Carbon in Minnesota's Forests: Current Status and Future Opportunities

A report prepared for the Minnesota Forest Resources Council[1]

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10 June 2022

[1] Funding and support for this project was provided by the Minnesota Forest Resources Council.

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Executive Summary

In 2021, the Minnesota Forest Resources Council (MFRC) funded the University of Minnesota, Department of Forest Resources to synthesize forest carbon resources in Minnesota and develop a scoping document that outlines the current status and future opportunities of forest carbon in the state. This team was made up of researchers and Extension professionals at UMN with experience in forest management, silviculture, forest biometrics, and remote sensing. Specifically, the team’s work centered around two activities:

1. Synthesize Minnesota forest carbon resources and develop outreach materials, and
2. Develop the scope of a Minnesota Forest Carbon Strategic Plan.

The team accomplished these activities through compiling relevant literature and data sources, delivering a series of outreach events, holding focus group sessions with key stakeholders, and performing data analysis and forest growth simulations. The project is also producing a data dashboard that includes an interactive format to visualize forest carbon attributes across MFRC’s regional landscapes. State-level estimates of Minnesota’s forest carbon resource compiled by the USDA Forest Service (Domke et al. 2021; Walters et al. 2021) form many of the quantitative results produced in this report. Two focus groups were held in fall 2021 with 17 middle- to upper-level natural resource managers as well as private landowners with the goal to understand perceptions and viability of carbon sequestration as a management goal for public and private forest landowners. In fall 2021 the Sustainable Forests Education Cooperative delivered the Minnesota Forest Carbon Series, a series of virtual educational programs and in-person field tours that discussed carbon in the context of forest management, ecosystem markets, and new technologies.

Despite human-induced and natural forest disturbances, carbon storage has increased over the last several decades in Minnesota. Total forest ecosystem carbon stocks in Minnesota have increased from 1,131 million metric tonnes (MMT) in 1990 to 1,224 MMT in 2020, an increase of 8.3%. Across the five primary component pools (aboveground biomass, belowground biomass, dead wood, litter, and soil), the largest increase over the past 30 years has occurred in the aboveground biomass pool, where carbon stocks have increased by 29.2%. Understanding how Minnesota’s trees and forests store and sequester carbon leads to a better knowledge of their importance in meeting future statewide challenges related to climate change.

Information needs and opportunities

Through this project, we identified nine major thematic information needs and opportunities that warrant closer exploration and research related to forest carbon in Minnesota. These themes derive from our series of focus groups with stakeholders and are discussed further in Section IV of this report (“Carbon Opportunities: A Needs Assessment for Minnesota”) and are summarized in Figure 1.

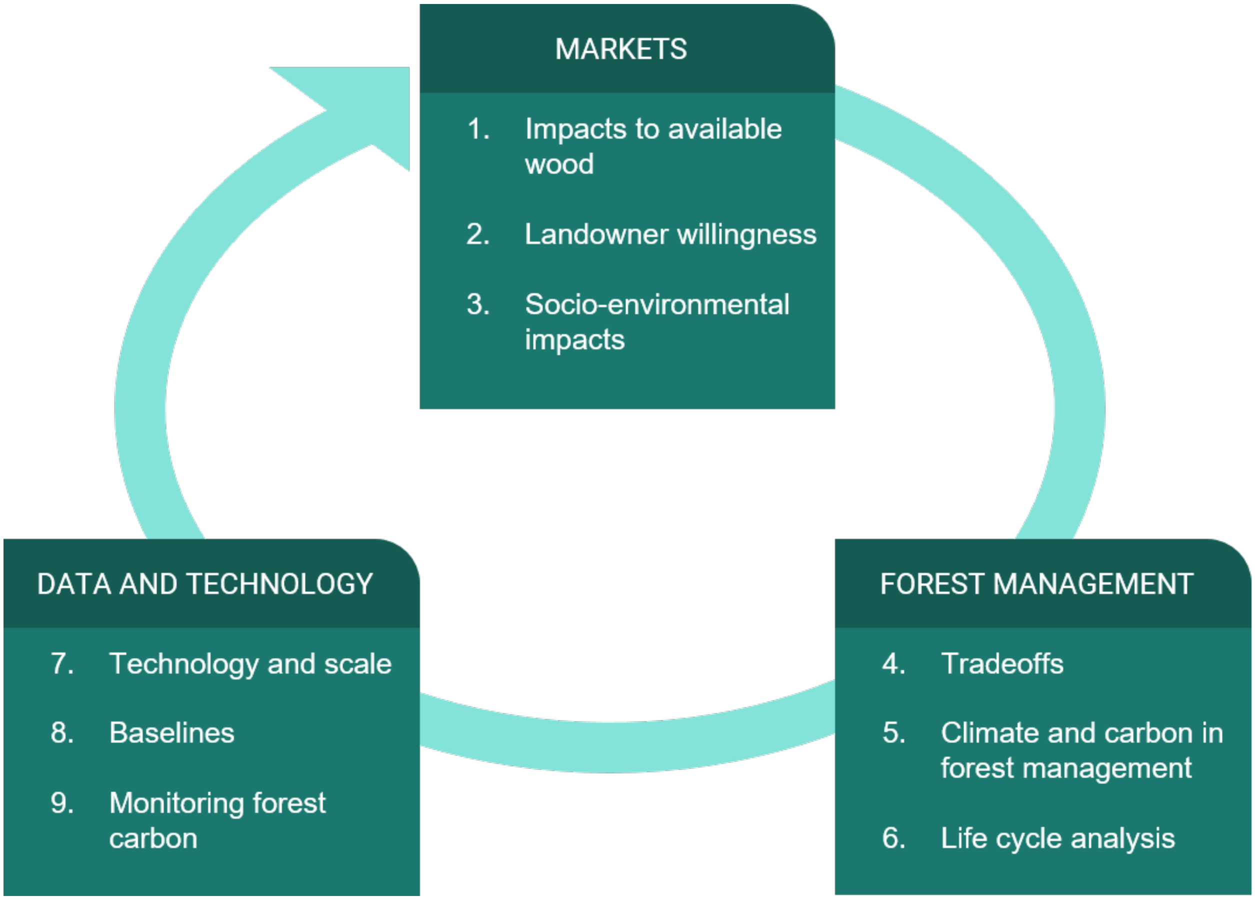

Fig. 1. Overview of nine major thematic information needs and opportunities that warrant closer exploration and research related to forest carbon in Minnesota.

Markets

1. There remains great uncertainty about the long-term effects of lands enrolled in forest carbon programs and impacts to available wood for forest product markets.

2. The opportunities, advantages, and barriers to entering voluntary and regulatory carbon markets for Minnesota's diverse landowners needs to be fully assessed. Research that investigates the price of carbon and landowner willingness to enroll in carbon markets should be a focus of future work.

3. Carbon markets are perceived in both a negative and positive manner from Minnesota's diverse landowners. The socio-environmental aspects of carbon markets need to be fully explored.

Forest management

4. Integrating carbon as a forest management objective needs to be evaluated along with several other management objectives.

5. Forest management is transitioning from managing forests for resources to managing them for multiple services and values including climate adaptation and now climate mitigation. A more thorough understanding of how different adaptive management treatments influence forest carbon storage and sequestration patterns should be carried out for Minnesota's primary forest types.

6. A complete life cycle assessment that focuses on timber harvesting, forest management for carbon, and in harvested wood products should be carried out for Minnesota's primary forest types.

Data and technology

7. Remote sensing technology can leverage existing forest inventory information to better understand forest carbon, yet applications are currently limited at a broad scale in Minnesota.

8. There is an urgent need to better understand baselines of forest carbon in Minnesota, for example, the amount of carbon being stored and sequestered annually in Minnesota. Continuing to develop and deliver this information in a form that is accessible and understandable to a broad audience should be prioritized.

9. Agreement needs to be met across the forestry community about how forest carbon is going to be monitored at a state, regional, and stand level.

I. Introduction to Carbon in Minnesota's Forests

Overview of forest carbon concepts

One of the primary benefits that trees and forests provide to society is removing carbon dioxide from the air. Carbon dioxide is the leading source of greenhouse gas emissions in the United States, accounting for approximately 80 percent of all US greenhouse gas emissions from human activities (Environmental Protection Agency 2020). Healthy trees and forests remove carbon dioxide and other greenhouse gases from the atmosphere. In 2019, forest land and trees in urban settlements and harvested wood products offset 14% of all US carbon dioxide emissions on an annual basis (Domke et al. 2021). Within forests, carbon can generally be referred to as how much is **stored** (the current amount of carbon in a tree or forest) or **sequestered** (the process by which trees and other plants use carbon dioxide and photosynthesis to store carbon as plant biomass). In other words, carbon storage reflects a physical amount that is the result of sequestration, hence, storage is referred to as an amount and sequestration a rate. A complete glossary and definition of terms used throughout this report can be found later in this section.

Understanding how trees and woodlands use carbon leads to a better knowledge of their importance in meeting future global challenges related to climate change. While much attention has emphasized the amount of carbon in trees, forests store carbon in five different pools:

- Live trees, aboveground: Includes trees, shrubs and other vegetation.
- Live trees, belowground: Includes coarse and fine roots.
- Dead wood: Includes standing dead trees and downed dead wood.
- Litter: Includes leaves and other small woody material.
- Soil: Includes mineral and organic soil with dead and decaying plant material and insects.

Most of the focus on understanding forest carbon has been on the aboveground live tree pool, as this pool is more easily measured and is directly altered through forest management or disturbance. Across large geographic scales, the amount of carbon in a tree or forest is rarely measured directly. Instead, foresters commonly measure tree attributes in a forest inventory such as species, diameter, and height, and then use a series of species-specific equations to predict the biomass of a tree (e.g., Jenkins et al. 2003; Woodall et al. 2011). Foresters then approximate that half of a tree's dry weight is carbon. For the same sized tree, hardwood species such as maple and oak will generally contain greater carbon storage than conifers such as pine and spruce. The amount of carbon that is stored in other non-live tree components such as dead wood and litter also depends on stand age, disturbance history, and species composition, among other factors.

Carbon can also can be stored "off site" in harvested wood products in a variety of forms that can be short-lived (such as paper) or long-lived (such as utility poles or wood-based construction materials). While forestry activities contribute to emissions through the harvest and transport of our trees, silvicultural activities, and forest management operations, harvested wood products in use and solid waste disposal sites (e.g., landfills) represent 4.5% of the total amount of carbon in the US (Domke et al. 2021). Societal benefits of harvested wood products include carbon storage and lower emissions than fossil fuel-intensive materials such as steel and concrete. Substituting the use of wood products as opposed to greenhouse gas-intensive construction materials is an environmentally sound approach with a lower overall carbon footprint. For example, mass timber buildings such as the T3 building in

Minneapolis, MN (https://mg-architecture.ca/work/t3-minneapolis/) are lighter than other traditional buildings designed with steel. Mass timber building are also fire-resistant, are built more quickly compared to a traditional concrete and steel building, and will continue to store carbon for at least decades into the future.

Components of carbon flux in US forest lands can be defined as an **emission** (or sources of carbon dioxide and other greenhouse gases) or **removal** (or sinks of carbon dioxide and other greenhouse gases). As presented in Domke et al. (2021), across all US forestlands, the largest removal in the land use, land use change, and forestry sector is represented by forest land remaining forest land, uptaking 583.3 million metric tonnes of CO_2-equivalent (MMT CO_2-Eq.) in 2019. The second and third largest removals are represented by urban trees in settlements (129.8 MMT CO_2-Eq.) and harvested wood products (108.5 MMT CO_2-Eq.), respectively. The largest emission in the land use, land use change, and forestry sector is represented by forest land converted to non-forest land (125.3 MMT CO_2-Eq.) and can be contrasted by the removal associated with non-forest land converting to forest land (-99.1 MMT CO_2-Eq.).

Minnesota's contribution to forest carbon

The state of Minnesota and its forests play an important role in understanding the relationship of carbon with ecosystem services and future climate change. Organizations and agencies within the state have made a number of significant investments to better understand the role of forest carbon and how the state is uniquely positioned to address future challenges and opportunities.

As an example, Climate Change Executive Order (19-37) created the Governor's Advisory Council on Climate Change directing state agencies to take action to reduce greenhouse gas emissions, build community resilience, and engage with Minnesotans on issues related to climate change. In response, forests, forestry, and forest products are widely discussed in the state's draft Climate Action Framework (https://climate.state.mn.us/minnesotas-climate-action-framework). Natural and Working Lands is one of five framework sections outlined in the Climate Action Framework to describe climate challenges, opportunities, and strategies. Specifically related to carbon, its goals as originally stated in 2021 publication were to:

- Increase carbon annually sequestered in natural and working lands by 25% by 2035 from 2014-2018 average levels, through restoration, management, and using carbon smart practices,
- Reduce [net] annual GHG emissions in the working lands sector by 25% by 2035 from 2018 levels, and
- Enhance biodiversity and protect habitat corridors on 350,000 acres by 2035.

As another example, Minnesota intensifies the number of Forest Inventory and Analysis (FIA) plots measured compared to other states, providing additional valuable information on its forest carbon resource. These FIA plots are remeasured approximately every five years, with one plot occurring on approximately every 3,000 acres. In the 2014-2018 measurement cycle, 6,307 plots were measured across Minnesota's 17.6 million acres of forests (Zobel et al. 2019).

In 2020, the Minnesota Forest Resources Council delivered the Climate Change and Minnesota's Forests report (Friesen 2020), including a detailed section on forest carbon storage and sequestration. It describes approaches to increase the sequestration and storage of carbon as a tool to mitigate effects of climate change. Specifically, forest retention, afforestation and reforestation, forest management, and forest products and markets are discussed. Differences between compliance and voluntary carbon markets are also presented, with several Minnesota landowner examples.

Other recent examples investigating the forest carbon storage and sequestration capacity in Minnesota forests include a project funded in 2020 quantifying the carbon storage potential and opportunity across 1.5 million acres of Minnesota's school trust lands, led by Dovetail Partners. Work has focused on quantifying the potential for improved forest management strategies and identified policy avenues to improve forest management for carbon storage.
(https://www.dovetailinc.org/blogdetail.php?id=5f69559a06a5f).

In the fall of 2021, a series of virtual and in-person field tours were hosted by the Sustainable Forests Education Cooperative as a part of the Minnesota Forest Carbon Series. Educational programs included a three-day virtual workshop and field tour at the Cloquet Forestry Center focused on carbon markets, a field tour at the Chippewa National Forest focused on silvicultural practices and forest carbon, and a three-part webinar series focused on technology and forest carbon. Recordings of the virtual components of these workshops can be found at https://z.umn.edu/CarbonSeries.

Given the widespread interest in understanding forest carbon opportunities and challenges, Minnesota's efforts to date appear to be at a similar stage compared to other states where forests make up a large portion of the land base. While some states have produced reports in the last one to two years that synthesize current information on carbon sequestration and storage (e.g., Oregon, Maine), other states like Minnesota are beginning to conduct similar assessments understanding the contribution of forest carbon within the state. Table 1 describes several recent or ongoing efforts by other states seeking to understand forest carbon baselines.

Table 1. Projects conducted at the state level investing in forest carbon research and impacts.

State	Description of work	Sources
Lake States		
Minnesota	• Climate Change and Minnesota's Forests report includes section on forest carbon storage and sequestration (2020). • Climate Change Executive Order (19-37) created the Governor's Advisory Council on Climate Change • Natural and Working Lands Action Team created to describe climate challenges, opportunities, and strategies. • Investment in Minnesota's Forest Carbon Strategic Plan, conducted by University of Minnesota (2021-2022). • MN Department of Natural Resources provided recommendations to MN Pollution Control Agency on measuring annual forest carbon contribution to greenhouse gas offsets. • The American Forest Foundation and The Nature Conservancy has conducted modeling scenario analysis and stakeholder workshops for its Family Forest Carbon Program.	• https://climate.state.mn.us/minnesotas-climate-action-framework • https://mn.gov/frc/assets/Climate_Change_and_Minnesota%27s_Forests_2020_tcm1162-471265.pdf
Wisconsin	• The Wisconsin Department of Natural Resources and Nelson Institute for Environmental Studies have created resources on climate change and forest carbon as a part of the Forestry Working Group in the Wisconsin Initiative on Climate Change Impacts (2020). • Second edition of *Climate Change Field Guide for Northern Wisconsin Forests* includes section on Forest Carbon Management. • Governor's Task Force on Climate Change Report mentions forest carbon as an opportunity to prioritize forest conservation and provide access to carbon markets for family forest landowners.	• https://wicci.wisc.edu/forestry-working-group/ • https://forestadaptation.org/field-guide-northern-wisconsin • https://climatechange.wi.gov/Pages/Home.aspx
Michigan	• The Bluesource/Michigan DNR Big Wild Forest Carbon Project is the first of its kind in the nation to sell forest carbon offset credits from state-owned forests. • The Forest Carbon and Climate Program exists at Michigan State University to connect professionals, natural resource managers, decision-makers, students and the broader public with the value of forested lands and forest products in addressing climate change.	• https://www.michigan.gov/dnr/0,4570,7-350-79134_103466---,00.html • https://www.canr.msu.edu/fccp/
Other states		
Oregon	• The *Carbon in Oregon's Managed Forests* document produced by the Oregon Forest Resources Institute synthesizes current information on carbon sequestration and storage in Oregon's working forests and in harvested wood products. • In 2018, the Oregon Department of Forestry received funding to develop an assessment of the amount of carbon in Oregon's forests.	• https://oregonforests.org/node/753 • https://www.oregon.gov/odf/forestbenefits/Pages/forestcarbonstudy.aspx

Washington	• In 2019 Washington State passed legislation directing its Department of Natural Resources to conduct specific activities related to carbon sequestration on natural and working lands. The Natural and Working Lands Carbon Sequestration Advisory Group was created to provide advice and guidance regarding DNR's efforts related to carbon sequestration on natural and working lands.	• https://www.dnr.wa.gov/CarbonAdvisoryCmte
California	• The California Forest Carbon Plan, released in 2018, describes forest conditions across California and provides a projection of future conditions under climate change.	• https://resources.ca.gov/CNRALegacyFiles/wp-content/uploads/2018/05/California-Forest-Carbon-Plan-Final-Draft-for-Public-Release-May-2018.pdf
Indiana	• Indiana Department of Natural Resources have completed a forest carbon assessment for Indiana State Forest properties	• https://www.in.gov/dnr/forestry/files/fw-carbon_assessment.pdf
Florida	• In 2021, the Florida Forest Service administered the Sequestering Carbon and Protecting Florida Land Program, a $10 million grant program to help remove up to 69,000 tons of carbon dioxide from the atmosphere.	• https://www.fdacs.gov/News-Events/Press-Releases/2021-Press-Releases/Commissioner-Nikki-Fried-Florida-Forest-Service-Launch-10-Million-Carbon-Sequestration-Grant-Program
Georgia	• The Georgia Carbon Sequestration Registry is a platform that facilitates exchanges between businesses that emit carbon and forest landowners that sequester it in their forests. It is a non-profit program established by Georgia Senate in 2004, but only provides a record of carbon storage in registered forestland that may be used for many different purposes and does not assign dollar value to carbon.	• https://gatrees.org/forest-management-conservation/carbon-sequestration/
Pennsylvania, Maryland, West Virginia	• The Family Forest Carbon Program, offered by the American Forest Foundation and The Nature Conservancy, began a pilot in these states in 2020.	• https://www.familyforestcarbon.org/
New York	• New York State has funded a forest carbon accounting project that includes high-resolution forest mapping, historical change detection, landscape monitoring and hierarchical forecasting. • State University of New York College of Environmental Sciences and Forestry will provide the New York State Department of Environmental Conservation analytic support needed to conduct an inventory and forecast of forest-based greenhouse gas emissions and carbon sequestration in the state and to incorporate feedback from technical advisory groups and stakeholders.	• https://cafri-ny.org/new-york-forest-carbon-assessment/ • https://portal.nifa.usda.gov/web/crisprojectpages/1021051-new-york-state-forest-carbon-assessment.html
Connecticut	• Working and Natural Lands Working Group - Forests Sub Group released report in 2020 with recommendations for policy, funding, conservation, research, and stewardship actions which would both make Connecticut forests more resilient and enhance their potential for sequestering and storing carbon.	• https://portal.ct.gov/DEEP/Forestry/Climate-Change/Carbon-and-Forests
Massachusetts	• Excellent information on forest carbon and forest management available on Massachusetts	• https://www.mass.gov/info-details/managing-our-forests-for-carbon-benefits • https://masswoods.org/caring-your-land/forest-carbon

	Department of Conservation & Recreation and UMass Amherst web pages	
Maine	• Governor's Task Force in Maine explored the creation of a Forest Carbon Program, with a report in 2021 • University of Maine has released the State of Maine's Carbon Budget as a part of their Forest Climate Change Initiative.	• https://www.maine.gov/future/initiatives/climate/climate-council/forest-carbon-taskforce • https://crsf.umaine.edu/forest-climate-change-initiative/

II. Carbon Storage and Sequestration in Minnesota's Forests

Data provided by the USDA Forest Service are available to quantify carbon storage and sequestration patterns in Minnesota's forests. Data contained in *Greenhouse gas emissions and removals from forest land, woodlands, and urban trees in the United States, 1990 – 2019* (Walters et al. 2021) were queried for Minnesota. The year 1990 is a common reporting year for climate and carbon-related data as it aligns with national and international protocols and agreements. Data tables present carbon stocks and flux estimates dating back to 1990 with a number of units, including carbon and carbon dioxide equivalent.

Minnesota's forest carbon profile

Over the last 30 years, in forests that have remained forests total forest ecosystem carbon stocks in Minnesota have increased from 1,131 million metric tonnes (MMT) in 1990 to 1,224 MMT in 2020, an increase of 8.3% (Fig. 2). Across all component pools, the largest increase has occurred in the aboveground biomass pool, where carbon stocks have increased from 202 MMT in 1990 to 261 MMT in 2020, an increase of 29.2%. In relative terms, the largest percent increase in carbon stocks have been in dead wood pools (+43.9%). Carbon stocks have also increased in belowground biomass (+30.1%), litter (+2.3%), and mineral soil (+0.51%) with a slight decrease in organic soil (-0.04%). In 2020, carbon stocks in belowground biomass represented 19.6% of the aboveground component. Carbon stocks in mineral and organic soil represented 63.7% of total forest ecosystem carbon in 2020.

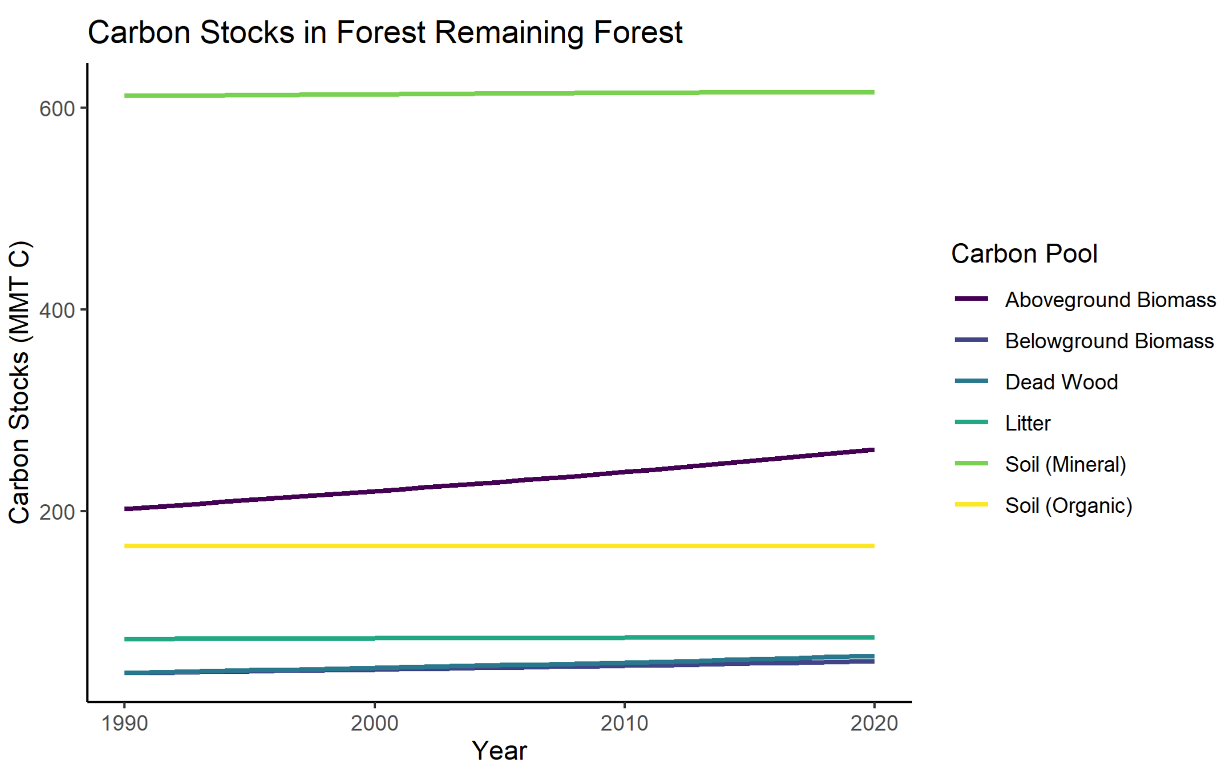

Fig. 2. Carbon stocks in forest remaining forest in Minnesota, 1990-2020.

The carbon flux in trees indicates a continual removal of carbon from the atmosphere over the last 30 years. The aboveground biomass pool shows the greatest removal of carbon across all pools, ranging from -6.63 MMT CO_2 Eq. in 1990 to -8.56 MMT CO_2 Eq. in 2019. Belowground biomass and dead wood pools also have seen increasing removals of carbon over the last 30 years (Fig. 2).

The carbon flux in litter and mineral soil have continued to show removals over the last 30 years, but at a decreased rate. Organic soils transitioned from being a removal in 1990 (-0.59 MMT CO_2 Eq.) to an emission in 2019 (0.26 MMT CO_2 Eq.). The carbon flux in drained organic soil has remained constant over the last thirty years, with an emission of 0.32 MMT CO_2 Eq. annually (Fig. 3).

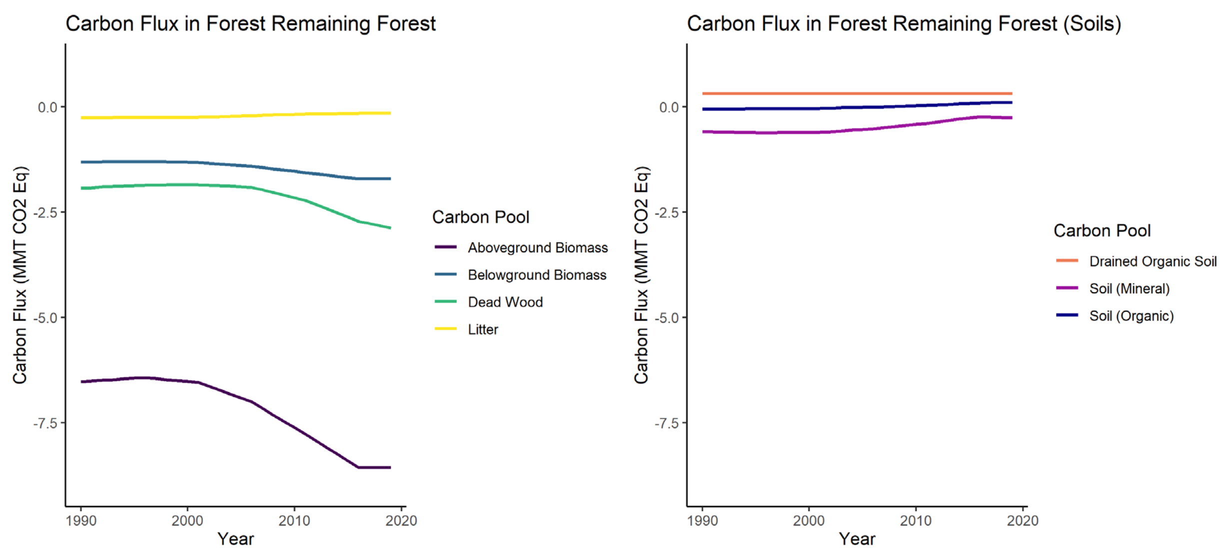

Fig. 3. Annual carbon flux in forest remaining forest for non-soil and soil pools in Minnesota, 1990-2019. Note: negative values indicate removals of carbon from the atmosphere and positive values emissions.

Urban trees growing in settlements continue to be an important sink of carbon dioxide in Minnesota. The net flux of trees in urban areas ranged from -0.68 MMT CO_2 Eq. in 1990 to -0.84 MMT CO_2 Eq. in 2019, an increase of 23.5% (Fig. 4). The net flux in Minnesota's urban trees is 9.8% of the net flux in the aboveground biomass of trees in Minnesota's forests, an important component of the overall sink strength of the state's growing trees.

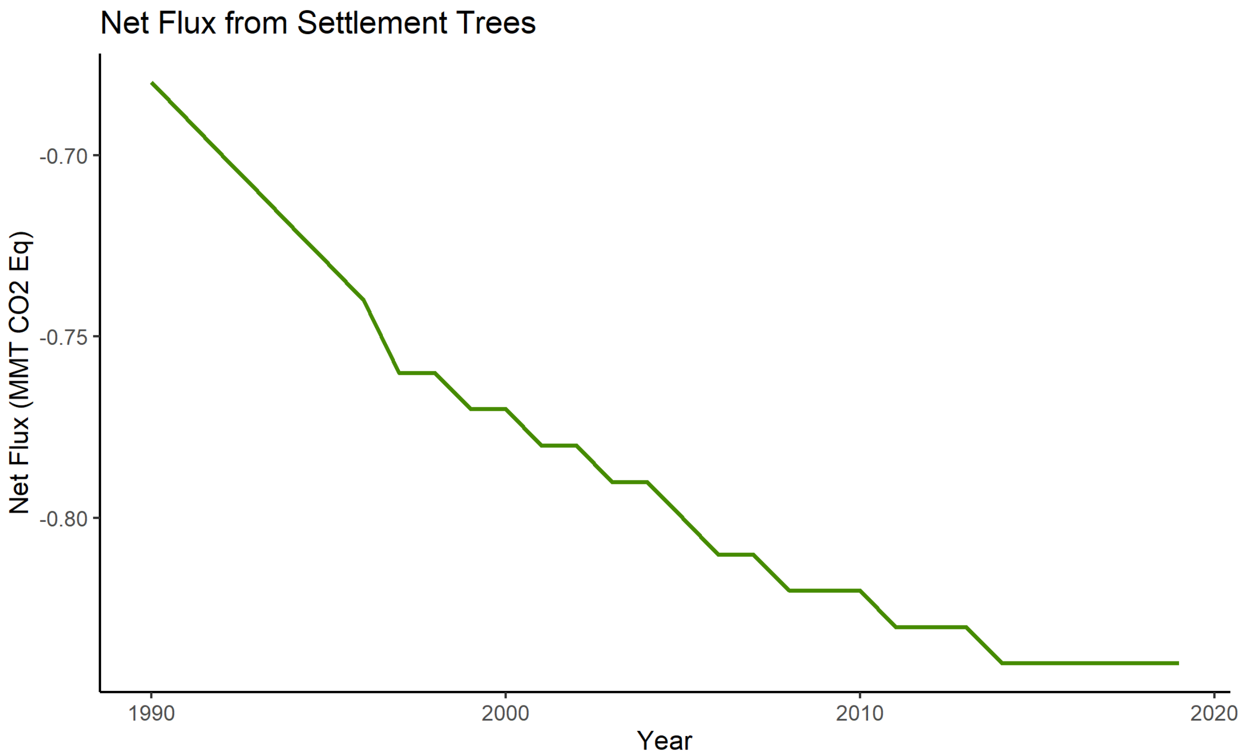

Fig. 4. Carbon flux in urban trees in settlements in Minnesota, 1990-2019. Note: negative values indicate removals of carbon from the atmosphere and positive values emissions.

Forest disturbances such as fire can result in large immediate emissions of greenhouse gases to the atmosphere. Data from Minnesota from 1990 through 2017 indicate carbon as the leading greenhouse gas emission from fires in forms such as methane (CH_4), nitrous oxide ($N2_O$), and other nitrogen oxides (NO_X). Greenhouse gas emissions from fire were as high as 286 kt in 2011 due to the Pagami Creek Fire, a 90,000-acre fire that burned in Lake County. Excluding 2011, greenhouse gas emissions from fire in Minnesota have averaged 4.8 kt per year (Fig. 5).

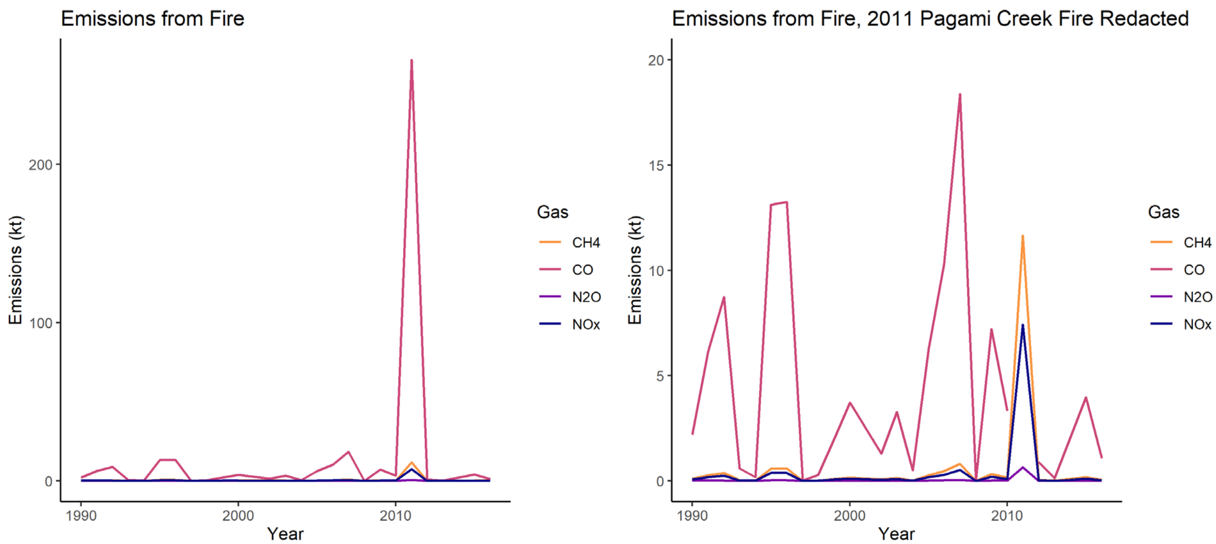

Fig. 5. Greenhouse gas emissions from fire in Minnesota, 1990-2017.

Forest land in Minnesota has increased from 16.8 million acres in 1990 to 17.6 million acres in 2019. Land transition to forest represented 79,100 acres in 2019, with the majority converting from wetlands followed by croplands. Land transition from forests to other land uses represented 49,500 acres in 2019, with the majority converting to wetlands followed by croplands and settlements. Conversion of forests to settlement has seen the largest increase of all land use changes since 1990 (Fig. 6). Forest land converted to other land use represents an overall emission for all carbon pools, while land use change into forests represents a removal for all carbon pools (Fig. 7).

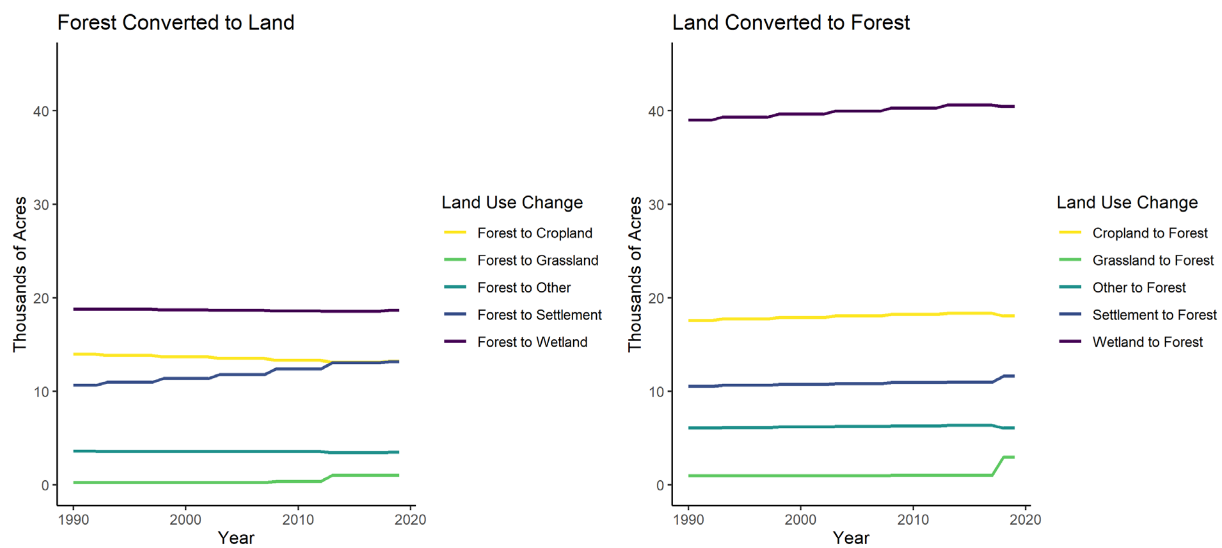

Fig. 6. Land use change involving Minnesota's forests, 1990-2019.

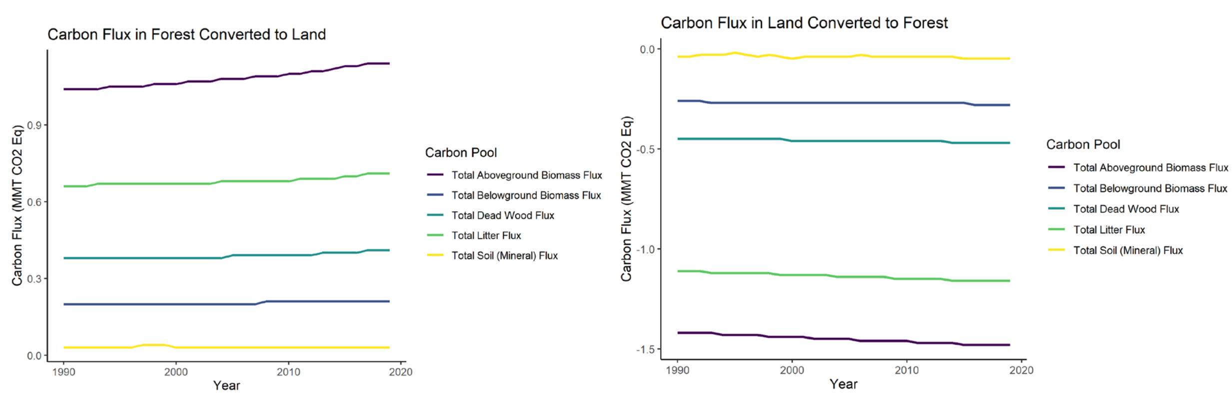

Fig. 7. Carbon flux associated with land use change of Minnesota's forests, 1990-2019. Note: negative values indicate removals of carbon from the atmosphere and positive values emissions.

Forest carbon simulations for Minnesota's primary forest types

To understand the carbon dynamics of Minnesota's primary forest types and the role of forest management, this project simulated carbon stocks for several forest types and forest management treatments. Three treatments were simulated for each forest type: a no management treatment, a "business as usual" treatment, and a climate-adapted treatment. The no management treatment assumes no management throughout a 100-year simulation period. The business as usual treatment represents a common forest management treatment being conducted in the forest type in Minnesota today. Business as usual treatments were informed from a recent survey of silvicultural actions in the state (Windmuller-Campione et al. 2019). The climate-adapted treatment was selected to represent a forest management approach that seeks to create resilient forests, typically by increasing species or structural diversity (Table 2).

Table 2. Overview of forest types simulated with Forest Vegetation Simulator for carbon attributes.

Forest Type	**Rotation age (years)**	**No management treatment**	**Business as usual**	**Climate-adapted treatment**
Red pine (of natural origin)	100	No management	Thin from below; thinning to 90 sq ft/ac every 20 years	Plant 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.
Aspen	50	No management	Harvest aspen at year 50. Simulate two cycles.	Plant mixed-woods systems and encourage conifer with aspen (40%), white spruce (40%), eastern white pine (10%), and northern white-cedar (10%). Harvest 50% of aspen at year 50 and let conifers grow
Mesic hardwood (sugar maple – basswood – northern red oak – paper birch)	100	No management	Thinning every 20 years beginning at year 30; thin to 90 sq ft/ac.	Selection harvests, with cuts every 20 years beginning at year 30 to promote uneven-aged stands.
Oak (northern red oak – white oak)	100	No management	Two-stage shelterwood cut; first cut at year 80.	Plant native future-adapted species in half of stand, including basswood, black cherry, and bur oak. Two-stage shelterwood cut; first cut at year 80.

Simulations were carried out with the Forest Vegetation Simulator (FVS), a model developed by the USDA Forest Service (Crookston and Dixon 2005). The FVS model is an individual tree model that uses lists of trees (e.g., species and tree diameter) to forecast forest growth through time. The model can simulate forest management activities and provide forest carbon and harvested wood products reports. This simulation model was selected because it is an approved growth and yield model in many forest carbon programs, including the California Air Resources Board's Compliance Offset Program (https://ww2.arb.ca.gov/our-work/programs/compliance-offset-program/compliance-offset-protocols/us-forest-projects/models).

For each forest type, the Lake States geographic variant of FVS was used (Dixon and Keyser 2008). Due to FVS not being able to capture gains in growth of trees following thinning, for all simulations, if management occurred in a simulation, tree diameter increment was set to occur at a rate 25% greater than that of the default equation following the management. Simulations began with a density of 1,000 trees per acre grown in stands with site index of 60 feet at 50 years and were simulated for an identified rotation age informed by the MN DNR (https://www.dnr.state.mn.us/forestry/ecs_silv/forest-cover-type.html). All other default parameters in the FVS models were used throughout the simulations.

Aboveground live carbon storage and sequestration varies for the four primary forest types through a 100-year simulation. Assuming no management, simulations indicate carbon storage is greatest at 100 years for red pine forests, followed by oak, mesic hardwoods, and aspen forests. For all forest types, simulations indicate that carbon sequestration rises rapidly early in stand development, peaks between age 20 and 40, then declines through 100 years (Fig. 8). It should be noted that these simulation do not represent observed data, but instead provide insight into how carbon storage and sequestration may develop through time under a common set of scenarios. If forest management history within a stand is known, future work could validate these results with observed data such as those from the FIA program or experimental forests with long-term records of tree growth (i.e., at least 10 years).

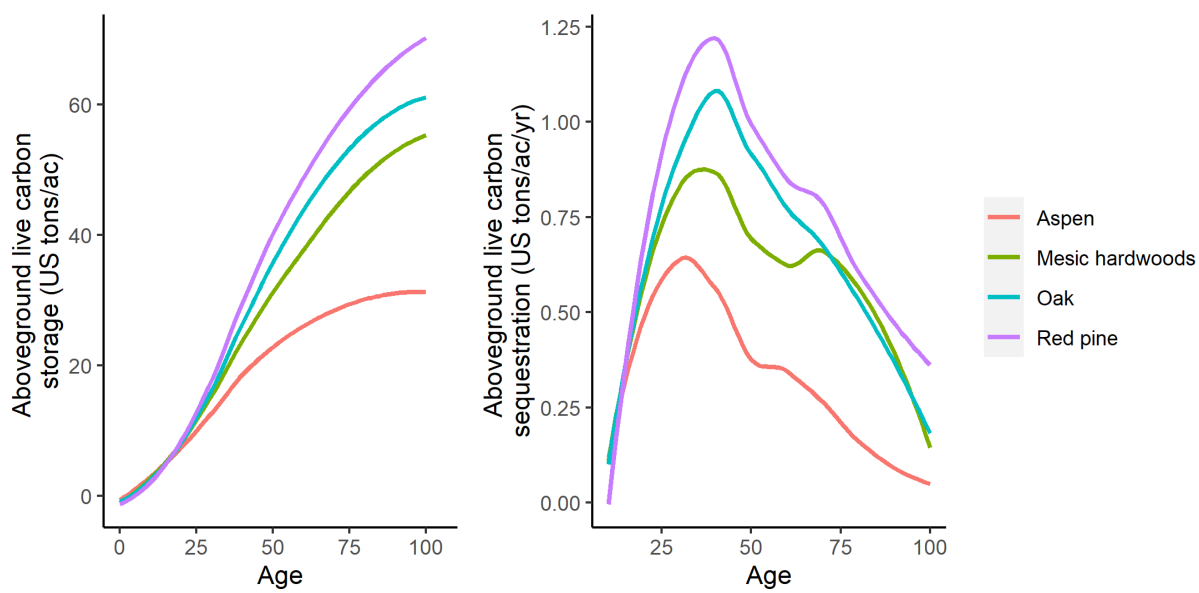

Fig. 8. Simulations from Forest Vegetation Simulator of aboveground live carbon storage and sequestration in four primary forest types in Minnesota.

Red pine

Red pine forest management treatments were simulated using thinning from below, where smaller-diameter trees are removed, leaving larger-diameter trees to grow (Gilmore and Palik 2005). Stands were thinned to a basal area of 90 sq ft/ac every 20 years. The climate adaptation treatment in red pine was modeled after the resilience treatment implemented on the Cutfoot Experimental Forest (Nagel et al. 2017). Simulations indicate 70.3 US tons/ac at 100 years for non-managed stands, with thinning treatments providing continual inputs into harvested wood products (Fig. 9-10; Table 3).

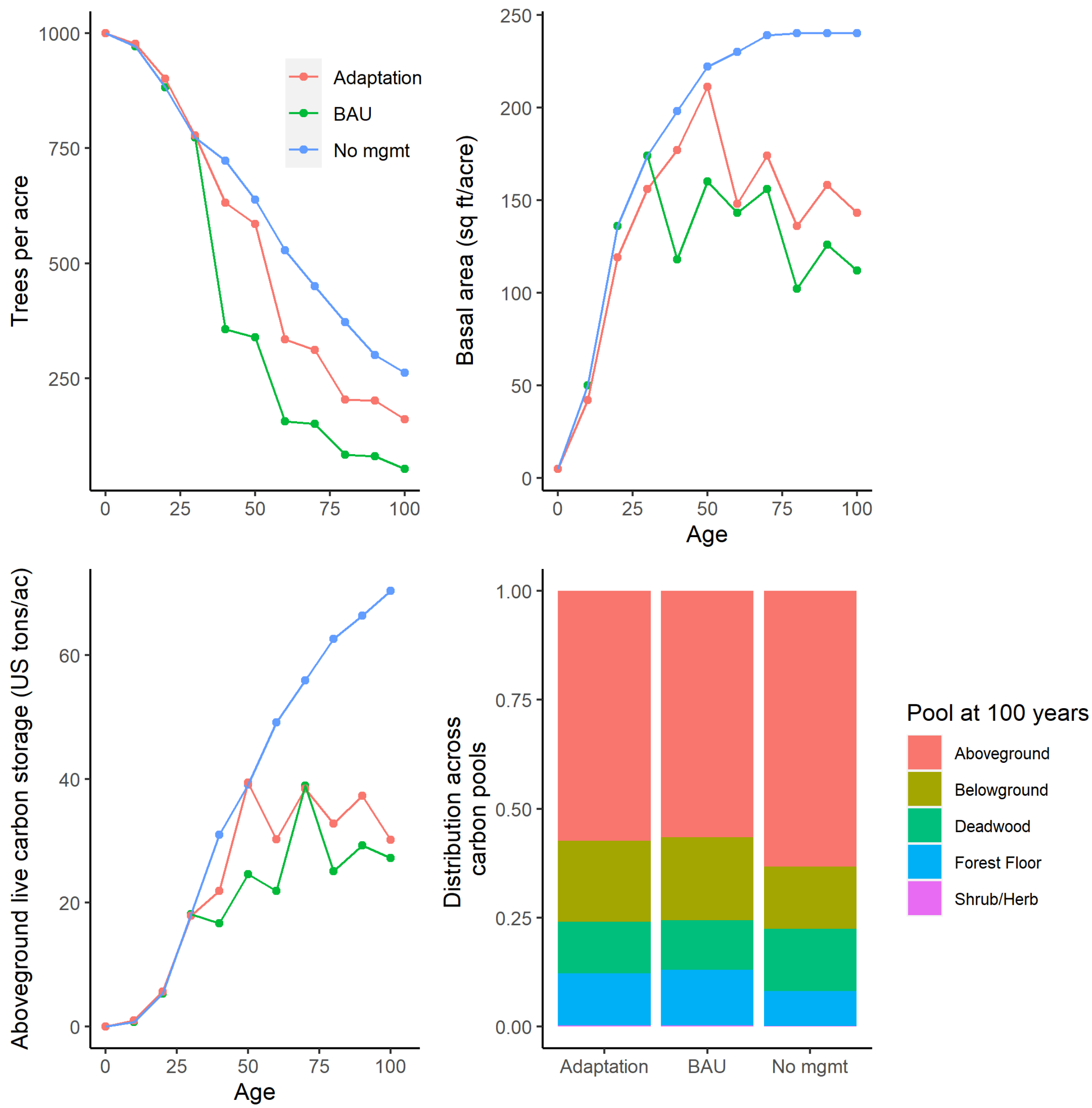

Fig. 9. Simulation of red pine forests assuming no management, business as usual, and climate-adapted forest management approaches.

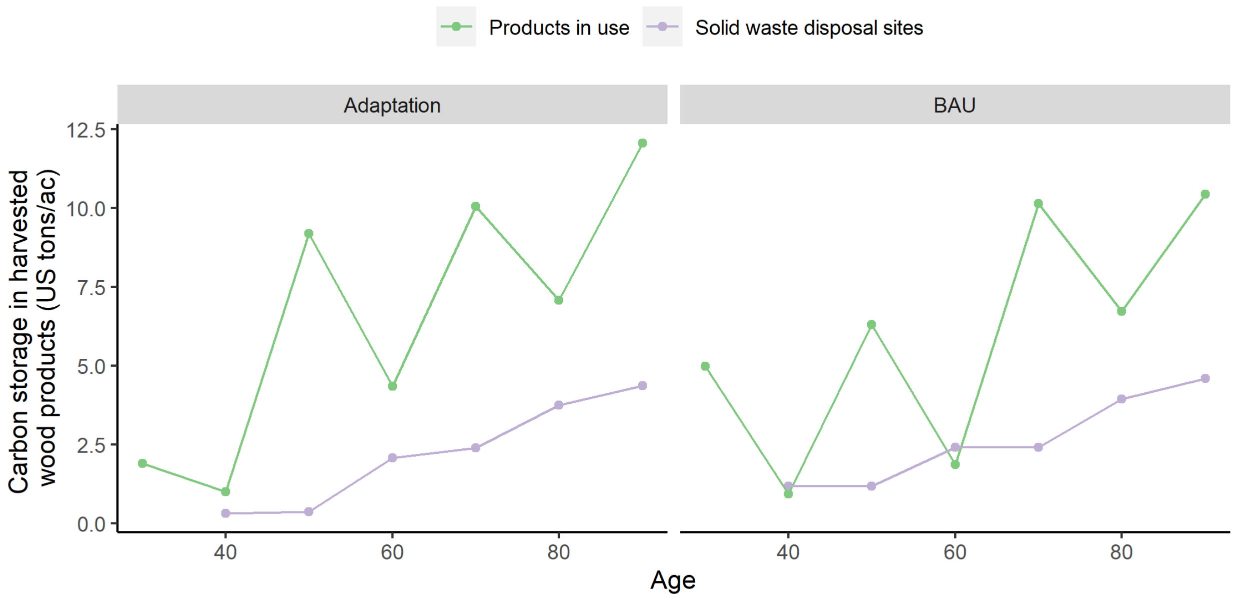

Fig. 10. Simulation of harvested wood products from red pine forests for business as usual and climate-adaptation forest management approaches.

Table 3. Mean carbon storage and removals for red pine grown under three forest management scenarios.

Stand age	Aboveground live carbon storage (US tons/ac)			Carbon removed (US tons/ac)		
	Adaptation	BAU	No mgmt	Adaptation	BAU	No mgmt
10	0.9	0.7	0.7	-	-	-
20	5.6	5.3	5.3	-	-	-
30	17.9	18.1	18.1	-	-	-
40	21.9	16.6	30.9	2.8	9.7	-
50	39.4	24.6	39.1	-	-	-
60	30.3	21.9	49.2	14.3	11.3	-
70	38.4	38.9	55.9	-	-	-
80	32.8	25.1	62.6	11.1	14.6	-
90	37.3	29.3	66.4	-	-	-
100	30.2	27.2	70.3	9.6	8.5	-

Aspen

A business-as-usual aspen forest management treatment was simulated by a clearcut harvest at age 50, the most common silvicultural technique for the forest type in the state (Windmuller-Campione et al. 2019). Two rotations of this treatment were simulated. The climate adaptation treatment in aspen represented a mixed-woods system with aspen, white spruce, eastern white pine and northern white-cedar and is analogous to approaches being implemented on industrial private lands in Minnesota (e.g., see https://silvlib.cfans.umn.edu/content/enrichment-planting-shade-tolerant-conifers-aspen-coppice-upm-blandin-paper-co) (Fig. 11-12; Table 4).

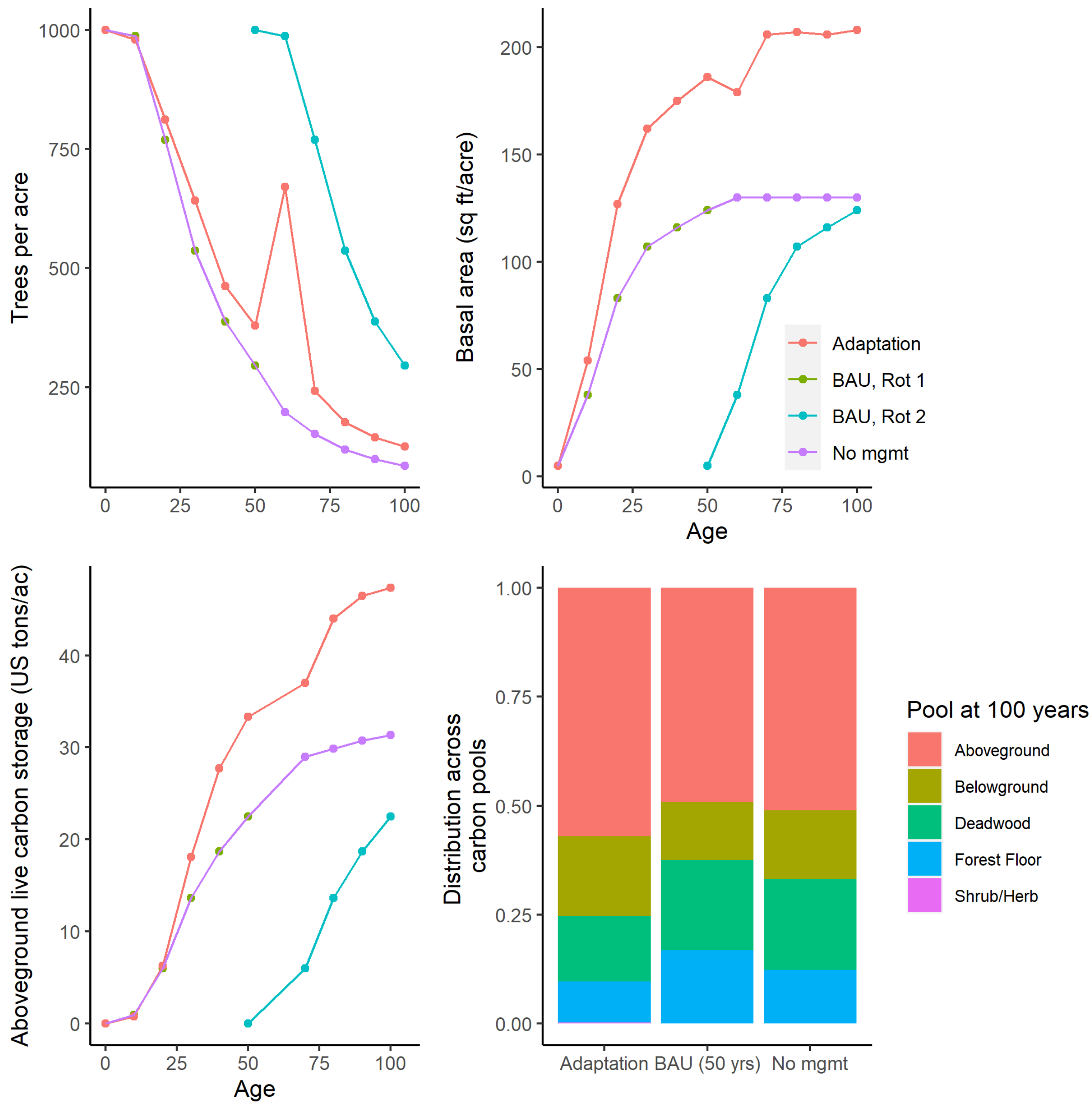

Fig. 11. Simulation of aspen forests assuming no management, business as usual, and climate-adapted forest management approaches. Note: Second rotation of business as usual ranges for 0 to 50 years, shown here as 50-100 years for illustrative purposes only.

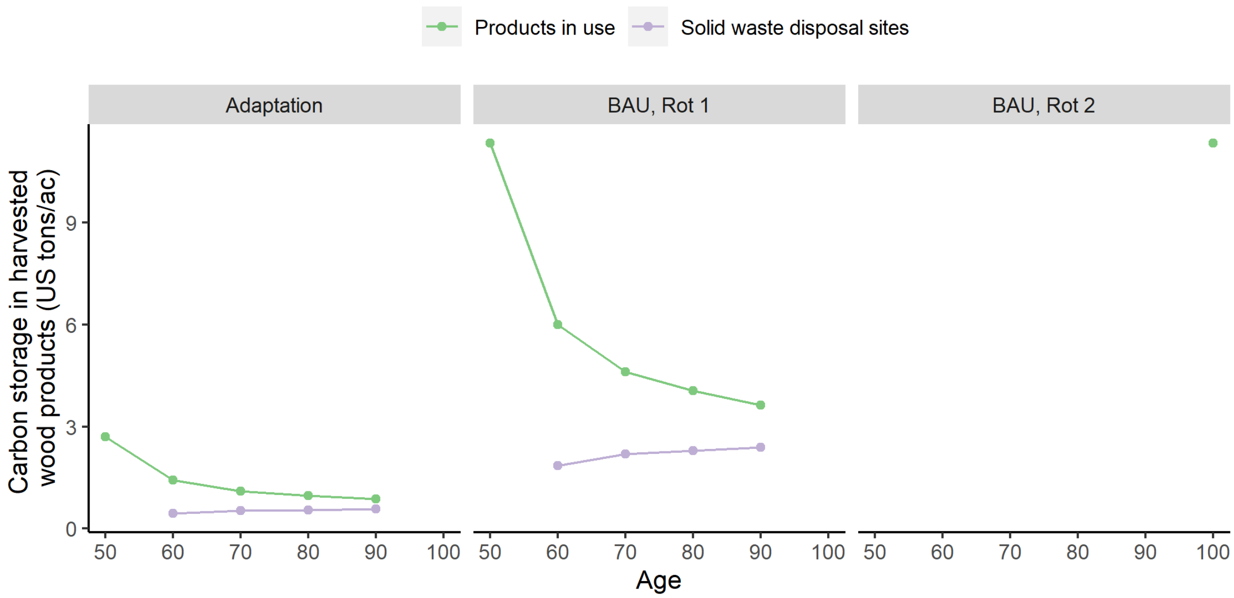

Fig. 12. Simulation of harvested wood products from aspen forests for business as usual and climate-adaptation forest management approaches.

Table 4. Mean carbon storage and removals for aspen grown under three forest management scenarios. Note

Stand age	**Aboveground live carbon storage (US tons/ac)**			**Carbon removed (US tons/ac)**		
	Adaptation	BAU	No mgmt	Adaptation	BAU	No mgmt
10	0.8	0.9	0.9	-	-	-
20	6.3	6	6	-	-	-
30	18.1	13.7	13.7	-	-	-
40	27.7	18.7	18.7	-	-	-
50	33.3	22.5	22.5	3.9	16.6	-
60 (10)	30.5	0.9	25.8	-	-	-
70 (20)	37	6	29	-	-	-
80 (30)	44	13.7	29.9	-	-	-
90 (40)	46.4	18.7	30.8	-	-	-
100 (50)	47.3	22.5	31.4	-	16.6	-

Mesic hardwoods

A business-as-usual forest management treatment in mesic hardwoods was specified to include thinning every 20 years beginning at year 30 to 90 sq ft/ac. The climate adaptation treatment in mesic hardwoods represented a selection harvest, where groups of trees are harvested to promote an uneven-aged stand structure. Cuts occurred every 20 years beginning at year 30, and this treatment is analogous to approaches being implemented on county-managed lands in Minnesota (e.g., see https://silvlib.cfans.umn.edu/content/multi-aged-northern-hardwood-forest-aitkin-county) (Fig. 13-14; Table 5).

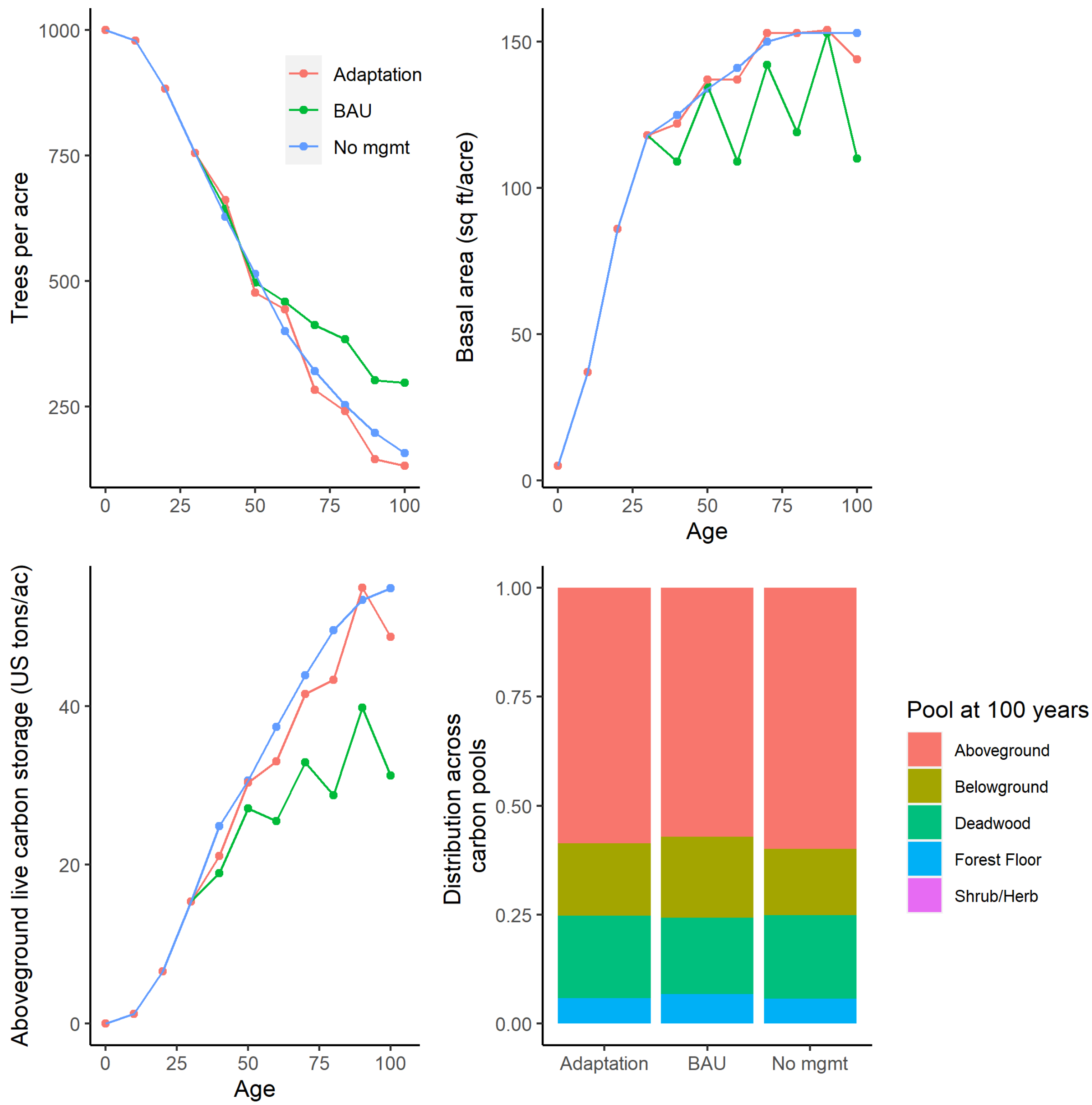

Fig. 13. Simulation of mesic hardwood forests assuming no management, business as usual, and climate-adapted forest management approaches.

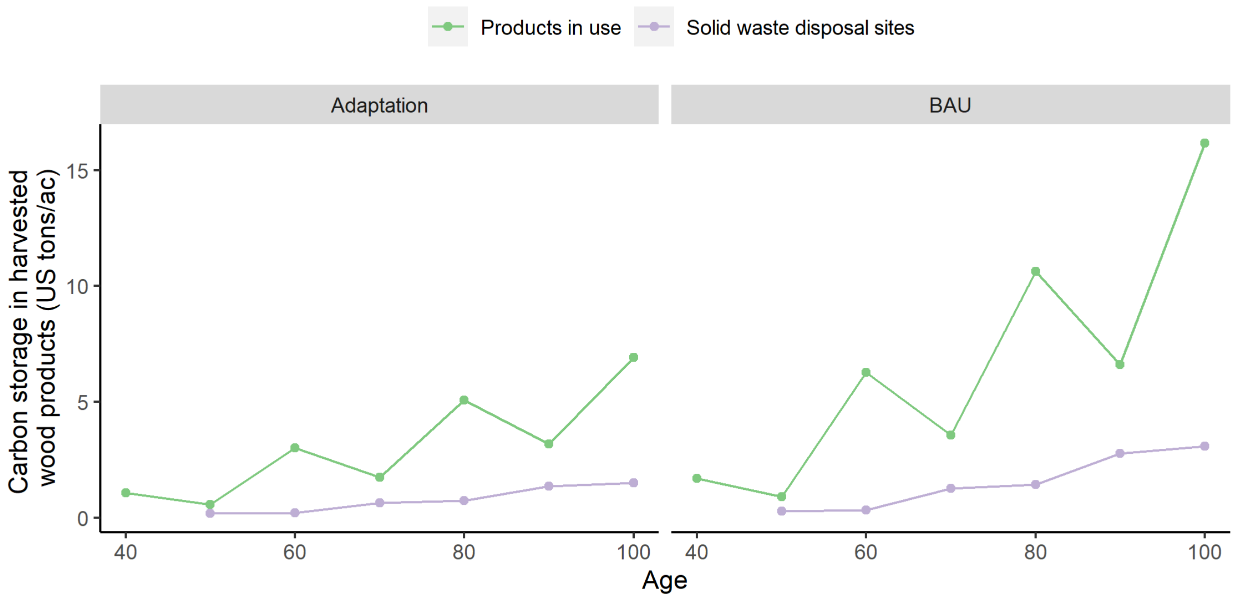

Fig. 14. Simulation of harvested wood products from mesic hardwood forests for business as usual and climate-adaptation forest management approaches.

Table 5. Mean carbon storage and removals for mesic hardwoods grown under three forest management scenarios.

Stand age	Aboveground live carbon storage (US tons/ac)			Carbon removed (US tons/ac)		
	Adaptation	BAU	No mgmt	Adaptation	BAU	No mgmt
10	1.2	1.2	1.2	-	-	-
20	6.5	6.5	6.5	-	-	-
30	15.3	15.3	15.3	-	-	-
40	21.1	19	24.9	1.6	2.5	-
50	30.3	27.1	30.6	-	-	-
60	33	25.5	37.4	3.8	8.2	-
70	41.5	32.9	43.9	-	-	-
80	43.3	28.7	49.6	5.4	11.4	-
90	54.9	39.8	53.4	-	-	-
100	48.7	31.2	54.9	6.3	15.7	-

Oak

Both the business-as-usual and climate adapted forest management treatment in oak forests included a shelterwood harvest, where a shelter of trees is left after removing the majority of trees to protect and facilitate regeneration (e.g., see https://silvlib.cfans.umn.edu/content/northern-red-oak-shelterwood-carlton-county). The climate adaptation treatment also simulated native future-adapted species in half of the stand, including basswood, black cherry, and bur oak (Fig. 15-16; Table 6).

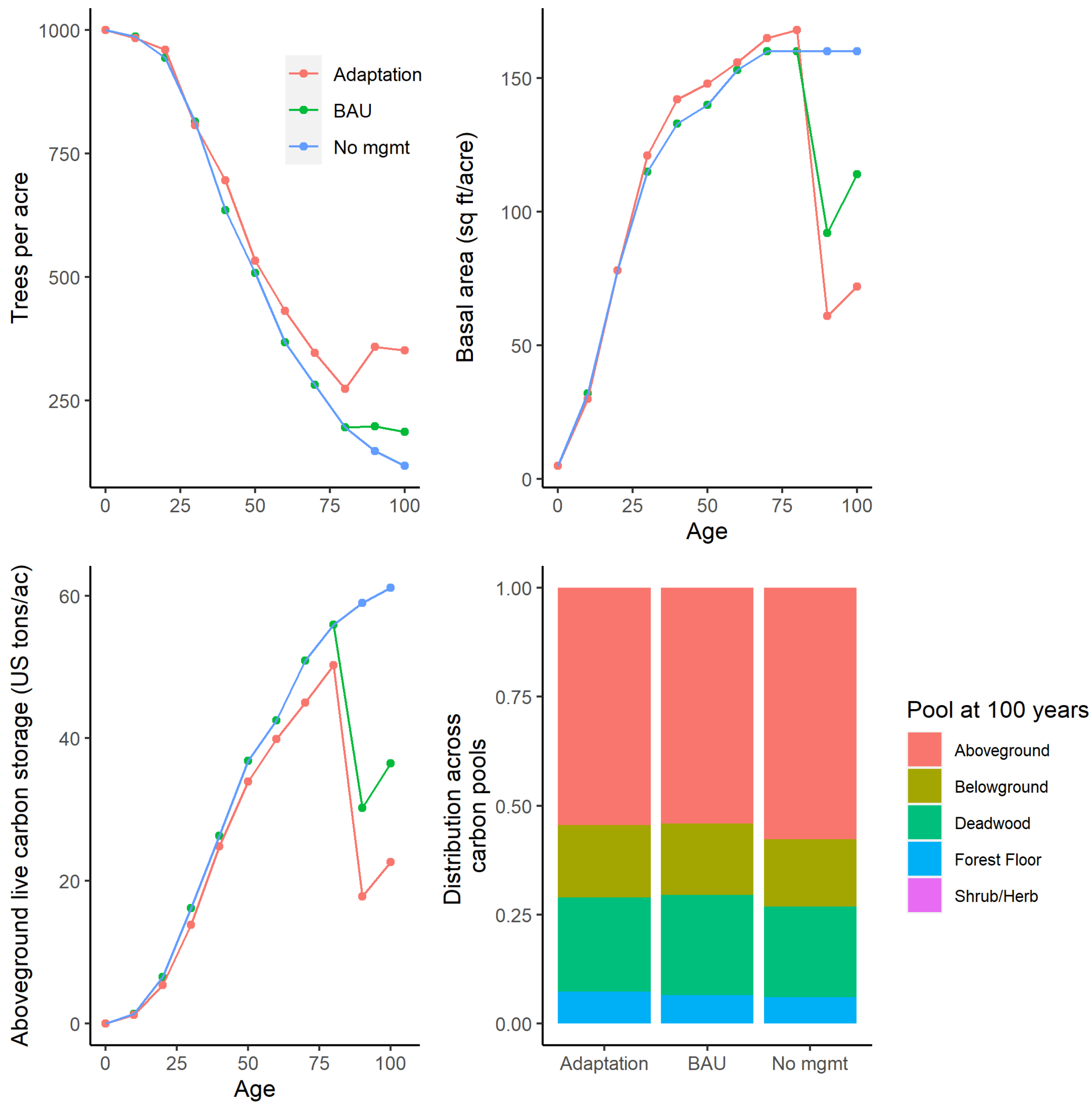

Fig. 15. Simulation of oak forests assuming no management, business as usual, and climate-adapted forest management approaches.

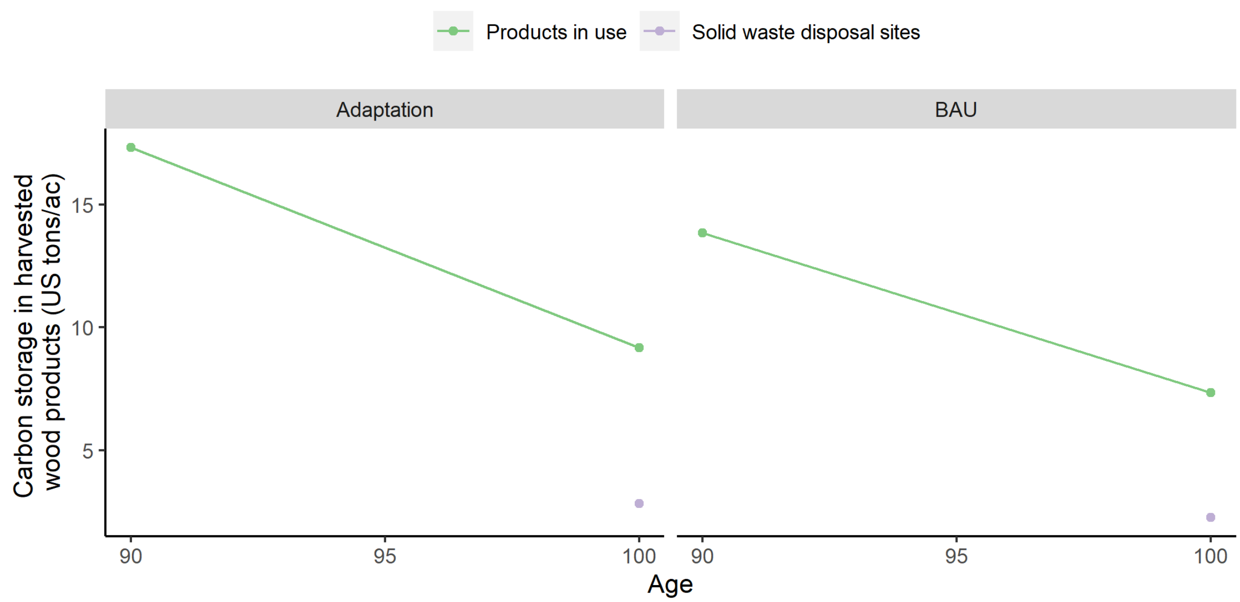

Fig. 16. Simulation of harvested wood products from oak forests for business as usual and climate-adaptation forest management approaches.

Table 6. Mean carbon storage and removals for oak grown under three forest management scenarios.

Stand age	Aboveground live carbon storage (US tons/ac)			Carbon removed (US tons/ac)		
	Adaptation	BAU	No mgmt	Adaptation	BAU	No mgmt
10	1.2	1.3	1.3	-	-	-
20	5.4	6.5	6.5	-	-	-
30	13.9	16.2	16.2	-	-	-
40	24.8	26.3	26.3	-	-	-
50	33.9	36.8	36.8	-	-	-
60	39.9	42.5	42.5	-	-	-
70	45	50.9	50.9	-	-	-
80	50.3	55.9	55.9	-	-	-
90	17.8	30.2	59	25.3	20.2	-
100	22.6	36.5	61.1	-	-	-

III. Carbon Markets for Minnesota Landowners

A number of forest carbon offset markets have been established that seek to capitalize on the value that trees and forests provide in storing carbon and removing carbon dioxide from the atmosphere. In these markets, corporations and individuals pay for carbon dioxide emissions to offset their own emissions. Landowners are paid for the carbon storage and sequestration their trees provide.

Carbon offset projects are structured so that woodland owners can receive payment through a variety of approaches. These include:

- Establishing a forest or stand of trees in an area where there was no previous tree cover (afforestation).
- Reestablishing a forest on understocked or recently harvested land (reforestation).
- Protecting a forest from being converted to non-forested land.
- Improving forest management activities to increase carbon storage in the forest or associated forest products.

Most landowners with currently forested lands will enroll in a carbon offset project that improves forest management activities. A private woodland owner can be paid for the value of additional carbon that their trees store and sequester due to the change in their management, but specific details vary across programs and market prices fluctuate. The following conditions are common across many carbon offset markets if landowners seek to enroll:

- The landowner provides evidence that the property is sustainably managed.
- The landowner agrees to terms and conditions that the property remains forested over a specified period of time.
- The landowner has a detailed inventory of the property, including the type, size and composition of tree species in the woodland.

Carbon markets are categorized as voluntary or compliance-driven. Voluntary markets are typically managed by private entities while compliance markets involve government agencies.

Compliance markets

Compliance-driven carbon markets are typically referred to as “cap-and-trade” markets where carbon offset purchases are required by governmental bodies. California’s Air Resource Board’s (CARB) Cap-and-Trade Regulation and their associated Forest Offset Protocol has existed since 2014 and is currently the primary regulatory carbon market operating in the US (https://ww2.arb.ca.gov/our-work/programs/compliance-offset-program). In the state’s legislature, Bill AB 32 required California to return to 1990 levels of greenhouse gas emissions by 2020. Although focused on emitters within the state of California, the program considers all property in the US. To date, the program includes forest carbon projects in 29 US states, including Minnesota. Landowners enter a 100-year contract term in the program.

Historically, compliance markets have primarily targeted large forest landowners. Kim and Daniels (2019) reported that the average size of improved forest management projects offered through the CARB program was 48,617 acres, with the vast majority of projects (91%) occurring outside of California.

Hence, enrollment in a compliance forest carbon offset program is generally restricted to large landowners due to high inventory and monitoring costs of forest projects. The benefits of compliance-driven include more market certainty given their regulatory backing.

Voluntary markets

Voluntary forest carbon markets, where carbon credits are sold on a voluntary basis, have expanded considerably over the last two years. The volume of voluntary carbon offsets reached their highest levels ever in 2021, with over $1 billion of voluntary credits sold between January 2021 and November 2021 alone (Donofrio et al. 2021). Voluntary programs continue to evolve and a number of new ones may be appealing to landowners with smaller ownerships.

The primary benefit of voluntary forest carbon programs is that they typically have small minimum acreage requirements, shorter contract lengths, and lower costs to enter. Hence, voluntary markets may be the greatest opportunity for private forestland owners with small properties (e.g., less than 100 acres). Some voluntary markets operate on a harvest deferral model, where landowners choose to forgo timber harvesting in favor of allowing their forest to store and sequester carbon and receive a carbon payment. There are several voluntary forest carbon market programs currently available to Minnesota landowners, or will be available in the near future. Each voluntary program has their own minimum acreage requirements, contract lengths, and restrictions on whether or not timber harvesting can occur over the contract period (Table 7).

As part of our effort to foster a common understanding of carbon terminology and practices, we hosted a series of outreach events highlighting carbon offset programs available or in development and targeting Minnesota's private forest landowners. In September 2021 the Sustainable Forests Education Cooperative hosted representatives of large companies owning and managing forest land and the carbon offset project developers listed in Table 7 to discuss their experiences and expectations with carbon offset markets. This three-day event attracted over 75 people and helped to build understanding around the rapidly evolving state of carbon offset programs and the terminology and practices involved.

Table 7. An overview of voluntary forest carbon programs, many of which are in the early stages of development and refinement for application to Minnesota landowners.

Project developer	Carbon program	Contract length	Minimum acreage	Is harvesting allowed?	Notes
American Forestry Foundation and The Nature Conservancy	Family Forest Carbon Program (https://www.forestfoundation.org/family-forest-carbon-program)	20 years	30 acres	Growing Mature Forests program restricts some timber harvests (including high grading or select cuts). Some limited and salvage harvesting are allowed, including for personal use, such as firewood.	Currently enrolling properties in Pennsylvania, West Virginia, and Maryland. Must be legally allowed harvest property and not be a plantation. Program is coming to Upper Great Lakes in 2022. Will focus on maple/beech/birch, aspen/birch, and white/red pine forests.
Finite Carbon	CORE Carbon (https://corecarbon.com/)	Unknown	40 acres	Unknown.	Website indicates program is coming soon. Uses a digital platform and mapping technologies to allow landowners to participate.
NCX	NCX (https://ncx.com/)	1 year	None	Focuses on deferring harvest over the contract year.	A "data-driven forest carbon marketplace". 1,800 landowners from 38 states went under contract in winter 2022 auction. Minnesota properties represented 0.3% of total acres across all projects in its winter 2022 auction.
EP Carbon	Forest Carbon Works (https://forestcarbonworks.org/)	125 years in renewable six year contract periods	40 acres	Extensive commercial harvests should not have occurred on the property within 10 years prior to the enrollment date. (Certain exceptions may apply). Landowners must be willing to limit harvesting.	Works with regulatory California Air Resources Board projects.

It should be noted that programs currently exist in Minnesota that provide incentive-based payments to private woodland owners. These programs include the Sustainable Forest Incentive Act, 2c Managed Forest Law, and establishing a conservation easement that limits the development of privately owned forests (https://www.dnr.state.mn.us/foreststewardship/index.html). While these programs are not structured to provide payments for carbon, carbon storage or sequestration could be a component of forest management plans for landowners enrolled in this program.

To better understand landowner willingness to participate in forest carbon programs, it is fitting to summarize what the annual price of carbon would need to be on a per acre basis if landowners seek to enroll. Russell (2021) summarized five different studies across different regions in the US that analyzed this (Table 8). Most studies analyzed private forest landowners through a mix of surveys or simulation analyses to quantify the price that landowners are willing to accept for carbon. Averaged across these studies, forest landowners are willing to accept $21.60 per acre for storing carbon annually. It should be noted that Table 8 is not a complete list of studies and prices are not all in 2021 dollars.

Table 8. Prices that forest landowners are willing to accept on a per acre basis for storing carbon annually, from Russell (2021).

State/Region	Price ($/acre)	Study	Notes
Vermont	$5 to $15	White et al. (2018)	Responses from a mail survey to landowners in the state's Current Use Program.
Texas	$20 to $27	Simpson and Li (2010)	Values range from being willing to accept a five-year contract versus a conservation easement.
Southeastern US	$4 to $49	Tanger et al. (2021)	Payment rates vary depending on four treatments including different ages at thinning and final harvest.
Florida	$20 to $30	Soto et al. (2016)	Conclusion that amount would have significantly stronger impacts on enrollment than $5 or $10.
Lake States	$18 to $28	Miller et al. (2012)	$18 payment required to generate 50% participation rate. $28 payment for survey respondents that expressed a high certainty in their response to a valuation question.

IV. Carbon Opportunities: A Needs Assessment for Minnesota

Forest carbon focus groups

This project conducted a needs assessment of forest carbon opportunities using focus groups. The objective of the focus groups was to understand perceptions and viability of carbon sequestration as a management goal for public and private forest landowners. Two two-hour focus groups were held over Zoom, one on Nov. 30, 2021 and one on Dec. 1, 2021. Across the two focus group sessions, 15 individuals participated, representing federal, state, county, tribal, industry, and non-profit groups:

- USDA Forest Service-Superior National Forest (1)
- USDA Natural Resources Conservation Service (1)
- Northern Institute of Applied Climate Science (1)
- Dovetail Partners (1)
- The Nature Conservancy (1)
- MN Department of Natural Resources
  - Office of School Trust Lands (1)
  - Division of Forestry (2)
- MN Forestry Association (1)
- MN Timber Producers Association (1)
- MN Forest Industries (1)
- MN Forest Resources Council (1)
- MN Shade Tree Advisory Committee (1)
- St. Louis County (1)
- Fond du Lac Band of Lake Superior Chippewa (1)

During the focus groups, an activity was shared with participants that asked them to rank four broad actions based on how viable they were for their land base. The list of actions included: (1) Increasing carbon in existing forests and products through silviculture, (2) preventing emissions by reducing risk of fire, disease, and mortality, (3) increasing forest area, and (4) avoiding emissions by reducing forest conversion. The top ranked actions from focus group participants, as measure by the number of first- and second-place votes, were increasing carbon in existing forests and products through silviculture and preventing emissions by reducing risk of fire, disease, and mortality. The third- and fourth-ranked actions were increasing forest area and avoiding emissions by reducing forest conversion, respectively (Table 9). Specific feedback on each of these actions are explained in detail in the sections that follow.

Table 9. Number of votes from focus group participants indicating how viable an action is for their landbase.

Action	Number of votes			
	1st place	**2nd place**	**3rd place**	**4th place**
Increase carbon in existing forests and products through silviculture	4	7	3	0
Prevent emissions by reducing risk of fire, disease, and mortality	5	4	4	1
Increase forest area	2	3	4	5
Avoid emissions by reducing forest conversion	3	0	3	8

Increasing carbon in existing forests and products through silviculture / preventing emissions by reducing risk of fire, disease, and mortality

Multiple participants viewed these two strategies as interchangeable with regards to their ranking. One participant noted: “You’re really doing both in terms of forest management, you’re always looking at the entire system—both silviculture as well as fire risk and disease and mortality.” Another participant noted that a healthy forest allowed them to better manage insects and diseases. However, markets were a limitation where management on some forest types was concerned: the loss of a mill and a lack of biomass markets in particular hindered their ability to remove dead material or ladder fuels off the landscape and were left to decay. In one area where there are chip mills, supply is markedly higher than their capacity to burn.

While public land managers generally felt these strategies were the most viable, there was concern that this was not as viable for private landowners. One participant observed that “these [strategies] seem hard if you're trying to connect with all of those private landowners out there—it's a lot of touches, it's a lot of convincing, it's a lot of nuance.” Multiple participants observed that there was a limited capacity to reach the large and diverse amount of private landowners through existing programs such as the MN DNR Forest Stewardship program or through consultants.

Increasing stocking on areas that had below-optimal stocking was viewed as one way to increase carbon through silviculture that was directly compatible with existing management goals. However, participants noted that some areas may be overstocked or require a climate treatment that would decrease stocking in favor of promoting resilience to changing future conditions. Increasing the amount of fire in fire-dependent systems was also viewed as a way that this strategy was incompatible with certain forest types.

In the context of urban forests, these two strategies were similarly top-ranked as participants emphasized actively managing diseases and maintaining large, healthy, mature trees.

Increasing forest area

Participants were undecided on the viability of increasing forest area as a forest carbon strategy on their land base. One participant felt that it would be the most viable to work with private landowners to plant trees in areas where stocking could be increased or on suitable sites that are currently non-forested. Another participant felt that increasing forest area among private landowners would be viable if the incentives to plant and maintain forests outweighed incentives to deforest in favor of other land uses. Increasing forest area was viewed as the path of least resistance, a management approach that would be comparatively easy to implement and have the most pronounced impact on carbon storage. However, one participant mentioned a logistical barrier to planting efforts could be nursery capacity and the ability to source enough trees.

Avoid emissions by reducing forest conversion

This was viewed by some public land managers as the easiest option, simply because of legislative mandates that required the land to remain forested. Other participants viewed it as one of the least viable options because forest diversion in their land base was not viewed as a possibility. The impact of this strategy was viewed as limited or less relevant compared to other strategies as multiple participants did not perceive that this was happening on a significant scale in Minnesota.

Recommendations for future work

Using the results from these focus groups and other findings presented in the report, we provide nine core recommendations to enable Minnesota to better understand future opportunities related to forest carbon. We center them around three themes: markets, forest management, and data and technology.

Markets

1. There remains great uncertainty about the long-term effects of lands enrolled in forest carbon programs and impacts to available wood for forest product markets.

> Minnesota has a strong forest products economy, with industry and fuelwood users harvesting 2.8 million cords of wood in 2019 and supporting 30,360 direct jobs with 63,825 jobs total employment effect (Minnesota Department of Natural Resources 2021). Several focus group participants stressed the need to understand the effect of regulatory and voluntary carbon market programs on available wood supply to pulp and paper manufacturers, sawmills, and other wood industries. Participants recognized that payments for carbon could compete with wood prices and impact the forest industry. In particular, the impacts of carbon programs which seek to defer or limit harvesting of wood should be quantified as it relates to the state's wood supply and current and future wood markets.
>
> As most public lands are not eligible for enrollment in regulatory carbon markets such as California's, a research opportunity exists to understand the impacts of carbon markets on wood supply from forests owned by Minnesota's non-industrial private landowners. Data on annual

harvest and management practices from this ownership are already limited; however, and additional wood supply and economic analyses should address this. Such analyses should integrate the contract terms outlined in some of the common voluntary markets in Minnesota today and integrate forest conditions such as expected rotation age, forest health, and merchantability standards.

2. The opportunities, advantages, and barriers to entering voluntary and regulatory carbon markets for Minnesota's diverse landowners needs to be fully assessed. Research that investigates the price of carbon and landowner willingness to enroll in carbon markets should be a focus of future work.

One focus group participant stated that there was a disconnect between the price of carbon and the cost of forest management and stewardship of forests. Hence, the current price of carbon may be insufficient for a landowner to enroll in a carbon market. Table 8 indicates a range of prices that forest landowners are willing to accept on a per acre basis for storing carbon annually, however, additional research is required to understand landowner willingness to enroll in carbon markets for Minnesota's diverse landowners. In particular, emphasis on understanding the willingness of Minnesota's private non-industrial landowners to enter carbon markets should be highlighted. There was consensus in our focus groups that markets require certainty before landowners choose to enroll in them.

Price is one motivating factor indicating willingness to enroll in carbon markets and other factors may include a sense of stewardship, family legacy of land, and other landowner goals and objectives. Studies such as Miller et al. (2012) could be updated and adapted to fit the contract terms and management activities outlined in emerging voluntary carbon markets. Studies such as Tanger's (2021) could integrate common forest management techniques for Minnesota's primary forest types to better understand landowner willingness to enroll in forest carbon programs and the economic implications to the landowner.

3. Carbon markets are perceived in both a negative and positive manner from Minnesota's diverse landowners. The socio-environmental aspects of carbon markets need to be fully explored.

While most focus group participants agreed that managing for carbon is a laudatory achievement that can maintain the sustainability of our natural resources, some brought up the need to understand the public perception of carbon programs from all landowners. For example, as payments are provided to landowners using funds provided indirectly from polluters, carbon markets may be perceived negatively.

Future work should investigate the socio-environmental aspects of carbon markets, including perceptions of markets and their environmental benefits. Such work would integrate perspectives from diverse landowners, especially private and tribal landowners, to better understand these social aspects.

Forest management

4. Integrating carbon as a forest management objective needs to be evaluated along with several other management objectives.

Carbon is one of many objectives that a landowner may have for their property, among other goals such as timber, recreation, and wildlife habitat. The amount of carbon stored and sequestered in a stand is influenced by forest management activities and the silvicultural strategies implemented. The proportion of clearcut harvests on Minnesota's public lands has decreased from 91% of the total harvested area in 1991 to 72 percent in 2017 with other silvicultural systems such as shelterwoods, seed trees, selections, and thinning treatments becoming more common (Windmuller-Campione et al. 2020). How carbon storage and sequestration patterns fit within a broad spectrum of silvicultural treatments remains largely undetermined across Minnesota's forests.

While some managers may have a mindset that managing for carbon competes with other management objectives, one focus group participant stated that "good carbon management is good forest management". Future work should survey Minnesota's primary landowners on current forest management strategies being used for carbon attributes in addition to potential silvicultural systems to promote carbon storage and sequestration. Data from several long-term studies investigating these trends are available from Minnesota forests (e.g., Powers et al. 2011; Muller et al. 2019) and future silvicultural experiments should integrate carbon measurements in a manner to better understand carbon dynamics across diverse stand conditions.

Furthermore, additional metrics on standard forest management costs across the primary forest types of the Lake States should be compiled. These values could include average costs of site preparation, tree planting, and precommercial thinning. These values could supplement analyses that compare management goals related to forest carbon with other management goals. For example, see a recent post that provides this baseline information to supplement economic analyses in the US South: https://www.aces.edu/blog/topics/forestry/costs-trends-of-southern-forestry-practices-2018/

5. Forest management is transitioning from managing forests for resources to managing them for multiple services and values including climate adaptation and now climate mitigation. A more thorough understanding of how different adaptive management treatments influence forest carbon storage and sequestration patterns should be carried out for Minnesota's primary forest types.

Participants in focus groups brought up that climate change was not a part of forest management strategies 20 years ago, yet since then, managers began integrating concepts of climate adaptation. Climate change is the priority for several organizations that were a part of our focus groups including the MFRC, as evidenced in its recent report (Friesen 2020). Our focus group discussions centered around aspects of carbon and climate adaptive management, where stands may be managed at lower densities to encourage multiple pathways of development in the face of uncertainties related to forest health and disturbance. Increasingly, fire-adaptive management is of significant interest across many of Minnesota's forests, particularly its oak- and pine-dominated forests.

Data from experiments such as the Adaptive Silviculture for Climate Change study (Nagel et al. 2017; Muller et al. 2019) can be instrumental in determining carbon storage and sequestration patterns in stands managed for climate adaptation. While most of the adaptation work in forest management has focused on red pine systems, future work should investigate climate change adaptation treatments across a range of Minnesota's diverse forest types. This should include focusing on the full ecosystem from standing trees, belowground soils, and dead wood in the system.

6. A complete life cycle assessment that focuses on timber harvesting, forest management for carbon, and in harvested wood products should be carried out for Minnesota's primary forest types.

Complexities abound when quantifying carbon emissions and removals associated with different forest management strategies and species which contain different wood density properties and have different end uses. Understanding the carbon impacts of this complete process, in terms of a life-cycle assessment, aka "cradle-to-grave" analysis, will be essential to quantify the interactions across many different carbon pools. Forests provide a low-cost solution to capturing carbon and can displace fossil emissions if and when carbon values or fossil fuel costs increase (Lippke et al. 2011). Life-cycle analyses can quantify these trends as they relate to Minnesota's primary forest types and end products. Such analyses could also incorporate scenarios that increase forest area through afforestation or reforestation and simulate biomass/bioenergy strategies depending on interests.

Data and technology

7. Remote sensing technology can leverage existing forest inventory information to better understand forest carbon, yet applications are currently limited at a broad scale in Minnesota.

Focus group participants mentioned the wide variety of remote sensing information available in Minnesota, particularly lidar data which is increasing in use. Currently, lidar exists at a coarse scale across Minnesota, but high-density lidar exists in a few key areas of the state that is appropriate for forest carbon estimation. Several people mentioned that the time of year of the collection of lidar data is essential to understand forest carbon attributes. Furthermore, many participants highlighted that repeated lidar collections over the same geographic area provide valuable information. An ongoing carbon assessment project being conducted by School Trust Lands and Dovetail Partners is a great example of how remote sensing can be used to estimate forest carbon across a vast landscape. Others mentioned the lack of remote sensing applications being conducted on private lands.

Ideally, remote sensing and imagery information should provide species, size, and density of forests with associated uncertainty levels. Future work should strive to develop a high-resolution forest carbon data layer for the state of Minnesota using a variety of remote sensing data products. Such a layer should be made available to the public for use in a variety of forest carbon and related applications.

8. There is an urgent need to better understand baselines of forest carbon in Minnesota, for example, the amount of carbon being stored and sequestered annually in Minnesota. Continuing to develop and deliver this information in a form that is accessible and understandable to a broad audience should be prioritized.

Participants in our focus groups noted the need to understand baselines with regard to carbon storage and sequestration in Minnesota's forests. For example, the state's draft Climate Action Framework seeks to "Increase carbon annually sequestered in natural and working lands by 25% by 2035 from 2014-2018 average levels, through restoration, management, and using carbon smart practices." Analyses that report these values and gain consensus among the forestry community in Minnesota will assist understanding baseline values, such as current stocking and sequestration rates across a range of forest types, stand ages, and stand conditions.

Data from the USDA Forest Service's Forest Inventory and Analysis program can be used to quantify baseline information on forest carbon. In 2018, information was gathered from 6,307 forested plots in Minnesota (Hillard et al. 2022), representing approximately one plot for every 2,791 acres. The FIA plot sample intensity in Minnesota, where plots are remeasured approximately every five years, is one of the greatest in the US. In addition to the usefulness of raw FIA data to inform forest carbon baselines, FIA data are also used in national greenhouse gas estimates of emissions and removals (e.g., Domke et al. 2021; Walters et al. 2021). In combination with other data sources such as remote sensing, Minnesota's vast network of data from the FIA program should be leaned on heavily to inform forest carbon baselines in the state.

9. Agreement needs to be met across the forestry community about how forest carbon is going to be monitored at a stand, state, and regional level.

Many natural resources organizations and agencies view carbon as an opportunity for the forest community to address natural climate solutions. The protocols and processes for monitoring forest carbon throughout Minnesota require a thorough review to understand which organizations are collecting various data related to forest carbon. A multi-agency understanding of how carbon data are collected in forest inventories and summarized and reported at the stand, ownership, landscape, and state level would assist managers and planners in understanding the data needs related to Minnesota's forest carbon resource.

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Appendices

Appendix 1: Glossary of terms

The following terms are compiled to standardize and make accessible the language used in this publication and potentially others that report on forest carbon. The terms refer to units of carbon, carbon markets, and terminology used in the USDA Forest Service's Forest Inventory and Analysis program for carbon pools and related definitions.

Aboveground biomass: All living biomass above the soil, including stems, stumps, branches, bark, seeds, and foliage.[3]

Biomass: Organic material, living or dead, such as trees, crops, grasses, tree litter, and roots.

The FIA program defines biomass as "The aboveground weight of wood and bark in live trees 1.0 inch (2.5 cm) DBH and larger from the ground to the tip of the tree, excluding all foliage. The weight of wood and bark in lateral limbs, secondary limbs, and twigs under 0.5 inch (1.3 cm) in diameter at the point of occurrence on sampling-size trees is included but is excluded on poletimber and sawtimber-size trees. Biomass is typically expressed as green or oven-dry weight and the units are tons."[4]

Belowground biomass: All living biomass of live roots, except for roots too small to be distinguished empirically from soil organic matter, and the below-ground part of the stump.[1]

Carbon budget: An assessment of carbon sinks and sources; OR the amount of carbon dioxide emissions deemed permissible based on such an assessment.[5]

Carbon credit: A standardized unit equal to one metric ton of CO_2 or CO_2e that has been reduced, avoided, eliminated, or sequestered instead of emitted. Carbon credits are often used in the calculation of a carbon budget or carbon footprint.[6]

Carbon cycle: The processes by which carbon moves between the atmosphere, oceans, and living things.[3]

Carbon dioxide (CO_2): A naturally occurring gas of one part carbon and two parts oxygen. It is produced as a by-product of burning biomass and fossil fuels. The IPCC describes CO_2 as "the principal anthropogenic greenhouse gas (GHG) that affects the Earth's radiative balance."[3]

[3] Forest Resources Assessment Programme. "Global forest resources assessment update 2005: Terms and Definitions." 2005. https://www.fao.org/3/ae156e/AE156E03.htm#TopOfPage
[4] Forest Inventory and Analysis. "Forest Inventory and Analysis Glossary." 2016. https://www.nrs.fs.fed.us/fia/data-tools/state-reports/glossary/
[5] IPCC 2018. "Annex I: Glossary." 2018. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_AnnexI_Glossary.pdf
[6] Cool Effect. "Important Definitions in the Carbon Market." 2021. https://www.cooleffect.org/important-definitions-in-the-carbon-market

Carbon dioxide emission: Release of CO_2 into the atmosphere.[7]

Carbon dioxide equivalent (CO_2e or CO_2 Eq.): A measure used to compare emissions of different greenhouse gases by standardizing them against CO_2. This value is calculated by determining the global warming potential (GWP) of a gas across a 100-year time horizon and comparing it to the equivalent amount of CO_2 that would have the same GWP across that horizon.[8]

Carbon flux: Fluctuations of CO_2 in the atmosphere, oceans, and land. [9]

Carbon market: A system to reduce GHGs by putting a price on carbon and trading carbon credits.[7]

Carbon offset: Reducing sources of GHGs, or increasing storage of GHGs, to compensate for other GHG emissions.[7]

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.[10]

Carbon registry: – An independent authority that approves, lists, and tracks a carbon credit's ownership.[7]

Carbon sequestration: The process of storing carbon in a carbon pool. For example, plants sequester carbon by using photosynthesis to convert carbon dioxide into plant biomass.[6]

Carbon sink: A source that removes CO_2 from the atmosphere.[6]

Carbon source: A source that places CO_2 into the atmosphere.

Carbon stock: The quantity of carbon in a reservoir or system which has the capacity to accumulate or release carbon.[6]

Carbon tax: A fee for GHG emissions, usually levied on companies rather than individuals, states, or countries.[6]

Cost-benefit analysis (CBA): A monetary assessment of all negative and positive impacts associated with a given action. A CBA can enable comparison of different interventions, investments or strategies and reveal how a given investment or policy effort pays off for a particular person, company or country.[6]

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[7] Texas A&M Forest Service. "Carbon Market Simplified Glossary." 2013. https://tfsweb.tamu.edu/uploadedFiles/TFSMain/Data_and_Analysis/Contact_Us(3)/CarbonMarketSimplifiedGlossary.pdf

[8] IPCC 2018. "Annex I: Glossary." 2018. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_AnnexI_Glossary.pdf

[9] Texas A&M Forest Service. "Carbon Market Simplified Glossary." 2013. https://tfsweb.tamu.edu/uploadedFiles/TFSMain/Data_and_Analysis/Contact_Us(3)/CarbonMarketSimplifiedGlossary.pdf

[10] Walters et al. "Greenhouse gas emissions and removals from forest land, woodlands, and urban trees in the United States, 1990-2019: Estimates and quantitative uncertainty for individual states." 2021. https://doi.org/10.2737/RDS-2021-0035

Down woody material (DWM): Dead material on the ground in various stages of decay. It includes coarse and fine wood material. The FIA includes the duff layer, litter layer, residue piles, and overall fuel bed as part of the DWM category.[11]

Dead wood biomass: Carbon in non-living woody biomass not contained in the litter, either standing, lying on the ground, or in soil. Dead wood includes wood lying on the surface, dead roots, and stumps.[12]

Emissions trading: An approach to reducing GHG emissions through the economic market. A cap or limit is set on the total amount of allowable emissions, and companies can trade "shares" of these emissions through buying and selling of permits.[13]

Forest diversion: The process when forest land is diverted to non-forest land.

Forest reversion: The process when non-forest land is reverted to forest land.

Greenhouse gas (GHG): Gaseous components of the atmosphere that absorb and emit radiation emitted by the Earth's surface, the atmosphere, and by clouds. This trapping of radiation resembles the way greenhouses trap heat, hence the name greenhouse gas. Some examples of greenhouse gases are carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and hydrofluorocarbons (HFCs). [11]

Land use: Land use refers to the total of arrangements, activities and inputs undertaken in a certain land cover type (a set of human actions). In national greenhouse gas inventories, land use is classified according to the IPCC land use categories of forest land, cropland, grassland, wetland, settlements, and other.[11]

Land-use change: Land-use change involves a change from one land use category to another. For example, forest land that has been converted to agricultural land.[11]

Life Cycle Assessment (LCA): Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product or service throughout its life cycle.[11]

Litter: all non-living biomass (undecomposed or only partially decomposed) above the mineral or organic soil.[14]

Soil carbon: Organic carbon in mineral and organic soils (including peat).[10]

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[11] Forest Inventory and Analysis. "Forest Inventory and Analysis Glossary." 2016. https://www.nrs.fs.fed.us/fia/data-tools/state-reports/glossary/

[12] Forest Resources Assessment Programme. "Global forest resources assessment update 2005: Terms and Definitions." 2005. https://www.fao.org/3/ae156e/AE156E03.htm#TopOfPage

[13] IPCC 2018. "Annex I: Glossary." 2018. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_AnnexI_Glossary.pdf

[14] Forest Inventory and Analysis. "Forest Inventory and Analysis Glossary." 2016. https://www.nrs.fs.fed.us/fia/data-tools/state-reports/glossary/

Substitution factor: The amount of greenhouse gas emissions that would be avoided if a wood-based product is used instead of another product to provide the same function (e.g., building a structure with wood instead of concrete or steel).[15]

[15] Leskinen, P., G. Cardellini, S. González-García, E. Hurmekoski, R. Sathre, J. Seppälä, C. Smyth, T. Stern, and P.J. Verkerk. 2018. Substitution effects of wood-based products in climate change mitigation. https://efi.int/sites/default/files/files/publication-bank/2019/efi_fstp_7_2018.pdf

Appendix 2: Carbon units and conversions

The following unit conversions are compiled to provide standardized values to convert carbon attributes from English to metric units:

1 lb = 0.453592 kg

2,000 lbs = 1 US ton

1 megagram (Mg) = 1 metric tonne

1 metric tonne = 1.10 US tons

1 teragram = 1 million metric tonne (MMT)

1 lb/acre = 1.120851 kg/ha

1 US ton/ac = 2.2417 Mg/ha

1 acre = 0.4047 acres

1 unit C = 3.667 units CO_2 equivalent