helpful.**

6. Finally, I believe the red pine cover type is 700,000 acres, but altogether there is about 1 million acres of red pine some of which is a component of other cover types. Which do you use when running the FVS model or thinking about results (i.e., are the results stand level cover type specific or tree species specific) -- **I believe manageable red pine cover type timberland is around 524,000 acres, and yes, red pine show up in other cover types as well. The FVS model follows species, not cover type when making projections. However, the harvest specs may differ for red pine in a plantation vs. naturally occurring as a sub-species in a stand, even one that is intensively managed. I think the spec differences most aptly apply the red pine cover type economic intensive scenario. If we had implemented it, however, I suspect we would have used the same specs for all scenarios to avoid turning another dial. Also, Matt brought up the good point that merch limits are set at the mill, not on a statewide basis. We examined the impacts of changing limits relative to say the Potlatch mill, but other stud mills/saw mills could have different limits. Thus, more variability across different wood producers. We faced a similar issue when deciding on business as usual. Different agencies/producers have different definitions of BAU, but we chose an "average" BAU. The default merch limits we used in our study might also be considered as this "average" condition.**

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