MINNESOTA FOREST RESOURCES COUNCIL

CLIMATE CHANGE AND MINNESOTA'S FORESTS

A REPORT PREPARED FOR THE MINNESOTA FOREST RESOURCES COUNCIL
BY THE RESEARCH ADVISORY COMMITTEE | SEPTEMBER 16, 2020

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EXECUTIVE SUMMARY

The purpose of the Minnesota Forest Resources Council (MFRC) is to "develop 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" (MN Statutes 89A.03). Pursuant to this statutory obligation, the MFRC tasked the Research Advisory Committee (RAC) with the development of a report assessing the impacts, challenges, and opportunities associated with climate change for Minnesota's forests. The RAC, under MN Statutes 89A.08, exists to "identify and initiate priority forest resources research" by encouraging collaboration, linkages, and communication between those conducting forest research in various disciplines and for various organizations, practitioners in the use of forest resources research, and the legislature. This report is the culmination of the RAC's effort to assess the potential effects of climate change on Minnesota's forests and forest management.

Climate change poses a major threat to our environment and natural resources. In Minnesota, there is increasing interest in how climate change will affect our forest ecosystems. Forests, which compose about one-third of the state's land area, perform highly important ecological, economic, and social services, including the protection and improvement of our water, air, and soil, providing habitat to numerous animal species, and helping the economy of our rural and tribal communities through the recreation and forest products industries. In addition to these services, our forestlands play a crucial role in sequestering and storing carbon. In this capacity, Minnesota's forests provide our state with a potential tool for mitigating emissions and building a comprehensive climate strategy.

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This report is structured in four sections. **Section 1** assesses the crucial services provided by Minnesota's forests, the likely climate change outcomes we will experience in the coming years, and how those outcomes might affect forest health and management. **Section 2** focuses on the role of forest cover in the carbon cycle, how to maximize carbon storage in our forests through forestation strategies and management practices, and innovative market solutions which may go hand-in-hand with a forest carbon strategy. **Section 3** reviews the resilience of five important Minnesota forest cover types and assess how they might be managed to increase climate adaptability. Lastly, **Section 4** provides concrete recommendations for actions that Minnesota could take to prepare for future climate change and its effects on our forests.

The major findings and recommendations from each of the four sections of this report are summarized on the next pages.

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SECTION 1: CLIMATE CHANGE CHALLENGES FOR FOREST MANAGEMENT

Climate change threatens Minnesota's forests and the goods and services those forests provide to families, communities, and businesses who depend on them.

- Minnesota's forests provide numerous environmental, social, and economic services to the state.
- Minnesota has already been experiencing the effects of climate change, with warmer temperatures (particularly in the winter), more severe rainfall events, and periods of water stress.
- The climate trends we have already experienced are expected to continue and exacerbate in the coming years if sufficient action is not taken to combat climate change.
- The effects of these changes will create numerous challenges for our forests and their management, including altered species composition, decreased access for management and recreation, and increased disturbance from extreme weather events, wildfire, and pests and pathogens. Importantly, these changes may also negatively affect the forest products industry, which in turn would reduce our capacity to effectively manage forest resources to increase their adaptability to changing conditions.

SECTION 2: FOREST CARBON STORAGE AND SEQUESTRATION

One of the most important services that forests provide is carbon sequestration: the absorption of atmospheric carbon dioxide and storage of carbon in trees' woody biomass and in forest soils. We have an opportunity in Minnesota to boost carbon sequestration through specific forest management strategies, thereby contributing to our state's carbon emissions reduction goals and mitigating climate change.

- Maintaining and increasing forest cover will enhance carbon storage on the Minnesota landscape, increasing the emission mitigation potential of our forestlands.
- Certain forest management strategies may be utilized to maximize carbon in forests.
- Maintaining and developing forest products industries which amplify the storage of carbon through long-lived wood products, mitigate the use of fossil fuels (e.g., bioenergy and biomaterials), and/or fund the enhancement of our forest cover (e.g., carbon markets) will be an essential component of any forest carbon strategy.

SECTION 3: CLIMATE CHANGE ADAPTATION STRATEGIES BY COVER TYPE

We also have an opportunity to design and implement forest management strategies that help family forest owners, public land managers, tribes, and the forest products industry adapt to and mitigate the adverse effects of climate change on forest goods and services.

- Understanding the innate resilience and vulnerability of Minnesota's diverse forest types is essential to developing effective forest management strategies for maintaining healthy forests.
- Various strategies may be employed which may help increase the climate adaptability of Minnesota's forests; the best strategy will vary by forest type, landscape, and other factors.

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SECTION 4: KNOWLEDGE GAPS AND NEXT STEPS FOR MINNESOTA

We propose several immediate actions that should be pursued to prepare Minnesota's forests for our climate future and their role in a climate change mitigation strategy.

- Keep forests forested, e.g., maintaining existing forest cover.
- Increase nursery capacity to ensure adequate access to and production of a diverse suite of conservation-grade tree seedlings for reforestation and afforestation strategies, particularly species considered climate "winners."
- Update the MFRC's Million Acre Report, which assesses afforestation opportunities within Minnesota, in light of new science and changing markets since the report's original publication in 2010.
- Enhance collaboration amongst stakeholder groups, including across agencies, organizations, states, and even countries to enhance forest health, productivity, and the effectiveness of management.
- Develop markets for the use of forest residuals as a bioenergy feedstock.
- Encourage the production of long-lived woody products, including innovative engineered-wood products and construction materials.
- Assess the feasibility of the development of a Minnesota-based carbon market, such as a regulatory cap-and-trade program or voluntary market, which may increase the competiveness of Minnesota forests in carbon market opportunities.
- Refer this report to the MFRC's Policy and Information Committee (PIC) for generation of strategic issues and policy recommendations.

In this paper, we provide in-depth analysis of the scientific literature and current understanding of the likely impacts of climate change on Minnesota's forests, the potential opportunity for increasing forest cover on our landscape, and how we might manage our forests to ensure they continue to thrive and provide essential services to our environment, residents and visitors, and economy. We also identify key research needs and questions that should be answered in order to develop a comprehensive and science-based approach to managing our forests in the face of a changing climate.

While climate change will present us with numerous challenges, through effective, strategic, and science-based management, Minnesota's forests may provide us with the opportunity to meet this threat while amplifying the benefits our forests have provided – and will continue to provide – to our communities and the environment.

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SECTION 1
CLIMATE CHANGE CHALLENGES FOR FOREST MANAGEMENT

Climate change is considered by many to be among the most pressing environmental concerns of our time. Understanding how climate change might affect our natural systems and how to mitigate the worst effects of a changing climate are open topics of scientific inquiry. In Minnesota, there is particular interest in how climate change may affect our vast forestlands and whether our forests can be managed to be both resilient to these changes and to mitigate climate impacts through forest diversification and increased sequestration of atmospheric carbon.

Forests are incredibly valuable. They provide a wide variety of ecosystem services and can be an economic boon for the communities associated with them. The value that forests provide can be broken into several broad categories:

- Protecting and improving water, soil, and air quality;
- Providing economic opportunity statewide and especially to rural communities, particularly through the forest products and outdoor tourism/recreation industries;
- Contributing spiritual and cultural significance to our tribal communities and those who reside in or visit our forestlands;
- Providing habitat for native plant and animal species; and
- Storing carbon and mitigating carbon emissions.

These services and values are already being threatened by a changing climate. Disturbances to forest cover can compromise water quality, habitat, carbon storage, and the economic viability of forest regions. Forest disturbance includes wildfire, forest harvest, land use changes (i.e., conversion from forest to agriculture or urban environments), wind and ice events, drought, and insect or pathogen outbreaks. These disturbances, particularly intense windstorms,

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catastrophic wildfire events, and dieback from pests and pathogens, are expected to increase as the climate warms[1].

At the same time, the ability of forests to store carbon may provide an opportunity to help mitigate carbon emissions and may be incorporated into a broader climate management strategy. In the U.S., forests currently help to offset around 11 percent of our total fossil fuel emissions, which corresponds to an annual reduction of approximately 742 million metric tons of carbon dioxide[2]. The process of absorbing carbon from the atmosphere and storing it in other carbon reservoirs is known as *carbon sequestration.* Because trees use carbon to build their leaves, stems, and roots, and deposit carbon-rich dead leaves, stems, and roots in the soil, forests have high carbon sequestration capacity. In addition, because of their long lifespans, biomass density, and slow decay once dead, carbon sequestration in trees leads to enormous stores of carbon on the landscape, both in the living forest as well as in forest products. This is known as *carbon storage.* The role of forest carbon sequestration and storage, and how to maximize this benefit, will be discussed in greater detail in Section 2 of this paper.

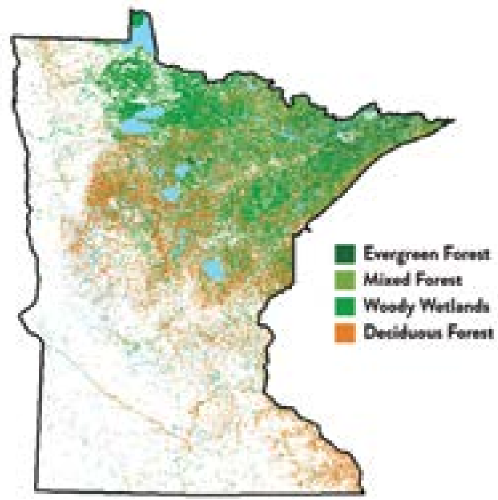
WHAT IS CLIMATE CHANGE?

According to the Intergovernmental Panel on Climate Change (IPCC), climate change is defined as "[a] change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer" [3]. In less technical terms, climate change is a long-term shift in the pattern of various climate markers, such as temperature and precipitation. Our day-to-day weather is not an indicator of climate change by itself; rather, the accumulation of weather events over time can show how the climate is changing if the pattern of cumulative weather is different than it was in the past.

While changes in the Earth's climate have occurred throughout the history of the world, the current climate change cycle is understood by scientists to be largely driven by human-generated emissions of greenhouse gases, especially carbon dioxide, since the Industrial Revolution of the 18th century.

MINNESOTA'S FORESTS

Of the approximately 54 million acres that make up the state of Minnesota, about 18 million acres, or about one-third of the state's land area, are considered forestland[7]. Minnesota's forests are biodiverse, with more than 50 native tree species and hundreds of herbaceous and woody species making up the forest understory. Maintaining healthy, biodiverse forests is essential to ensuring that Minnesota's ecosystems are properly-functioning and continue to provide essential services to the state, such as protecting water and soil quality, filtering pollution, recycling nutrients, providing economic opportunity through the forest products, recreation, and tourism industries, and aiding in ecosystem recovery following disturbances.



Extent of forest cover in Minnesota, 2016. Data sourced from National Land Cover Data (NCLD).

PROTECTING AND IMPROVING WATER, SOIL, AND AIR QUALITY

In Minnesota, a state where our identity is closely tied to our water resources, forests play an integral role in protecting our lakes and rivers and improving surface- and groundwater[4]. Forest cover can act to lessen the impact of rainfall on soil, preventing soil erosion, and helps to maintain water levels by promoting water storage in forest soils, which reduces both flooding and drought effects[5]. Climate change is likely to affect the amount and timing of precipitation we receive, making the moderating role of forests on our water supply ever more important. However, climate-change threats to our forests, such as increasing catastrophic wildfire and die-off due to pests and pathogens, may hinder the ability of our forests to perform these crucial functions.

PROVIDING ECONOMIC OPPORTUNITY TO MINNESOTA COMMUNITIES

Climate change will also affect the communities that rely upon our forests for economic opportunity. Rural Minnesota is perhaps the greatest beneficiary of Minnesota's forest and outdoor recreation industries. Many rural communities depend upon forests either for direct employment, such as those in the logging, paper, or sawmill industries, or for recreational value, like hunting, hiking, and skiing[6]. In turn, the forest industry addresses the societal demand for diverse forest products, and the associated logging infrastructure provides the capability for forest management actions (e.g., increased stocking and enhancing age-class and structural diversity), which will be essential for sustainable adaptation to climate change.

Forest Products Industry

Nearly 16 million acres of Minnesota's forestland is considered sufficiently productive for commercial use and is not restricted from harvest by policy or law. This productive timberland is owned by a variety of stakeholders, including private owners (42 percent), state (23 percent), county and municipal (16 percent), industrial (7 percent), and USFS/other federal agencies (approx. 12 percent)[7]. In 2016, the forest industry was Minnesota's 5th largest manufacturing sector, with 30,500 direct jobs and 64,000 total employment effect[7]. The forest products sector directly contributed $3.4 billion in value-added to the State's economy in 2016, with a total of $8 billion value-added effect[7]. Although the forest products industry continues to provide important economic benefit to the state, the industry

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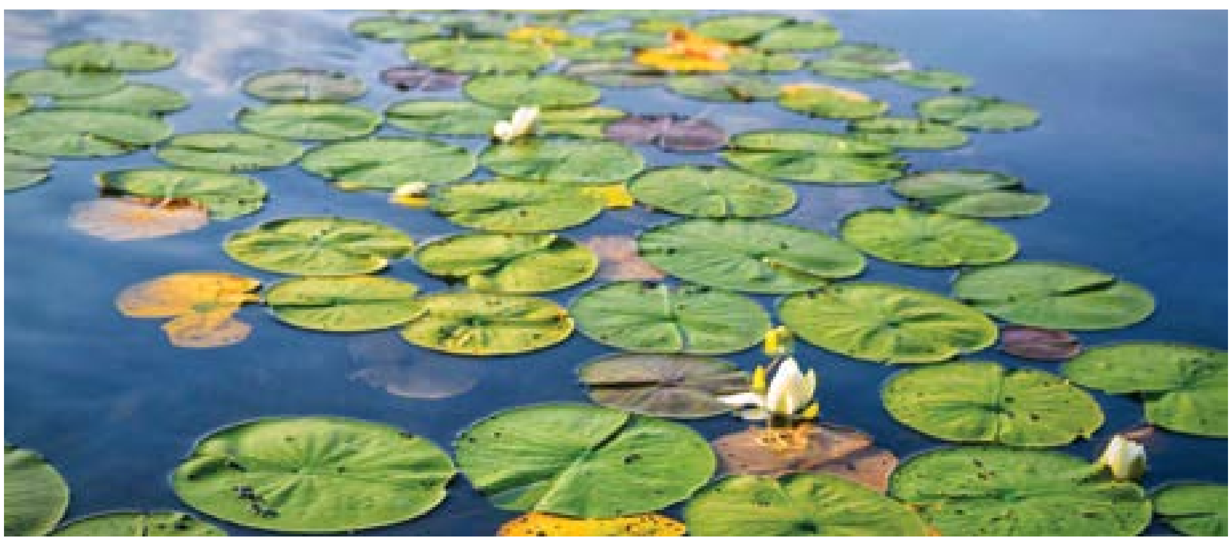

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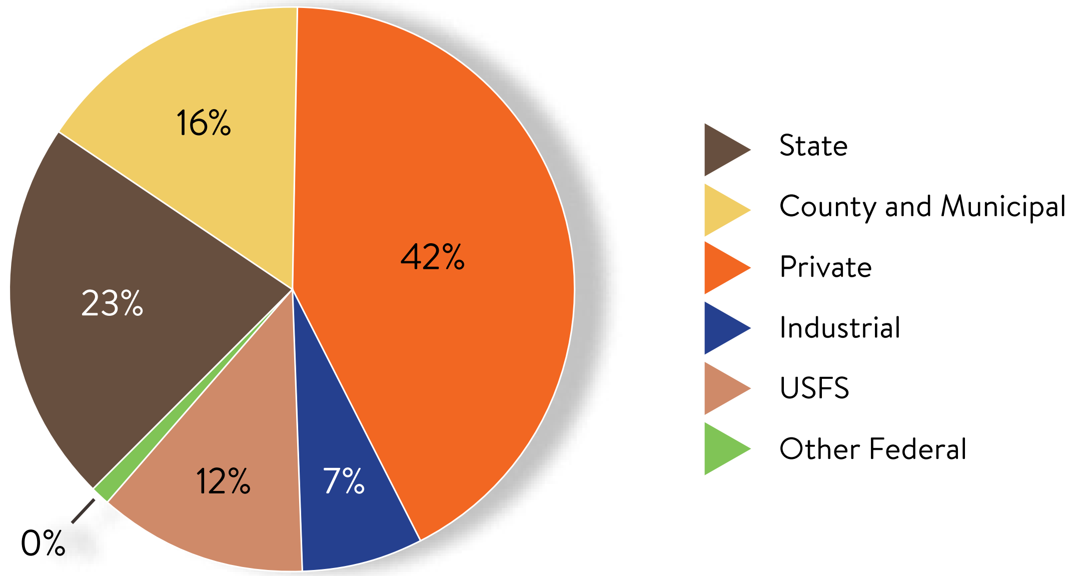

Timberland ownership in Minnesota by ownership type[7].

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is facing a number of challenges, including: disposal of waste (sawmill byproducts, chips, etc.); quality of wood; quantity of wood; accessibility of wood; and utilization of secondary species.

Outdoor Tourism and Recreation Industry
Minnesota's tourism industry generated an estimated $15.3 billion in gross sales during 2017, with the Central and Northeast tourism regions making up approximately $2.25 billion of those sales[8]. These tourism regions largely make-up what is affectionately known as "cabin country" and may offer some proxy of the role of the outdoor recreation and tourism industry on the State's economy, particularly from the heavily-wooded regions of the state. Another measure of the size and impact of the outdoor recreation economy is the use of public lands. Minnesota's State Parks accommodate an average of over 9 million visitors each year, with four of the five most popular parks located in the forested north and northeast areas of the state[9]. Estimates of the overall impact of Minnesota's outdoor recreation economy include 140,000 direct jobs, $16.7 billion in consumer spending (including the purchase of equipment, goods, and services), and $1.4 billion in state and local tax revenue[10].

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CONTRIBUTING SPIRITUAL AND CULTURAL SIGNIFICANCE

Minnesota's forests also play important cultural and spiritual roles. For many native people, including the indigenous Ojibwe whose traditional homelands include much of northern Minnesota, a holistic relationship with nature is an essential part of their cultural and spiritual identity. Anishinaabe scholar James Dumont described his culture as one in which the "person is inseparable from the land; identity, sense of place and history [are] intimately related to the land..." and stated that "[p]lants, trees, animals, rocks, and unseen forces of nature are also considered as 'persons' ... and "[t]he whole of creation are relatives to the human being" [11]. The spiritual significance of natural lands for Anishinaabe and other native peoples is directly tied to their heritage and historic role as stewards of the land. This historic role is acknowledged in the statutory, usufructuary, and treaty rights provided to native peoples to uphold their holistic forest ideology. Forests also provide spiritual value to non-native peoples. There is a growing body of literature on the benefits of forests and trees for the mental, physical, and emotional wellbeing of all people[12, 13, 14].

PROVIDING HABITAT FOR DIVERSE COMMUNITIES OF NATIVE PLANT, ANIMAL, AND MICROBIAL SPECIES

Our forests also provide habitat for iconic wildlife species, including moose, timber wolves, ruffed and spruce grouse, lynx, pine marten, and black bears. While these large vertebrates may be more recognizable, their numbers pale in comparison to the number of micro-vertebrates and invertebrates that also rely upon suitable forest habitat. Because of our position at the transition zone (ecotone) between the prairie-temperate forest and boreal forest, Minnesota contains several plant and animal species found at or near the edge of their range[15]. Large areas of continuous forest cover with a patchwork of age dynamics and linkages is essential for the success and health of Minnesota's wildlife, but the warming trend associated with climate change may change the forest composition and structure in ways that could hinder the success of many native plant and animal species[16]. For example, Minnesota has already begun to witness a decline in moose populations. Several of the factors that may be contributing to this decline are related to climate change. In particular, research has found that infection with brain worm, a parasite associated with white-tailed deer, may account for up to 45 percent of moose deaths since the species experienced large declines in population beginning in 2006[17]. The northward migration and increasing populations of white-tailed deer

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into historically moose-dominated habitat is a documented result of a warming climate[1]. In addition, moose may have a low tolerance to increasing summer temperatures, a climate change outcome that is likely to continue and exacerbate in the coming years.

The microscopic life in our forests, although receiving less of the spotlight, are no less important to forest and ecosystem health. The importance of microbes intimately associated with individual plants and animals – and the ecosystems they are part of – to forest health and function has been increasingly documented in the past decade (the 'microbiome'). Trees and forests provide habitat to an enormous diversity of microbes responsible for decomposition, nutrient cycling, plant acquisition of nutrients, and protection against pathogens, among other benefits, as well as to those disease-causing pathogens themselves[18]. Microbes play essential roles in all aspects of forest function.

Forests collectively house diverse communities of plants, animals and microbes. The value of this diversity to the stability, health, and function of forests – including in the face of climate change - is increasingly recognized, documented, and quantified[19, 20, 21, 22, 23]. Maintaining such diversity will be key to maintaining healthy productive forests in Minnesota.

Climate change is expected to affect all of the ecosystem services that forests provide, from wildlife habitat and water quality to economic benefits. Understanding climate change outcomes for Minnesota and their effects on forests and forest management is essential to our ability to plan for a climate-resilient future.

CURRENT AND PROJECTED CLIMATE CHANGE OUTCOMES IN MINNESOTA

The outcomes of climate change in Minnesota can largely be broken into four categories: 1) increasing temperatures; 2) a disproportionate effect of changing climate on our winters; 3) more frequent and intense precipitation events; and 4) intermittent periods of drought and water stress. These outcomes are supported by scientific evidence and general agreement within the scientific community[16]. The increasing temperatures and disproportionate effects on winter conditions are widely agreed upon and are strongly supported based on existing evidence. Changes in the amount of precipitation and length and frequency of drought are less certain, but the overall outcomes described below are generally agreed upon by scientists[16].

INCREASING AVERAGE ANNUAL TEMPERATURES

Current

Since Minnesota began maintaining statewide temperature data in 1895, the average annual temperature in the state has increased by an average of 0.23 degrees Fahrenheit per decade, for a total average increase of just under 3.0 degrees Fahrenheit during the past 125 years. However, this trend has accelerated in the past 45 years, with the average annual temperature increasing at a rate of 0.43 degrees Fahrenheit per decade since 1975, for a total increase of over 1.0 degree Fahrenheit in recent decades[24].

Projected

By the end of this century, Minnesota is expected to warm by another 3.0 to 8.8 degrees Fahrenheit[16, 25]. Seasonal variation in the warming of our climate is expected, with larger and more immediate effects on winter season temperatures, as will be described below. Summer temperatures are also expected to increase, with up to nine more days with maximum temperatures above 95 degrees Fahrenheit by 2050, and as many as 20-31 more 95 degree days by 2090[26]. This shift in our climate will likely be accompanied by changes to the ecosystems that have historically defined our state.

DISPROPORTIONATE EFFECTS ON WINTER CONDITIONS

Current

Some of the greatest changes to our climate may be most apparent during the winter months. Since 1895, the average wintertime temperature for the months of December-February has increased an average of 0.40 degrees Fahrenheit per decade, for a total increase of 5.0 degrees Fahrenheit in the past 125 years[24]. Over the past 45 years, this rate of increase has

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more than doubled to 0.81 degrees Fahrenheit per decade, leading to a rise in winter temperature of over 3.5 degrees Fahrenheit in just the past several decades (1975-2020)[24]. During the 20th century, there was a slight increase in wintertime precipitation amounts; this increase has largely been attributed to an increase in intense snowfall events of 6 inches or greater during the recent decades[16]. The variability of the snowpack from year-to-year and within a single season may have contributed to colder and more frozen soils during the past century, despite warming temperatures, due to insufficient ground insulation from snow cover[16, 27].

Projected

Temperatures are expected to disproportionately increase during the winter months over the coming years, with average winter temperatures (December – February) increasing by 3.9 to 9.8 degrees Fahrenheit[16]. This increase in temperature will likely be partnered with a change in winter precipitation, with an increasing proportion falling as rain rather than snow and associated decrease in snow water equivalent[16]. The change in temperature and snow cover will indirectly affect the development of soil frost throughout the region, decreasing the number of frost weeks in the coming decades. Northern and northeast Minnesota is expected to have two-to-three fewer weeks of frost by 2050 and potentially as many as seven fewer weeks of frost by the end of the century (under high emissions scenario, compared to a baseline from 1990)[16, 26, 27].

GREATER INTENSITY RAINFALL AND HIGHER ANNUAL PRECIPITATION

Current

Average annual precipitation has increased across Minnesota since 1895 at an average rate of 0.29 inches per decade[24]. This trend has accelerated in the most recent 45 years, with the rate of precipitation increasing at a rate of 0.66 inches per decade[24]. This corresponds to an increase in average annual precipitation of nearly 3.0 inches since 1975. The increase in precipitation in the past century has tended to be concentrated in the summer, fall, and (to a lesser extent) spring months[16].

Projected

In the coming decades, intense precipitation events, particularly rainfall, may become more frequent[16, 25, 28]. This increase in precipitation may be particularly acute in the Arrowhead region of northeast Minnesota, along the North Shore of Lake Superior[26]. Annual precipitation across the state may increase by 15-25 percent by 2090, but along the North Shore, that number could be as high as 55-75 percent[26].

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INTERMITTENT PERIODS OF DROUGHT AND WATER STRESS

Current

Since 1895, Minnesota has been experiencing generally fewer periods of extreme drought. While there have been periods during the past 20 years where more than 80 percent of the state has experienced at least moderately dry conditions, the general trend over the past century has been decreasing drought and water stress across the state[16].

Projected

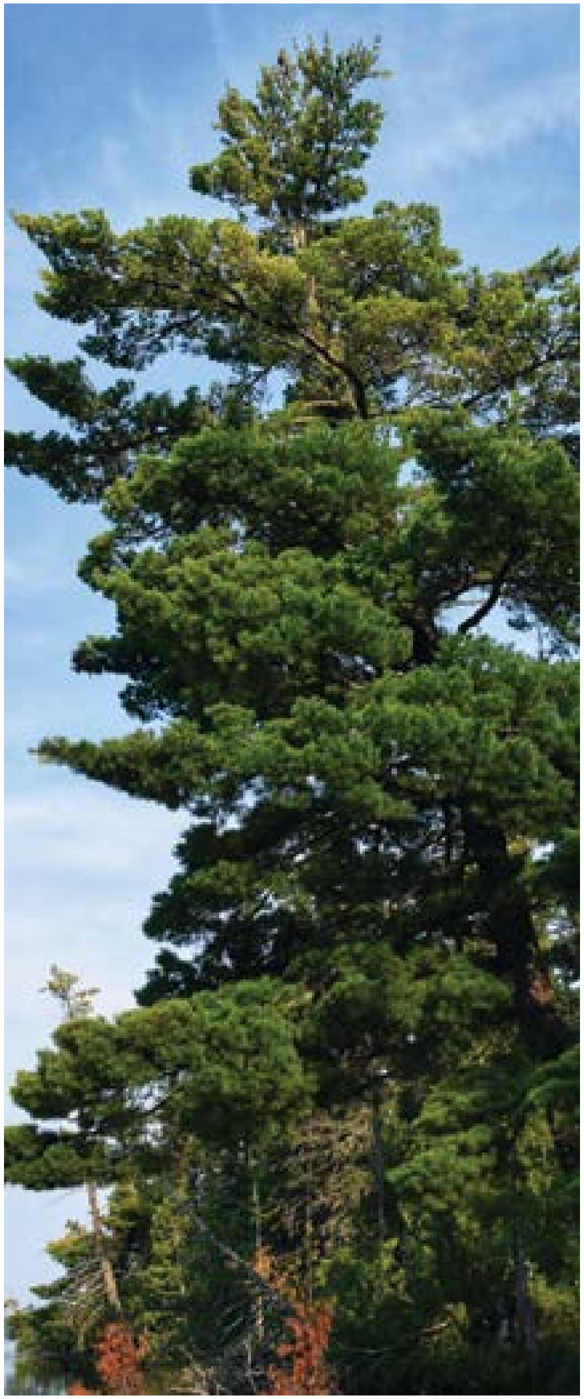
Although an increase in precipitation is expected in the coming decades, this overall increase is likely to be concentrated early in the growing season (March-May). The anticipated concentration of precipitation in the spring, coupled with increased summer evapotranspiration from warmer plants and soils, leaves open the potential for increased droughts and water stress in the summer months (July-August)[26, 29, 30, 31]. A state-scale study suggests this is likely to occur particularly during the early part of this century before 2050[25], but modeling at larger continental scales suggests these effects may grow more pronounced throughout the century[29, 31].

POTENTIAL CLIMATE CHANGE EFFECTS ON MINNESOTA'S FORESTS

All of this change is likely to impact Minnesota's forests. These changes to our climate will also affect our ability to manage forests to provide necessary environmental services and economic, spiritual, and cultural vitality to our communities. Several potential implications of climate change on our forests are described below. This list is not intended to be comprehensive; rather, its purpose is to describe some of the most likely scenarios and challenges that may arise in the management of our forests under a changing climate.

ALTERED SPECIES COMPOSITION AND MIGRATION OF ECOSYSTEMS

Studies have found that a changing climate could result in a change to the composition of our forest cover or an overall decrease in that cover as native species struggle to adapt to a new climate regime[1, 22, 32, 33, 34, 35, 36, 37, 38]. In particular, species that are found in Minnesota near the southern edge of their native range are likely to struggle under warming conditions[38]. These include native species such as quaking aspen, paper birch, balsam fir, white spruce, jack pine, and red pine[37, 39, 40]. Analysis of past climate change events indicates that in the Lake States region, a loss of boreal forest cover is a likely outcome of a warming climate,



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with those species being replaced by temperate-forest species such as basswood and sugar maple[36, 41]. Indeed, certain hardwood forest species are seen as likely climate change "winners" in Minnesota, with a likely expansion in suitable habitat for temperate hardwood species and the potential for increased productivity from these forests[16]. However, in contrast to past changes in climate that occurred at a slower rate and allowed for a change in forest cover over centuries, the current change in climate is projected to occur at a much faster rate[36, 41]. This may foreshadow a potential dieback of boreal forest cover before temperate hardwood species are able to establish in new suitable territory[39, 41]. Further, boreal forest understory conditions may also prove unfavorable (e.g., needle cover, cooler, darker) and may hinder the recruitment of temperate species into the boreal zones in the absence of wildfire or other disturbance[42].

INFRASTRUCTURE CHALLENGES FOR MANAGEMENT AND RECREATION ACCESS

Several likely outcomes of climate change may affect access to Minnesota's forest resources for management. Higher intensity rainfall events and rapid snowmelt may lead to wetter soils in the spring and summer months, hampering the ability of loggers to access stands, and also creating a potential risk for the erosion of access trails and skid roads and increased rutting[43]. In addition to their importance for forest management access, many forest roads and

other rural infrastructure are also essential for outdoor tourism and recreation. A study on the effect of climate change on infrastructure in Alaska found that the greatest impact of climate change on infrastructure would likely be the flooding of roads[44]. Similarly, the Intermountain Adaptation Partnership identified flooding and erosion as major concerns affecting existing infrastructure[45]. In particular, culverts, which are typically used for stream crossings on forest access roads, are more sensitive to flooding[45]. Little literature appears to exist which investigates the effect of projected climate change outcomes on rural infrastructure and forest roads in Minnesota or the Lake States; it is clear that there is an opportunity for additional research in this area.

Perhaps more concerning for forest managers and the forest products industry in Minnesota is the change in winter conditions that are expected as a result of climate change. The large reduction in soil frost days by the end of the century will severely constrain the ability of managers to access forest resources[16, 26, 27]. Historically, winter season harvest has been the most productive season for loggers in the upper Midwest[42]. For many forest species, winter weather conditions are one of the primary factors influencing the ability of loggers and other forest managers to access sites, transport

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equipment, and conduct harvests[43, 46]. The length of the frozen season has undergone an observable decrease over the past several decades in the Lake States region; this trend is expected to continue as wintertime temperatures continue to rise[26, 27, 43, 46]. Shorter winter harvest seasons may be of particular concern for the harvest of species such as black spruce, which are often found in wetland areas that require frozen ground for management access[43].

INCREASING DISTURBANCES AND MIGRATION OF PESTS AND PATHOGENS

As noted, climate change will increase the number and severity of forest disturbances due to extreme weather events (including windstorms and derechos), catastrophic wildfire, and pests and pathogens[1, 47, 48, 49, 50, 51, 52]. These disturbances may also interact to cause additional impacts. For example, the accumulation of dead wood in forests following windstorms could increase the rate and severity of catastrophic wildfire in Minnesota's forests, especially under increasing periods of drought[1, 48, 49].

Minnesota's forests are also facing an unprecedented risk due to native and invasive pests and pathogens. Some invasive species, such as gypsy moth, emerald ash borer, and common buckthorn, are already present in the state, and their impact is only expected to increase in

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the coming years as our climate warms. Warmer temperatures, particularly in the winter, may allow for increased spread of these invasive species in northern Minnesota, where their proliferation has previously been hampered due to cold winter temperatures. Others, such as mountain pine beetle and Asian longhorned beetle, as well as the fungus known as sudden oak death, have not yet been found in the state, but could have devastating consequences to some of the state's forest species should they arrive in Minnesota. The warming conditions expected throughout the northern portions of North America are likely to facilitate the migration of these pests and diseases to Minnesota and the Lakes States region.

Other pests, such as the native eastern larch beetle will also likely contribute to loss of forest cover in the coming years. Eastern larch beetle has been in a prolonged outbreak for the past two decades due to longer growing seasons and warmer conditions associated with a changing climate. More than 666,000 acres of forest in the state contain infected tamarack as of 2019[53]. The conditions which have allowed for this extended outbreak are likely to continue as Minnesota continues to warm.

A CASE STUDY: EMERALD ASH BORER

Emerald ash borer (EAB), which was first detected in Minnesota in 2009, has decimated populations of ash in the eastern United States[52, 54]. Although the spread of this pest is currently constrained by its inability to survive cold winters, warming climatic conditions make the future spread of EAB to the vast black ash wetlands of northern Minnesota all but certain[54]. Due to the perniciousness of EAB – killing nearly 100 percent of all mature ash trees in portions of the eastern US near where it was introduced – the potential for a loss of forest cover in Minnesota's black ash wetlands is a distinct possibility[52, 54].

Minnesota's black ash stands cover around 1 million acres of forestland, with most of the black ash found in single-species stands in wetland areas[55]. These low diversity stands make ash particularly vulnerable to pest outbreaks. Die-off of black ash stands in Minnesota could result in a loss of many million metric tons of carbon, as well as a potential for ash forestland to be converted to non-forested wetlands, with cascading effects on water quality and quantity[54].

Alan Toczydlowski, UMN

This image depicts black ash trees that were girdled for a study in northern Minnesota's Chippewa National Forest that investigated the potential impact of EAB on ash in northern Minnesota. Girdling ash trees to mimic die-off from EAB was one of three "treatments" that researchers utilized to assess the likely effects of EAB on hydrologic conditions, regeneration of ash and other species, and ecosystem transition. The other treatments included clearcutting ash trees from selected sites and leaving sites undisturbed.

REGENERATION FAILURE AND DIFFICULTY ESTABLISHING REGROWTH

In addition to affecting the amount and quality of forest cover due to increasing disturbances, climate change may also affect the ability of forests to regenerate following these disturbances, as well as their long-term growth. While warmer temperatures are associated with longer growing seasons, the increase in temperature may be detrimental to the survival of seedlings for some species, especially fir and spruce, while favoring others, like oak or the invasive buckthorn[34, 38, 40, 56]. In addition, regeneration of native species may be hindered by increases in herbivory and the presence of pests or pathogens. The range of white-tailed deer has expanded across the state as the climate has warmed, leading to increased herbivory of many tree species, including northern white cedar, yellow birch, northern red oak, and white pine seedlings[1]. The increasing presence of non-native earthworms and native and invasive pests, such as emerald ash borer and eastern larch beetle, could also lead to reproductive failure or dieback of existing forests[1].

The effect of climate change on the growth of native tree species is likely to vary and may be controlled as much by access to water and nutrients as by increased temperatures[30, 37, 57]. While the general thought is that tree growth in Minnesota and the Lakes States region is constrained by cold temperatures, the potential fluctuations in soil moisture due to variable precipitation and increased evapotranspiration as a result of climate change could hamper the ability of trees to increase their growth rates[30, 37, 38, 58].

EFFECTS ON RECREATION, TOURISM, AND FOREST-BASED ECONOMIES

The changing climate will also affect the industries that rely upon healthy forest ecosystems. These include Minnesota's outdoor recreation and tourism industries, in addition to the forest products industry. Of Minnesota's most popular tourist destinations, not including the Metro region, twenty-six (of 40) are state or regional parks, recreation areas, national parks, or locations associated with outdoor recreation (e.g., Lutsen Mountains)[59]. The combined visits to these destinations totaled near seven million in 2017[59]. When including attendance at popular Metro region local and regional parks, the number of visits expands to nearly 27 million combined visits; these numbers demonstrate the importance of Minnesota's outdoor heritage to our recreation and tourism-based economies[59]. Popular pastimes related to this heritage, including hunting, fishing, hiking, skiing, snowmobiling, and camping are closely tied to the health of our waters and forests, as well as climatic conditions. Winter tourism activities, which provide over 7,000 jobs and economic value-added of over $400 million to the state, will be particularly impacted by climate change, as temperatures warm and the season-length decreases[60].

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SUMMARY & CONCLUSION

Forests provide essential ecosystem, environmental, social, and economic services to Minnesota. These services, which include providing high water quality and moderating water quantity, providing habitat to numerous plant and animal species, and benefiting rural communities through the outdoor recreation and forest industries, are all at risk under a changing climate.

- **Warming Temperatures:** Minnesota's climate is expected to become warmer over the coming decades, resulting in warmer, shorter winters, warmer summers, and longer growing seasons. The warming temperatures may result in a decreased ability for some native species to grow and thrive in the state and a migration of other species northward. Some species may be extirpated or nearly extirpated from Minnesota's forests.
- **Greater Amount & Intensity of Precipitation:** Increasing precipitation, especially if it falls in higher intensity events, may result in more erosion and rutting damage at forest harvest sites due to wetter soils. This could also lead to more flooding events, as rainfall may occur faster than forests are able to absorb the precipitation, resulting in increased run-off, erosion of roads and trails, and decreased water quality.
- **Intermittent Drought:** While more total rainfall is expected on an annual basis, this increase may not be evenly distributed throughout the year, leaving the potential for drought-like conditions to develop given greater evapotranspiration water losses almost certain to occur in the future. This may increase the likelihood of catastrophic wildfire, as well as forest die-off from pest or pathogen outbreaks due to water stress. Water stress and periods of drought may also hamper the ability of some tree species to regenerate following disturbance events.
- **Disproportionate Effects on Winter:** The warming winters are likely to negatively affect the forest products industry due to the lack of winter access to forest stands for management. The changing conditions may also impact the outdoor recreation industry, particularly winter activities such as skiing and snowmobiling. Warmer and shorter winters are also likely to facilitate the spread of native and invasive pests and pathogens.

Addressing the changes and impacts associated with climate change is a significant challenge and will require investment in research, forest management capability/practices, and policy development. Section 4 of this report develops a number of these suggestions. Key research questions which will further address these challenges and uncertainties are described on page 25.

KEY RESEARCH NEEDS

The following research needs and questions were developed by the Research Advisory Committee based on their relevance to the topics reviewed in this section and importance to developing effective forest management strategies.

MINNESOTA'S FORESTS

- What are the unique roles of the diverse landownerships in Minnesota for being resistant/resilient to climate change, and what partnership or collaborative opportunities could enhance these roles?
- How will climate-driven disturbances affect vulnerable forest systems in Minnesota?

CURRENT & PROJECTED CLIMATE CHANGE OUTCOMES IN MINNESOTA

- What are current trends in forest conditions and the latest projected climate change outcomes in Minnesota?
- How do shorter frozen ground seasons impact our ability to harvest timber and recreate in the forest while maintaining best practices for protection of soil and water?

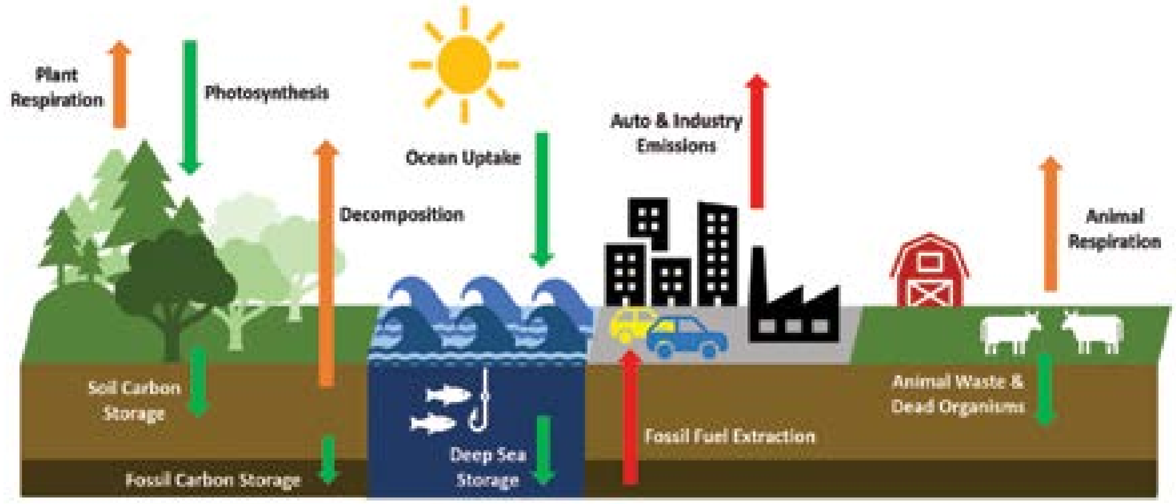
POTENTIAL CLIMATE CHANGE EFFECTS ON MINNESOTA'S FORESTS

- What effects might climate change have on infrastructure (e.g., harvesting and stand treatment capacity, access roads, bridges, culverts) necessary for on-the-ground forest management?
- How do we measure and assess the effect of climate change on forests?

SECTION 2 FOREST CARBON STORAGE & SEQUESTRATION

Forests compose a large portion of the earth's terrestrial carbon sink. As trees grow, they absorb carbon dioxide (CO_2) during photosynthesis, sequestering some of this carbon in tree biomass and forest soils. This carbon sequestration effect is not small – in the United States, forestland currently offsets somewhere between 8 and 15 percent of total fossil fuel emissions annually, depending on the accounting and modeling system used to assess forest sequestration[61, 62, 63]. Increasing the sequestration and storage of carbon is considered one tool that may mitigate some of the effects of climate change. Key approaches to doing this include:

- **Forest Retention:** Preserving and enhancing existing forests;
- **Afforestation & Reforestation:** Increasing the net amount of forest area through planting or seeding;
- **Forest Management:** Improving forest management practices to increase sequestration rates; and
- **Forest Products:** Increasing production and utilization of wood products that offset fossil fuel energy, replace greenhouse gas-intensive materials (e.g. concrete or steel), or store carbon for long time-periods.



Representation of the carbon cycle. Green arrows represent removals of carbon from the atmospheric carbon pool and storage in terrestrial reservoirs. Orange arrows represent natural, biogenic emissions of carbon to the atmosphere, while red arrows are representative of human-caused carbon emissions via the extraction and combustion of fossil fuels.

THE CARBON CYCLE

Before considering how the above factors may be utilized to increase carbon sequestration rates in Minnesota, it is important to understand the carbon cycle and the various carbon pools that are considered when accounting for carbon on the landscape.

Carbon is stored in several pools, or reservoirs. Plants (e.g., trees and forests) absorb carbon from the atmospheric carbon pool, and store most of that carbon in plant tissues such as leaves, roots, and woody biomass. Carbon can also be removed from the atmospheric pool through the uptake of carbon by oceans and other bodies of water and the associated deep-sea storage of carbon.

Some of the carbon taken in by plants is released back into the atmospheric carbon pool through plant respiration, while other carbon remains in the terrestrial carbon pool in the form of plant matter, or is transferred to the soil carbon pool through plant and animal wastes or dead organisms. Animals consume plant material and utilize the carbon to build their own body tissues while releasing carbon into the atmospheric pool through respiration. Over extremely long periods of time, soil carbon may be converted

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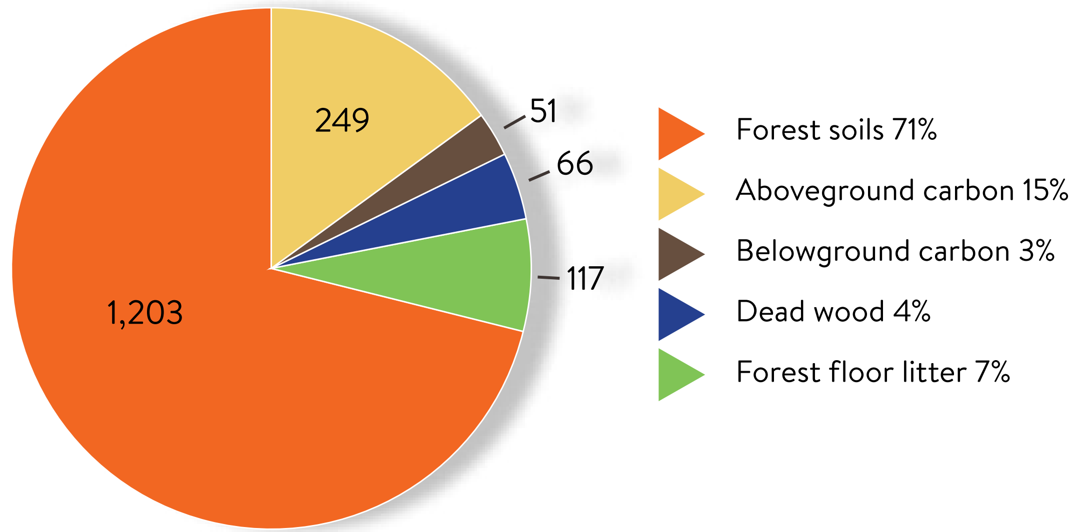
to fossil carbon, such as coal or other fossil fuels. However, more frequently, soil carbon is returned to the atmosphere through the process of decomposition.

The extraction and use of fossil fuels for energy to power electric grids, heating and cooling, and transportation represent an active increase in the amount of carbon stored in the atmosphere, represented by red arrows in the graphic on the previous page. Without human extraction and use of fossil fuels, this reservoir of carbon would remain largely inert below the earth's surface and would not contribute to the normal cycling of carbon. This increase in atmospheric carbon and the associated greenhouse effect are the primary factors driving observed and predicted climate change outcomes.

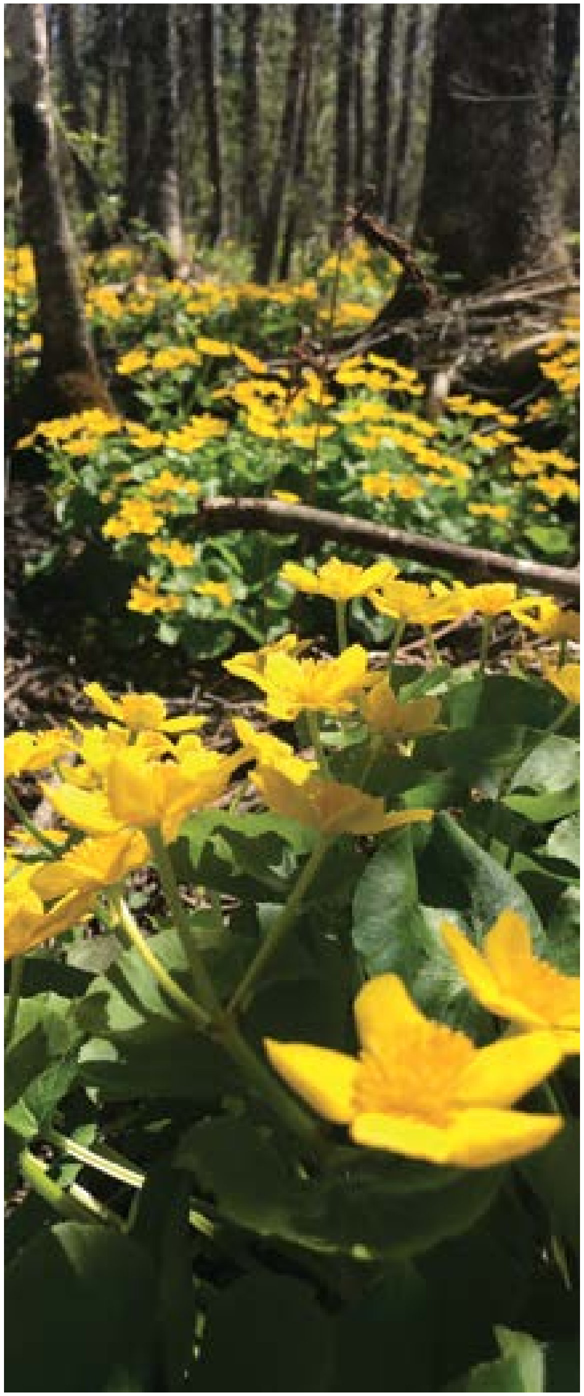
The United States Forest Service (USFS) considers five main pools of carbon when assessing the amount of carbon stored in our forests:

- Living aboveground biomass, which includes tree trunks, branches, and leaves of live plants;
- Living belowground biomass, such as the roots of living trees;
- Dead wood, such as any fallen or standing dead trees;
- Carbon in forest litter, such as fallen leaves or needles; and
- Carbon stored in forest soils.



Estimated carbon storage (in million metric tons) in Minnesota forests by USFS FIA carbon pools, including the 2019 inventory results (added to FIA database May 8, 2020)[55]. Forest soils compose 71 percent of Minnesota's terrestrial carbon storage, while aboveground carbon composes 15 percent, belowground carbon composes 3 percent, dead wood composes 4 percent, and forest floor litter composes 7 percent.

In Minnesota, the USFS estimates that forests store roughly 1,685 million metric tons of total carbon[55]. This breaks down to approximately 249 million metric tons of living aboveground carbon, 51 million metric tons of living belowground carbon, 66 million metric tons of carbon stored in dead wood, 117 million metric tons stored in forest floor litter, and 1,203 million metric tons of carbon stored in forest soils[55]. The large soil carbon storage reservoir can be partially attributed to the organic peatland soils found throughout northern Minnesota, as well as the abundance of decaying plant roots and other material and the associated soil organisms and fungi that dwell in the soil.



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FOREST RETENTION

Maintaining existing forests on the landscape is the most effective method of preserving stored forest carbon. For example, conversion of forestland to agricultural land or for urbanization results in a net increase of carbon released into the atmosphere on an annual basis[64]. Further, forests that remain forests tend to have higher carbon stocks, both in aboveground and soil carbon pools, than do forests that result from afforestation or reforestation of formerly cultivated lands[64, 65]. If northern forests are allowed to persist without disturbance or land-use change, they could increase their carbon storage capacity by nearly 40 percent by the end of this century[66]. Certain practices, both from policy and management frameworks, can increase the ability of landowners to maintain forest cover.

Parcelization, which is the fragmentation of large blocks of land into smaller land holdings, is closely linked with conversion and loss of forest cover[67, 68]. A growing human population and the associated demand for homes in the forest regions of Minnesota is tied to parcelization, particularly near lakes, rivers, and roadways[67, 69]. The estimated market value of a piece of land is also closely related to the likelihood of the land being parcelized[67].

Preventing parcelization is key to protecting and retaining Minnesota's existing forestland. Land acquisitions through donation, purchase, and land exchange are one tool by which parcelization of forest can be combatted. Conservation easements, in which a partial interest is acquired for a piece of land, can provide conservation organizations or government agencies the ability to encourage the maintenance of forestland[70]. These agreements aim to protect a piece of land from development or conversion in perpetuity, and often require that current and future landowners refrain from conducting certain activities on their properties in order to achieve conservation interests and conserve the physical and ecological characteristics of a landscape[68, 70]. While conservation easements can play an important role in avoiding the parcelization of Minnesota's forestland, they require robust and well-funded programs in order to negotiate easements and manage them over time[68].

Tax policies and incentive programs are also tools that can be utilized to discourage land-use conversion and parcelization of landscapes[71]. Preferential forestland property taxation provides an opportunity to influence parcelization by providing a tax incentive to maintain intact forestland[71]. However, in order for tax policy to produce the intended reduction in parcelization and development, the benefit to landowners must be sufficiently high to outweigh the value of development[71]. Minnesota also

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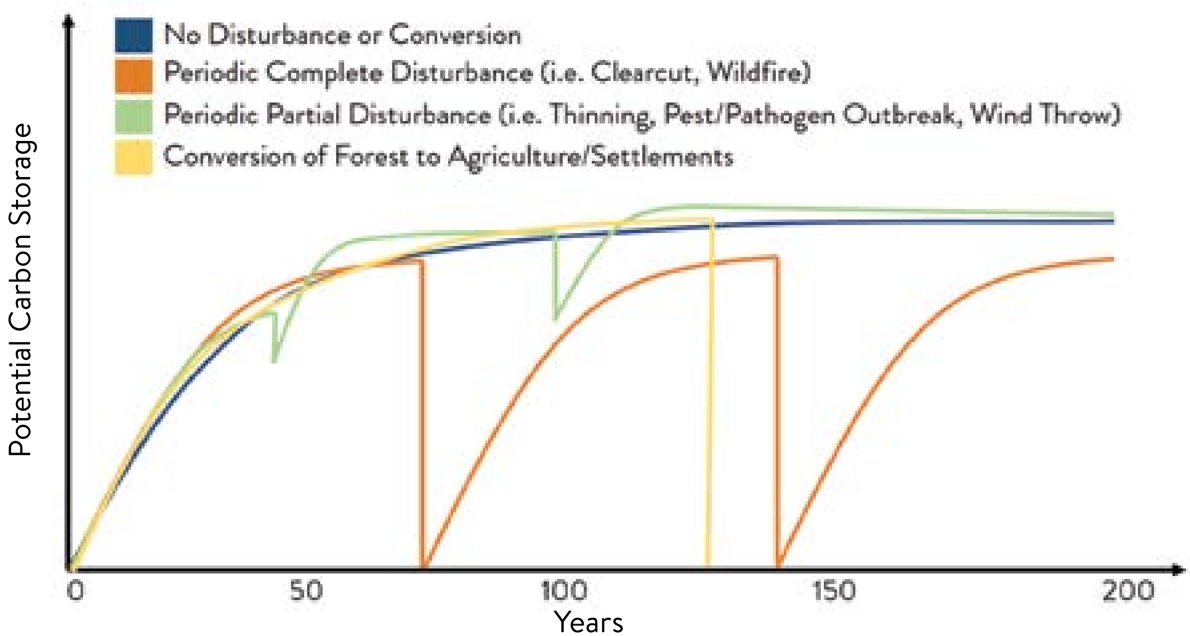
offers forestland owners an incentive to maintain their forest cover through the Sustainable Forest Incentive Act (SFIA). This program, in which private landowners receive an annual payment for each acre of enrolled woodland, requires the land remain undeveloped and follow a forest management plan for a period of eight, 20, or 50 years[72].

Local land use planning and zoning laws are also used to help avoid parcelization of forestland; however, addressing forest parcelization has not generally been a motivating factor in the development of county and local land plans[69]. Because of the potential economic benefit associated with parcelization and development, many rural counties with significant holdings of undeveloped land have not tended to implement zoning restrictions to curb the parcelization of their lands[69]. A larger role could be played at the state level to encourage the development of comprehensive land management plans for the reduction of parcelization. This work could piggy-back on legislation related to climate change mitigation planning at the state- and/or local-levels.

Regardless of the strategies taken to improve the retention of forestland in Minnesota, it is unrealistic to assume that forests can perpetually grow and accumulate carbon without disturbance. Natural events, such as windstorms, wildfire, and insect outbreaks can decrease forest carbon storage, as can human-driven changes such as the conversion of forest to cropland or settlements, harvesting of timber, and removal of forest cover for other economic considerations, such as infrastructure or mining[73]. Over the past several decades (1990-2018), land-use changes and forest harvesting reduced the forest carbon pool in the northern states (including Minnesota) by over 0.2 tons of carbon per acre per year[74]. Over that same time period, undisturbed forests in the same region sequestered over 0.8 tons of carbon per acre per year[74]. The effect of various potential disturbances or land-use changes on carbon storage is illustrated in the graphic below. It is important to note that although forest harvest can temporarily reduce forest carbon, it is not considered a conversion or loss of forest cover, so long as adequate regeneration of forest cover occurs following harvest. However, the timing of harvest should be planned and structured so that the impact on forest carbon sequestration and storage potential is minimized, ideally when forest productivity and potential carbon sequestration ability have slowed.

Of course, some forest ecosystems are more important to the storage of carbon than are others. In Minnesota, we



Hypothetical forest carbon storage over time, with and without disturbance and/or forest conversion.

have approximately 4,971,360 acres of peatlands[75]; these are areas with carbon-rich organic soils that contain vast soil carbon stores. Around 3 million acres of those peatlands are forested, many by black spruce and other lowland conifers, and are a natural trove of both living and dead organic material. Preserving these peatlands and avoiding their conversion and drainage should be a top priority of any carbon storage and climate mitigation strategy for the state of Minnesota. Working to restore degraded peatlands and improve their hydrologic function may also help to enhance carbon storage on the Minnesota landscape.

AFFORESTATION & REFORESTATION

Afforestation, which is the practice of adding forest cover to land where it has not existed in at least 50 years, is commonly cited as a primary strategy to increase carbon on the landscape[61, 62, 76, 77, 78]. This practice, which aims to increase the overall quantity of forest cover, has the potential of increasing carbon sequestration rates by several hundred million metric tons of carbon per year in the United States. This could amount to an increased offset of between 2 and 8 percent of total carbon emissions in this country (depending on the model and assumptions used to calculate carbon sequestration potential)[61, 62, 78]. *Reforestation*, which is the practice of regenerating forest cover on land where it once existed (within the past 50 years) but has since been converted, such as in some agricultural, urban, or other developed areas, may provide additional opportunities for increasing current levels of forest cover. However, the efficacy of forestation practices (e.g., afforestation and reforestation) as a carbon mitigation strategy varies by location, species, and other biophysical factors[77, 79].

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WHERE IS FORESTATION MOST EFFECTIVE AT SEQUESTERING CARBON?

Recent work has indicated that afforestation and reforestation practices may result in a net climate benefit in the Great Lakes region (including Minnesota)[77]. The ability of forestation strategies to provide a net climate benefit is likely constrained at higher latitudes due to changes in the biophysical environment that can occur when growing trees in previously non-forested areas[77]. Of particular concern is how the difference in albedo, or surface reflectance, of forest cover compared with non-forested land might result in unintended consequences (see Albedo sidebar, page 32). Despite these concerns, it is likely that the increase in carbon sequestration potential resulting

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from increased forestation in Minnesota will outweigh the potential negative climate outcomes associated with changes in the biophysical environment, including the decrease in albedo associated with forest cover[73, 77, 80, 81].

In order to maximize this climate benefit, afforested areas in Minnesota would need to be stocked to maintain around 60 percent cover and be managed on approximately 50-year rotation schedules, assuming the planting of coniferous forest cover[77]. This will ensure that the added carbon sequestration benefits of forestation exceeds the potentially detrimental effects from the alteration of the biophysical environment[77].

It is also important to note that forestation strategies should not replace efforts to protect, conserve, and regenerate other native ecosystems, such as prairie grassland and wetland habitats. In areas where forest is not the historic or natural habitat, special care should be taken to ensure that the potential benefits of a forestation strategy are appropriate for the landscape. Minnesota's "Prairie Conservation Plan" identifies prairie core areas, corridors, and habitat complexes, and provides a good source of information on the importance of conserving Minnesota's prairie ecosystems[82].

ALBEDO

Albedo is the amount of incoming radiation, or sunlight, that is absorbed by Earth's surface. The type of land cover affects the albedo of a landscape. For example, a snow-covered field or plain has a high albedo, meaning that much of the incoming radiation is reflected from the surface, resulting in a net cooling effect, while dense forest cover may have a low albedo due to the dark color of the forest canopy, and can result in a net warming effect[79].

Because of the effect that albedo can have on localized warming and cooling, it is possible that changing a landscape from one with a high albedo to one with a lower albedo could result in a net negative climatic outcome, even when considering the added carbon storage potential[77, 79].

WHAT SPECIES PROVIDE THE GREATEST FORESTATION BENEFIT?

There is also a question about whether there are specific species or cover types that may provide the greatest carbon sequestration and climate mitigation potential in Minnesota. Coniferous species, including northern white cedar, white spruce, balsam fir, tamarack, and black spruce, tend to have the greatest carbon sequestration potential over time in Minnesota[79, 81]. Unfortunately, all of the aforementioned species are likely to decrease in abundance in Minnesota as the climate warms. Deciduous species, such as cottonwood and silver maple, also have high sequestration rates and have the added benefit of having a higher albedo during winter months and greater transpiration rates, which may increase summertime cloud cover, leading to localized atmospheric cooling[79, 81]. Ultimately, the determination of which species is most appropriate for forestation will depend largely on local conditions, such as soil type, moisture availability, and desired management strategy[79, 81]. For example, fast-growing species are likely to experience greater carbon sequestration rates in the early stages of growth and would be more appropriate in a region where short-rotation ages are desired. Meanwhile, long-lived, slow-growing species may be able to accumulate larger carbon stocks over time and may be more suited to unmanaged or long-rotation

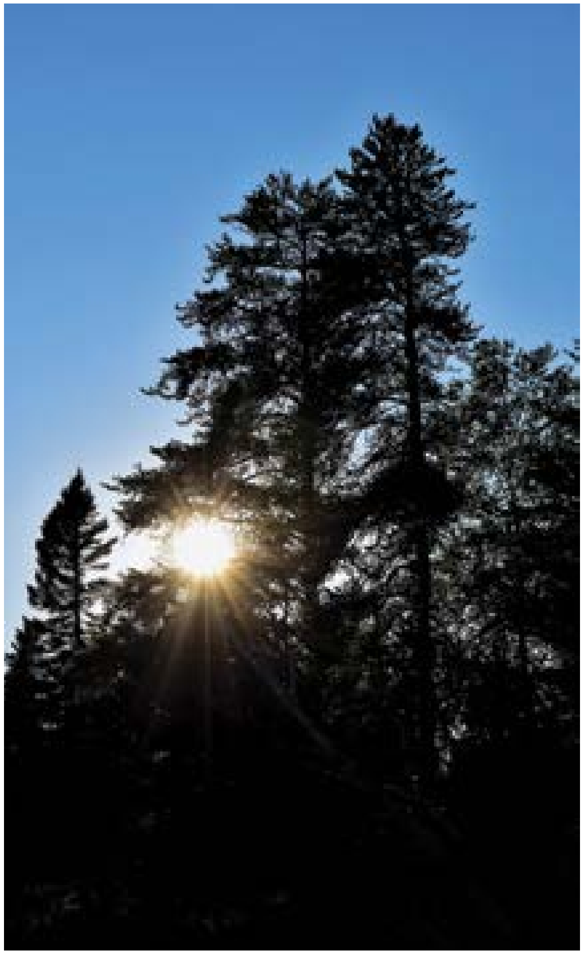
stands[73]. This could include species such as red and white pine, which have high productivity, can be long-lived in the forest, and can provide additional carbon storage in long-lived wood products.

ECONOMIC CONSIDERATIONS OF AFFORESTATION & REFORESTATION

Afforestation and reforestation strategies must be economically feasible to be successful on a large scale. For this reason, many forestation proposals have focused on the conversion of marginal and non-productive agricultural land to forestland[61, 78, 83]. The Million Acre Study, produced by the Minnesota Forest Resources Council in 2010, assessed the economic conditions, including incentives, such as carbon credit payments, and markets (e.g., pulpwood) that would be necessary to create one million new acres of forestland within the state[81]. This report found that the creation of one million new acres of forestland would require payments of approximately $114 per acre per year[81]. This could be achieved by increasing the price of pulpwood, combined with carbon credit incentives or other incentive payments[81]. For comparison, the average 2020 annual rate paid by the Conservation Reserve Program (CRP) for the removal of sensitive lands from agricultural use in Minnesota is approximately $135 per acre, although this varies by county[84]. Allowing landowners to convert CRP land to forest while remaining in the program could provide an opportunity to fund forestation efforts[81].

Additional benefits of forestation could be assessed and monetized to increase economic incentives, including co-benefits associated with a reduction in soil erosion, enhanced wildlife habitat, and improved water quality[83]. Currently, the social cost of carbon is estimated at greater than $45 per ton of CO_2, making the economic benefit of additional carbon storage associated with an afforestation strategy greater than the associated costs[62]. Compared with the cost of other emissions reductions strategies (e.g., in the energy sector), the investment in a forestation strategy is likely a competitive method for emissions reduction[85]. Funding through the NRCS's Environmental Quality Incentives Program (EQIP), which provides financial and technical assistance to landowners wishing to promote conservation, may also be available to help fund forestation practices for eligible landowners[86]. Providing incentives to landowners for these environmental co-benefits of forestation may also aid in making forestation policy economically feasible[83]. These could also include programs such as direct environmental benefit (DEB) payouts or Climate, Community, and Biodiversity (CCB) standards.

Of course, before any forestation strategy can be successfully deployed, the physical resources must be available. Current capacity in Minnesota's tree nursery system may be (and in fact is likely) insufficient to meet the future demand for seedlings of native and more southern-adapted replacement species, especially in conjunction with existing reforestation practices[81]. Between private and state-run nurseries, Minnesota currently produces approximately 22 million seedlings per year, enough to plant 23,000 acres. Much of this supply is already in high demand, leaving few seedlings available for expanded planting opportunities[81].



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FOREST MANAGEMENT PRACTICES TO INCREASE CARBON STORAGE/SEQUESTRATION

Several forest management strategies may help to increase the carbon sequestration and/or storage potential of Minnesota's forests. The scientific literature generally focuses on four main practices that could enhance carbon sequestration:

- Increasing forest stocking levels;
- Thinning forests to encourage the growth of remaining trees;
- Maintaining or encouraging high biodiversity; and
- Increasing the rotation ages of stands in managed forests.

In the following pages, we evaluate these strategies based on available literature specific to Minnesota and the surrounding region.

INCREASED STOCKING LEVELS

Forest carbon storage may be enhanced through appropriate forest management that maintains healthy, well-stocked forests. Increased forest stocking levels are a widely-agreed upon approach

for enhancing forest carbon[61]. Higher stocked forests tend to correspond with higher carbon stores in both pine- and maple-dominated forest systems in the Lakes States region[87]. As of 2019, about 40 percent of Minnesota's forests are considered to contain only poor or medium stocking levels[55]. Northern hardwood forests, considered a likely climate change "winner" in Minnesota, contain poor or medium stocking on over one third of their acreage in the state – over 600,000 acres of this cover type could be considered understocked[55].

The caveat of increased stocking practices is that the risk of catastrophic wildfire increases with the potential accumulation of fuels in the forest, and should also be a consideration for forest management. For example, balsam fir is considered understocked in over 50 percent of its total acreage; however, this species is overstocked on about 10 percent of stands[55]. In the areas where balsam fir is overstocked, it contributes to increased wildfire risk, demonstrating the need to achieve stocking levels appropriate for specific species.

Maintaining healthy, well-stocked forest cover may require more physical and financial resources in the future than has historically been the case[65]. This is because natural regeneration and regrowth of native species may be hampered by our changing climate and associated increases in pests and pathogens, disease, and herbivory from deer[1, 63]. This loss of forest cover may be enhanced by a lag in the natural migration of replacement forest species[40, 88]. In order to overcome these challenges, investments in tree planting, competition management, and protection from herbivory – all of which will require additional financial resources – will need to be made[63, 65].

Increased stocking levels are largely constrained by a lack of necessary physical and financial resources. These include insufficient quantities of seedlings for planting and the cost associated with planting and implementation of anti-browse measures. In addition, in order to achieve higher stocking levels, forest stands often must be harvested and primed for optimal regeneration and/or success of planting, leaving the likelihood of increased stocking levels subject to the economic viability of conducting harvest activities. Regardless of these constraints, the evidence for increased stocking levels on increasing carbon storage is clear, and programs and incentives to encourage stocking of forests should be implemented.

Evidence for increased stocking levels as a carbon strategy: Strong

THINNING

Forest thinning may provide a dual benefit from the perspective of carbon storage: thinning may 1) allow the remaining trees to grow larger at a faster rate due to increasing the availability of water and nutrients and 2) reduce forest fuel sources, thus reducing the risk of catastrophic wildfire[61]. However, evidence for thinning resulting in a net-carbon benefit is mixed, particularly in forests like those in Minnesota where fire tends to occur on a less frequent basis than forests in the western United States[61]. Further, in pine- and maple-dominated systems in the Lakes States region, thinning tends to decrease live forest carbon, regardless of the initial stocking level or thinning method used[87]. If stands must be thinned for management objectives, removal of suppressed trees from the understory or proportional removal of all tree sizes may minimize the decrease in carbon storage

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relative to removing the tallest trees only[87]. However, the cost of removing suppressed trees is typically higher than more traditional thinning methods, which may limit the ability of managers to utilize this strategy.

Others have suggested that a moderate disturbance, such as thinning mature forests, may result in sustained carbon uptake and wood production from remaining forest cover[89]. Additional study is needed to determine how thinning affects carbon storage in Minnesota's forests before adopting thinning management practices to enhance carbon sequestration in our state. In particular, understanding how the amount of carbon stored in thinned stands compares to unthinned stands over long time scales is essential for a better understanding of the effectiveness of thinning as a carbon sequestration/storage strategy. While its use as a strategy for increasing carbon storage requires more study, thinning is associated with increased growth rates and enhanced resistance to drought, pest and pathogen outbreaks, and wildfire[87, 90]. Thinning forests that are more susceptible to droughts, such as pine forests growing on sandy soils, may over time result in greater carbon stores than unthinned stands due to lower mortality and dieback[90].

Evidence for thinning as a carbon strategy: Weak to Moderate (more study is needed)

BIODIVERSITY

Maintaining or enhancing tree species diversity in forests could be another method for increasing forest carbon storage potential. Increased species biodiversity may be associated with increased adaptive capacity, as diverse forests are less susceptible to the effects of species-specific insect or pathogen outbreaks and replacement species may be more readily available for species less adapted for our climate future[35, 63]. Additionally, resource use complementarity seems to be a keystone component of diverse vegetation, leading to long-term maintenance of healthy soils and


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productive plant communities[19, 21, 91, 92]. Comparison of more- and less-diverse forests in the Lakes States region suggests that a decline in tree species biodiversity may be associated with decreased forest productivity, indicating that biodiversity may be related to a forest's ability to grow and sequester carbon[35]. Elsewhere, there is strong evidence that higher tree diversity in temperate and boreal forests is associated with higher productivity[19, 20, 22, 93]. Forests with a variety of tree species, age classes, and structural diversity are also associated with added benefits such as providing habitat for a wide variety of plant and animal species[63]. Tree species diversity can be increased by planting or encouraging the regeneration of a variety of tree species following disturbance and maintaining forests to allow for a patchwork of age classes and structural diversity, which will favor a more biodiverse suite of species across the landscape.

While increasing biodiversity may provide opportunities for enhancing carbon storage and forest productivity, the reality for some of Minnesota's forests is that they have inherently low diversity due to the physical conditions in which they grow and the species that can persist in those environments. These include black ash, which grow largely in wetland forests; jack or red pine, which are often found on sandy soils; and black spruce, which can be found thriving in Minnesota's peatlands. While the options for increasing the biodiversity in some of these forests may be limited or non-existent, there may be opportunity to increase tree species diversity in some stands that tend to have low diversity. In particular, upland forests – even those with sandy soil – may be able to support tree species diversification if they are planted and/or managed to facilitate the growth of temperate hardwood species in a woodland mosaic[35, 94]. Also, because the effects of higher biodiversity are proportional, increasing tree diversity in a low-diversity Minnesota forest by even one species can have as much positive effect as increasing diversity by more species in a more species-rich temperature upland forests[93].

Evidence for enhanced biodiversity as a carbon strategy: Moderate to Strong

INCREASED ROTATION AGE

Increasing rotation age for forest harvest is a commonly cited management strategy for enhancing carbon storage, with the assumption that as trees continue to grow, more carbon is fixed and stored over time. However, the effectiveness of this strategy depends on the cover type that is being managed and whether conversion to a forest cover type that may increase carbon storage is appropriate and desired[73]. Younger forests tend to have higher carbon sequestration rates per unit time than older forests[73, 95]. However, older forests contain greater total carbon storage than do young forests and carbon stores tend to increase with forest stand age[87, 95]. Understanding how carbon sequestration rates and storage change over time for various species is key in determining whether increased rotation age is likely to provide a carbon benefit. For example, forests that are fast-growing and short-lived, such as aspen, sequester carbon quickly in their early years, and only exhibit modest increases in carbon sequestration after age 30[73]. Other, more slow-growing and longer-lived species, such as oak, may benefit from extended rotation age, as they are able to continue to sequester and store more carbon over longer time scales than fast-growing species[73]. Because climate change is likely to favor many temperate tree species, which tend to be longer-lived and relatively shade tolerant, extended rotation could enhance carbon storage in these forests.

The effectiveness of a strategy of increased rotation ages may be tempered by a consideration of actual tree and stand ages in Minnesota. While individual trees within forest stands may survive well beyond typical rotation ages, few forest cover types in Minnesota demonstrate the ability to survive and thrive past the point of maturity. Only five forest types in Minnesota – eastern white pine, northern white cedar, sugar maple/beech/yellow birch, aspen, and paper birch – have been found (based on analysis of FIA data) in stands older than 200 years[96]. Other old forest stands certainly exist – Minnesota's Lost 40 Scientific and Natural

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Area contains white and red pine forest estimated to be 230-240 years old – but these old growth forests tend to be few in number. Natural dieback and the increasing likelihood and impact over time of experiencing a stand-altering disturbance (e.g., windstorms, pest and pathogens outbreaks, wildfire) make the feasibility of implementing very long rotations challenging on the Minnesota landscape. Still, there may be opportunity in some instances to adopt biological rotation ages as compared to economic rotation ages, which are shorter and more commonly used in active management.

The life cycle of harvested wood products also plays an important role in determining how long carbon is stored. If wood is used primarily for pulp or bioenergy production, as is common for short-rotation wood harvests, there may be less carbon storage benefit due to the short-lived nature of the product; long-lived wood products such as building materials or furniture store carbon longer[73].

Evidence for increased rotation age as a carbon strategy: Moderate

MULTI-AGE MIXWOOD

Forest management which combines components of the aforementioned management strategies may amplify the carbon storage potential of forests

beyond that of a single management strategy. One such strategy is known as multi-age mixwood management. This strategy combines site thinning and stocking of diverse tree species (enhancing both stocking levels and tree-species diversity)[97]. Compared to other common management strategies, including even-aged management and clearcutting combined with planting, multi-age mixwood management may provide greater average carbon storage, more consistent carbon storage potential, and higher live above- and belowground carbon stores[97]. This suggests that utilizing appropriate management that combines increased stocking, increased diversity, extended rotation, and/or thinning may provide the greatest carbon storage benefit in some Minnesota forests. However, more research is needed to verify the effectiveness of this strategy.

Evidence for multi-age mixwood management as a carbon strategy: Moderate (requires more study)

FOREST PRODUCTS AND MARKETS

Our forest products industry and forest-associated markets may provide additional opportunity to increase carbon on the landscape, as well as fund reforestation, afforestation, and other efforts aimed at maximizing our carbon storage. Here, we focus on three main market opportunities for Minnesota's forests: 1) the woody biomass for energy market; 2) growing carbon market opportunities; and 3) the role of wood-based products.

WOODY BIOMASS FOR ENERGY

Bioenergy is a highly versatile renewable energy source, which, unlike most other renewable energy sources, can be stored and utilized as needed[98]. The use of bioenergy accounts for about 10 percent of the global total primary energy supply, and it is the primary form of residential energy production throughout Africa and Asia[98]. Bioenergy is derived from a number of sources including fuel wood, charcoal, agriculture and forestry residues, waste from the paper/pulp industry, and renewable municipal wastes.

Bioenergy is considered a renewable energy source by the International Renewable Energy Agency (IRENA) because it is an energy source that can be managed sustainably. Unlike fossil fuels, the combustion of biofuels for energy emits carbon that is a part of the biogenic carbon

cycle; the long-term benefits of utilizing biofuels as a substitute for fossil fuels may even surpass those of carbon sequestration in forests[99]. Whether or not the use of bioenergy is truly carbon neutral is an on-going topic of debate within the scientific and policy community, and its answer depends on several factors, including transportation and feed source. However, the IPCC considers biomass from sustainably managed forests to be either carbon-neutral or a low-carbon fuel at the point of combustion (after accounting for emissions linked to harvesting and transport)[100].

Studies vary in their estimates of the amount of time necessary to obtain a net reduction in atmospheric carbon dioxide from the use of bioenergy over its fossil fuel counterparts[99, 101, 102]. On the low end, some estimates calculate a carbon payback period (the amount of time it takes for the carbon savings from reduction of fossil fuel use to convert a system from net emissions to net sequestration of carbon) could be immediate for use of residuals or around 15 years for the use of thinned material[102]. Others estimate this point of neutrality to be more likely on the scale of decades or longer[99, 101]. Key assumptions that influence these estimates include the type of tree species used, the accessibility of harvest sites, the size and moisture content of biomass material, the efficiency of energy production, and climatic conditions influencing tree decay in the forest if it was not utilized for bioenergy[101].

One of the largest factors influencing the potential carbon savings of woody biomass for bioenergy is the distance of transportation of the raw material. While the use of biomass as energy can reach "theoretical neutrality" over time, the emissions from the harvest and transport of woody material represent a net addition of carbon to the atmosphere over time[101]. Because of the carbon cost associated with the transportation of materials, any facilities that are constructed to process woody material for bioenergy production should be located as close to the source as possible to minimize emissions and maximize carbon benefit. However, even when considering international transport, the use of wood pellets for bioenergy is likely to result in fewer overall emissions over the use of coal[103, 104]. In addition, there is the potential for biofuel and bioenergy to work together should technologies be developed that allows harvest machinery and transport trucks to run on renewable diesel, thus further reducing reliance on fossil fuels and limiting the emission of non-biogenic carbon to the atmosphere.

While the combustion of biofuels is preferable over any fossil fuel from the perspective of the biogenic carbon cycle, the fuel source replaced will play a major role in how quickly and the extent to which the use of biofuels results in a carbon savings over traditional fuel sources. Replacing carbon-intensive energy sources, like coal, will provide a greater

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opportunity to reduce emissions than replacing less-carbon intensive sources, like natural gas[99, 101, 105]. Without considering emissions associated with harvest and transport, the use of woody biomass for energy production could result in a net decrease in carbon emissions over the use of coal in approximately 10 years, natural gas combustion systems in approximately 30 years, and natural gas combined cycle systems in approximately 48 years[101].

When is using woody biomass for bioenergy feasible?

Perhaps the greatest opportunity for the use of woody biomass for bioenergy lies in the use of harvest and sawmill residuals, such as treetops, branches, sawdust and shavings, as feedstock for bioenergy generation. The use of residuals is considered a potentially cost-effective and eco-friendly alternative to the use of bole wood for energy production[100, 101, 106]. Based on current harvest levels and forest practices in Minnesota, a considerable amount of residual wood is left in the forest; the use of these residuals for bioenergy production may be sufficient to meet all or a significant portion of the demand from bioenergy facilities[101]. However, removal of harvest residuals may have unintended consequences such as decreased species diversity and reduced nutrient availability in forest soils following harvest, versus standard stem-only removal[106]. Because of these potential impacts, the Minnesota Forest Resources Council (MFRC) has established guidelines for the sustainable use of woody biomass for bioenergy in Minnesota, including minimum levels of residual retention to minimize negative ecological impacts.

While using forest residuals generally provides a greater opportunity for the use of woody material for bioenergy, some species of tree provide a greater carbon benefit when used for bioenergy than do others. Quick-growing and -decaying species, such as those common in aspen-birch forests, provide a faster route to reaching theoretical carbon neutrality than do slow-decaying species, such as oak and hickory[101]. This is because slow-decaying species may provide a longer-lasting carbon benefit if left in the forest than if the material is used for energy production (i.e., they contribute to carbon storage for longer time periods). Focusing on the use of quick-growing and quick-decaying species, such as aspen and hybrid poplar, is likely to provide the greatest carbon benefit and opportunity for the use of woody material in bioenergy production. In addition, tree species that are in need of management but have little demand in conventional markets (e.g., tamarack and ash, which may require increased management for pest control) may provide another opportunity as a bioenergy feedstock.

In order to make the collection and transportation of forest residuals economical for the production of bioenergy, policies and incentives may be needed to achieve desired outcomes. Up to 50 percent of the cost of electricity can be attributed to the cost of feedstock for energy production[98]. In using forest residuals for bioenergy, the cost of harvest and transportation compose the bulk of the associated costs of this energy source[98]. This fact, combined with the relatively low energy density of biomass, requires bioenergy facilities to be located relatively near harvest sites in order for the transport of woody material to be economical[98]. Because natural gas prices have remained low over the past several years, the cost associated with the production of energy using woody biomass has been seen as potentially prohibitive. Legislation which can help to offset associated costs of bioenergy production and development, such as Minnesota's AGRI Bioincentive Program, may help to encourage bioenergy production if sufficiently funded and supported[107].

CARBON MARKETS

Carbon markets have the potential to provide additional economic benefit to landowners while providing increased carbon storage over time. Markets for forest carbon offset credits date to the 2000's, and to date, hundreds of forest carbon projects have been developed across the United States, providing millions of dollars in revenue for landowners,

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including tribes, family forestland owners, timber companies, conservation forestland owners, and institutional investors. However, with a few exceptions, Minnesota landowners have largely not benefited from this non-traditional revenue stream. This portion of the paper will focus on the opportunities and barriers for entering carbon markets specific to the particular forest types, growing conditions, and management activities common in Minnesota.

Minnesota forest landowners have two broad options for selling carbon credits: compliance and voluntary markets. These markets are distinguished by whether offset purchases are required by state regulation or occur voluntarily, e.g., for corporate social responsibility.

Compliance Market

The California carbon compliance market, which was launched in 2014 as part of California's cap-and-trade program, is unique as the only regulatory forest carbon market currently operating in the United States. Many view the regulatory market as having more rigorous accounting methods and permanence requirements because its methodology was specifically designed to create compliance-grade offsets[108]. This can benefit landowner participation through higher price-points and greater market stability[108]. In the California market, higher demand and prices have thus far translated into greater landowner participation than the voluntary market within the United States[109]. On the other hand, from a landowner perspective, greater accounting rigor and longer contracts can increase the cost and technical complexity of project development, reducing landowners' willingness to enter the market[110]. Greater accounting rigor and more stringent program rules also increase participants' reliance on third-party experts to facilitate access to the market, at a cost to landowners[111].

Because of the greater cost and complexity of the California market, participation has mostly been limited to landowners with large land holdings, such as industrial and foundation forestland owners[111]. Participation in California's market is also shaped by the rules articulated in the Compliance Offset Protocol for U.S. Forest Projects (Compliance Protocol)[112]. This includes a 100-year contract, forest management requirements that emulate the California Forest Practice Rules, and long-term reporting and verification requirements. One noteworthy limitation of the Compliance Protocol is that, although it can be used to enroll forestlands across the US, its rules for participation were designed by and for California forestry interests. Therefore, they may translate poorly to forests outside California. The Compliance Protocol was also designed to favor private forestlands and tribes. While non-federal public land is eligible to enroll in the compliance market, it faces a less-lucrative baseline scenario compared to private lands, and project development is generally not economically viable.

Voluntary Market

The voluntary market is an umbrella term that refers to carbon offsets purchased voluntarily, e.g., to reduce carbon footprints at the individual or organizational level, to demonstrate corporate social responsibility, and/or as a strategy employed by industry to prepare for future carbon regulation. The purchase of voluntary carbon offsets has occurred since the 1990s, most commonly in greenhouse gas (GHG) intensive industries, such as the transportation (e.g., air travel, car rental) and energy utility sectors.

From a landowner perspective, participation in the voluntary market generally yields lower prices and less certain demand than the compliance market. This has generally discouraged landowner participation because it reduces the financial viability of projects, particularly when they are small in scale. One important exception to this is for so-called "charismatic carbon projects" — those owned by tribes, family forest owners, or preservation land trusts who offer exceptional social and/or ecological co-benefits — which have in some cases garnered prices on par with or even exceeding those of the compliance market. Yet on average, low prices mean that

landowners are less willing to invest in the upfront costs of registering voluntary projects, especially when the future demand for offsets is unknown.

Despite the uncertainties in the voluntary market, it does offer certain benefits to landowners, including project development that is often faster and less costly than in a regulatory or compliance context. In addition, a major distinction to the voluntary market is that landowners have multiple established methodologies to choose from, including those produced by the American Carbon Registry (ACR), the Verified Carbon Standard (VCS), and the Climate Action Reserve (CAR). Methodological options mean that landowners can potentially choose a program that better fits their unique ecological resource, administrative framework, and management context. Access to methodological options also means that, unlike the California compliance market, it is possible within a voluntary context to aggregate (or pool together) multiple ownerships, reducing cost and increasing the feasibility for small landowners to enter the market.

Though demand in the voluntary market has historically been low and volatile compared to the compliance market, recent reports suggest that buyer interest in the purchase of voluntary forest carbon offsets may grow, due largely to industry efforts to prepare for possible future GHG regulation at the regional, national, or international level[113]. One example of voluntary offset demand in a currently unregulated industry is the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), an effort by the International Air Transport Association (IATA) to voluntarily track and offset airline GHG emissions using voluntary credits.

CHARISMATIC CARBON: AN EXAMPLE FROM THE YUROK TRIBE OF NORTHERN CALIFORNIA

The Yurok Tribe of Northern California has generated over 1.8 million carbon credits, resulting in an estimated $23 million in carbon revenue for the tribe. With this revenue, the tribe has been able to successfully leverage the carbon market to purchase over 22,000 acres of former industrial timberland, allowing them to re-acquire ancestral territory.

Carbon credits produced through the Yurok project are considered charismatic because, in addition to carbon sequestration, they provide important cultural/spiritual benefits to tribal people. The Yurok carbon project also promotes ecological co-benefits, including the production of larger, older trees, and watershed improvement, with restoration of historically important but degraded fish populations, including Chinook and Coho salmon, steelhead and cutthroat trout, and sturgeon.

TABLE 1 – LAKE STATES CARBON PROJECTS LISTED ON CARBON REGISTRIES AS OF DECEMBER, 2019.

Landowner	MICHIGAN	MINNESOTA	WISCONSIN	Total Acres
Huron Mountain Club	18,800			18,800
The Conservation Fund			12,252	12,252
The Nature Conservancy	31,935			31,935
UPM Blandin		187,000		187,000
Blue Source			47,600	47,600
Forest Investment Analyst			29,000	29,000
Great Lakes Forests 1 LLC	247,427			247,427
Lyme Timber			65,000	65,000
Molpus Woodlands Group	139,370	1,070 (Project is listed but is not yet registered. It is currently undergoing inventory and verification processes.)		140,440
The Forestland Group			13,000	13,000
Wolf River ATP, LP			17,700	17,700
Total Acres	437,532	188,070	184,552	810,154

Current & In-Progress Projects in Minnesota & the Lake States

Compared to some regions within the US — e.g., the Pacific Northwest, the Northeast, and the Southeast — the Lake States have thus far had fewer projects entered into forest carbon markets. Extant project development in the Lake States currently consists of just over 800,000 acres, mostly in Wisconsin and in the Michigan Upper Peninsula. In this region, institutional landowners and large conservation landowners have been early actors in developing forest carbon projects. These projects are mostly large in scale, with an average project size of 62,000 acres. Most have conservation easements, are managing for timber, and are third-party certified for sustainable harvest.

In Minnesota, there are currently no projects enrolled in California's compliance market, and only one registered forest carbon project in the voluntary market. This project was developed by the UPM Blandin branch of the Finnish Company UPM Kymmene, and it consists of 187,000 acres of UPM Blandin Forestry land. As the only registered forest carbon project in Minnesota, the UPM Blandin Forestry project is helping to demonstrate forest carbon market participation to other landowners in the state.

There is currently a high degree of interest among Minnesota forest managers, including tribes, the state Department of Natural Resources (DNR), conservation organizations (including The Nature Conservancy), and counties in exploring carbon market opportunities. Some of these entities are now in various stages of testing market feasibility, including the Leech Lake Band of Ojibwe and Fond du Lac Tribe, who are utilizing the assistance of a non-profit organization, the National Indian Carbon Coalition, in the development of their carbon market strategies. Molpus Woodlands Group (MWG), a timberland investment management organization (TIMO) that manages timberland throughout the South, Northeast, and in the Lake States, has listed a forest carbon project in northern Minnesota and is currently undergoing inventory and verification. Once registered, MWG will be Minnesota's first forest carbon project enrolled in the California market.

UPM BLANDIN CARBON OFFSET PROJECT

In 2015, the UPM Blandin Paper Company — located in Grand Rapids, Minnesota — listed an Improved Forest Management project with the American Carbon Registry, entering 187,000 acres of timberland into the voluntary carbon market. In so doing, Blandin committed to increasing the carbon sequestration and storage of their timberland, through practices such as:

- promoting long-lived conifers;
- increasing diversity in patch sizes through small and large harvests;
- promoting cohort, size class, and species diversity on the forest;
- extending rotations where possible; and
- utilizing early treatments to accelerate development of diverse forest conditions.

Registration with the American Carbon Registry requires a forty-year minimum contract. To date, Blandin's project has generated over 2 million forest carbon credits, which have been sold to a variety of buyers looking to voluntarily offset their carbon emissions. As a working forest, Blandin's carbon project produces multiple benefits, including traditional wood products, watershed improvement, biodiversity, habitat, and recreation. Blandin's property is also SFI certified since 1999 and under a permanent conservation easement, signifying maintenance as working forestland with public access in perpetuity.

Opportunities and Constraints relative to Minnesota

Minnesota landowners have particular opportunities and constraints in accessing forest carbon markets based on the unique ecological, social, and economic conditions of the state and its forest resource.

Opportunities

One opportunity for Minnesota forests with regard to carbon market participation is the high proportion of forestland that is third-party certified for sustainable forestry, through either the Forest Stewardship Council (FSC), the Sustainable Forest Initiative (SFI), or both. Certification is a requirement under certain forest carbon programs. Even when not required, certification is generally viewed as an asset for carbon project development because it helps to satisfy program requirements for sustainable harvest. Certification can also indicate that carbon market participation is compatible with landowners' overarching goals and objectives. Finally, familiarity with the administrative components of third-party certification can prepare land managers for the requirements of registering a forest carbon project, speeding initial enrollment, and facilitating ongoing reporting and auditing requirements.

While forest carbon markets are not right for all landowners, in some cases they can provide an important revenue stream, which can work in tandem with timber harvest or be targeted at non-merchantable species and/or inaccessible sites. This can help landowners achieve a range of objectives, including forestland restoration and conservation. A higher price-point for carbon offsets would increase project feasibility for Minnesota landowners by reducing the need for economies of scale, by helping to offset the upfront and ongoing expenses of monitoring and reporting, and by giving landowners additional motivation to enter long-term contracts. In addition, the creation of a Minnesota-specific market for forest carbon offsets could facilitate project development. A Minnesota-specific market could take the form of a regulatory cap-and-trade program, similar to California's compliance program, or through the development of a voluntary market that incentivizes in-state businesses to purchase carbon offset-credits locally. Besides increasing the demand for forest offsets produced in Minnesota, this could also spur the creation of forest carbon methodologies that would specifically accommodate the particular forest resource, growing conditions, and ownership patterns of the state.

There are still a number of questions regarding what strong carbon market participation in Minnesota would require, how this participation would affect our landscape, and whether it is feasible, given the large proportion of small, privately-held forestlands in the state. There is opportunity for collaboration and research amongst interested parties to help answer some of these questions and position Minnesota to be able to take advantage of the carbon market opportunities.

Constraints

Minnesota landowners face numerous constraints when entering forest carbon markets, including the high up-front costs of project development, as well as the timeline needed for return on investment. An additional constraint is that, in general, forest carbon markets reward landowners for maintaining and/or increasing carbon stocks. This is most true for programs that reward "Improved Forest Management"— the most popular and lucrative forest carbon project-type to date. This means that forest carbon programs are most profitable for forests that are fast growing, and/or which have relatively large and/or long-lived trees. Forests in Minnesota tend to be slow growing (influenced by our climate and short growing seasons), have relatively shorter biological rotation ages (compared with many forests in the western states), and produce overall smaller trees. Because of this, Minnesota landowners have less potential to increase the carbon benefit of their forest by extending rotation age — a common strategy in regions with long-lived or fast-growing trees — because for many forest types in Minnesota, any increase in carbon storage would be offset by increased natural mortality as forests age. This is particularly true for aspen and/or spruce/fir forests in Minnesota.

In general, this makes it harder for Minnesota landowners to profitably develop Improved Forest Management projects under the California compliance market; however, voluntary forest carbon protocols with shorter contract lengths and greater baseline flexibility may still present viable opportunities. Particularly, enrollment of mixed hardwood and/or mixed pine-oak forests, which contain more long-lived species, may provide the needed carbon benefit to landowners via extended rotations.

Silvicultural practices in Minnesota can also constrain feasibility and profitability for carbon markets. For instance, the common use of even-aged management in Minnesota can reduce overall growth on a year-to-year basis (and limit the production of carbon credits), compared to uneven-aged management, which lends itself more readily to net incremental growth and can be a good fit for carbon management. This means that projects undergoing even-aged management will generally need to be large in scale to avoid yearly reductions in carbon stocks. Alternatively, such projects could demonstrate maintenance and growth of carbon stocks by transitioning to uneven-aged management.

The particular pattern of ownership regimes in Minnesota can also affect the feasibility of carbon-offset projects. For example, public lands face greater constraints to participation in carbon markets, because non-federal public land is subject to a less lucrative baseline scenario than private lands[114]. Relatedly, most large mills in Minnesota no longer have land bases and therefore cannot benefit from forest carbon revenue, in contrast to timber companies elsewhere that have retained their land holdings and are entering the carbon market.

Hannah C. Friesen

WOOD PRODUCTS

The life cycle of wood products following harvest will affect the carbon balance of any forest carbon storage initiative[73, 115]. The use of wood for pulp and paper products, which have a relatively short lifespan of 5-6 years (on average), may release carbon to the atmosphere more rapidly than if the wood decayed naturally in the forest. Conversely, the use of wood in long-lived products, such as building materials, may extend the carbon storage capacity beyond the natural growth and decay cycle[61, 73]. In 2015, estimates indicated that more than 2.6 billion metric tons of carbon were stored in wood products; about 60 percent of this was accounted for in products currently in use, while the remainder was in landfills[61]. The carbon storage from harvested wood products, both in use and in landfills, is about one-fifth of the total carbon storage in forestland in the United States[64]. This indicates that wood products have the potential to be a powerful storage mechanism for carbon, particularly if more effort is placed on the production of long-lived wood products, as well as those that can replace carbon-intensive materials such as steel and concrete[61]. However, even shorter-lived pulp and paper products can provide environmental benefits through the replacement of plastic products.

Because long-lived wood products can provide opportunities for carbon storage beyond the ecological lifecycle of trees, encouraging the production of these products via policy is a tool by which Minnesota can increase its carbon storage. The production of long-lasting, wood-based products for the construction industry may represent a particularly advantageous market opportunity. Engineered timber products, such as oriented strand board (OSB), laminated veneer lumber (LVL), and cross laminated timber (CLT) may provide the construction industry with material that provides high dimensional stability, tolerance, and performance standards while also storing forest carbon in products long term. Thermally modified timber may also provide an opportunity to transform Minnesota's sawtimber into architectural material with specified dimensional stability and rot-resistance, making them a potential supply for window and door industries in Minnesota. These technologies could provide dual incentives to new and existing forest products businesses.

The production and use of mass timber in buildings, which most often utilizes CLT technology, presents an opportunity for the use of softwood and smaller diameter trees while storing carbon and decreasing carbon emissions from traditional building materials, such as steel and concrete[116, 117, 118]. Using wood substitutes for steel and concrete may provide a reduction in global carbon dioxide emissions, as well as a reduction in global fossil fuel consumption[116]. CLT mass timber buildings can decrease global warming potential an average of approximately

26 percent when compared to a comparable concrete structure, and store on average an additional 1,500 to 2,500 metric tons of carbon dioxide equivalent[117].

In addition to lumber, paper, and pulp products, forest products take many forms, including a wide variety of specialty chemicals, adhesives, biofuels, cleansers, composite materials, foods, packaging, pharmaceuticals, preservatives, pesticides, biodegradable plastics, nano-based products, and more. Some of these products are well developed, yet may have potential applications in new areas. A number of others are currently the subject of basic and developmental research within the University of Minnesota and firms in Minnesota and beyond. While the focus here is on carbon storage, encouraging the development of diverse forest and wood products can add to the strength of Minnesota's forest industry and the sustainability of our forest resource management capability.

It is important to note that for wood products to have a positive carbon impact, they must be combined with sustainable forestry practices. Minnesota contains nearly 8 million acres of SFI and/or FSC certified forestland; the DNR alone manages nearly 5 million acres of dual FSC/SFI certified land. The MFRC's development of comprehensive forest management guidelines (FMGs) is a key component of the Sustainable Forest Resources Act (SFRA), the legislation that established the Council and guides the work performed by the MFRC. The use of these FMGs by loggers, forest managers, and forest landowners during harvest can help to reduce negative environmental impacts resulting from harvest activities and other forest management work, and their use is important to the sustainability of forest management in Minnesota.

Hannah C. Friesen

SUMMARY & CONCLUSION

Minnesota's forests have the ability to hold vast amounts of carbon from the atmosphere, providing a potentially important tool for the mitigation of climate change outcomes in the state. While numerous strategies to conserve or increase forest carbon exist, these strategies can largely be placed into four distinct categories:

- **Forest Retention:** Maintaining Minnesota's forests as forestland is crucial to protecting our existing carbon reserves. The loss of forestland through parcelization, development, and conversion to agriculture represents a net loss in our carbon storage capacity. Policies and programs that incentivize maintenance of existing forests should be promoted at the state and local levels.
- **Afforestation & Reforestation:** Creating forests where they did not recently exist (afforestation) and regenerating forests where they recently existed (reforestation) can provide powerful tools for increasing carbon on the landscape. Forestation efforts, however, should be consciously undertaken with the understanding that there are factors that limit the effectiveness of this strategy at mitigating climate change. These include constraints on net climate warming offset associated with forestation in Minnesota and the development of effective incentives for landowner participation. In addition, resource constraints, such as the availability of seedlings, make forestation policies difficult to implement at scale.
- **Forest Management Practices to Increase Carbon Storage/Sequestration:** Forest management practices may provide additional tools for increasing carbon on our landscape. The main practices reviewed here include: increased stocking levels, thinning, increased biodiversity, and increased rotation age. While these practices are shown in the literature to have varying levels of effectiveness, there is strong evidence for increasing stocking levels in Minnesota's forests as a carbon sequestration strategy and moderate evidence for extended rotation and biodiversity strategies. However, these practices may be constrained by biophysical factors and other resources (e.g., seedling availability).
- **Forest Products & Markets:** The forest products industry and other markets related to forestry have the potential to increase carbon storage on the landscape and help make possible the forest management necessary for enhancing forest carbon on the Minnesota landscape. The main markets assessed here included: woody biomass for bioenergy, carbon markets, and wood products. We discussed the potential opportunities and challenges with each of these markets, including policy options for encouraging participation in the various markets.
    - **Biomass for Bioenergy:** The use of residuals for bioenergy production represents a good potential opportunity for biomass as an energy market in Minnesota.
    - **Carbon Markets:** Due to constraints in Minnesota and current carbon accounting methodologies, carbon markets might not be developed on a large scale in the state. However, opportunities do exist for interested parties and several projects are currently in development.
    - **Wood Products:** Policies and market-strategies focusing on the development of long-lived wood products may incentivize the additional carbon storage potential of these products.

KEY RESEARCH NEEDS

The following research needs and questions were developed by the Research Advisory Committee based on their relevance to the topics reviewed in this section and importance to developing effective forest management strategies.

THE CARBON CYCLE

- Develop an assessment of the costs (per additional ton of carbon sequestered) for different forest management practices and strategies.
- What projection methods and models provide the most effective methods and tools for quickly responding to questions on forest carbon?
- How might various policy proposals related to afforestation, reforestation, management, etc. positively or negatively impact carbon storage and sequestration?

FOREST RETENTION

- How might policies related to taxation and land-use planning help to reduce parcelization of forestlands?
- How might we account for forest carbon in order to minimize the negative effects and maximize the positive effects of management (e.g., harvesting) on carbon storage/sequestration?

AFFORESTATION & REFORESTATION

- Where in Minnesota should afforestation, reforestation, and other tree-planting efforts be targeted in order to maximize carbon benefits and co-benefits?
- Compare cost estimates for afforestation programs with the costs of emissions reduction programs in other economic sectors, including agriculture, energy, transportation, and construction.
- How can the accounting and valuation of the co-benefits of forestation strategies be improved?
- Improve the understanding and modeling of landowner perceptions of incentives provided by an afforestation program.

FOREST MANAGEMENT PRACTICES TO INCREASE CARBON STORAGE/ SEQUESTRATION

- Improve estimates of the carbon storage effects of various forest management practices that are specific to forestry in Minnesota/Great Lake States.
- Conduct cost/benefit analysis for enhancing carbon storage/sequestration via various management strategies.
- Incorporate consideration of catastrophic wildfire risk into carbon-focused management practices.

FOREST PRODUCTS & MARKETS

- What is the maximum amount of bioenergy that could be produced from harvest residuals based on current harvest levels and residual retention guidelines?
- Are carbon markets a feasible opportunity for Minnesota landowners and public land managers?
- How might barriers to entry in the carbon and other markets be addressed for Minnesota forests?
- How does the production of engineered lumber products affect the life cycle of carbon storage in short-lived species? Is the demand for engineered lumber sufficient to justify the market development?

SECTION 3
CLIMATE CHANGE ADAPTATION STRATEGIES BY COVER TYPE

For forest managers, a major area of concern is how various forest types and tree species will respond to future conditions associated with a changing climate. Silviculture, which is the art and science of growing and cultivating trees, provides numerous treatments and management strategies that may be used by forest managers to help adapt to likely climate change outcomes. Determining the desired future condition for a forest stand is an essential step to implementing the appropriate silvicultural adaptation strategies for meeting management objectives[119]. Adaptation strategies for climate change generally fall into three main categories:

1) *resistance strategies*,
2) *resilience strategies*, *and*
3) *transition strategies.*

RESISTANCE –RESILIENCE – TRANSITION

RESISTANCE

Resistance strategies are those that are focused on maintaining a relatively unchanged ecosystem. This requires enhancing forest defenses against potential disturbances or anticipated changes, often through thinning[119]. This approach will likely become more costly as future climate changes intensify and may be best utilized as either a short-term option or to specifically maintain highly-valued economic, ecological, or cultural forest resources[119]. The maintenance of black spruce peatlands, which are highly ecologically valuable due to their carbon-holding capacity, is one example where a resistance approach to management may be implemented. While maintaining these ecosystems is important, the costs of regenerating sites and avoiding loss due to pests or pathogens will likely increase over time.

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RESILIENCE

Resilience strategies are those that allow for some change to current conditions with the ultimate goal of increasing the ability of the ecosystem to adapt to the effects of climate change while maintaining its essential functions[120]. These strategies focus on how best to manage an ecosystem in order to maximize its ability to cope with and rebound from possible future disturbance events, while understanding the variability of climate at local and regional scales and the diversity of landforms and soil properties[119, 121, 122]. Although resilience strategies may increase the range of climatic shifts that an ecosystem can tolerate, they may also require increasing investments in effort and resources to maintain ecosystem resilience over time[119]. Resilience strategies can often include harvesting sites or practicing prescribed burns to emulate a natural disturbance at a particular site. It can also include thinning of stands to remove fire ladders and increase the ability of forestlands to recover from natural disturbances. Resilience practices can help to increase the resilience of systems by creating a patchwork of age classes and by facilitating the growth of biodiverse native species, especially by focusing on site-based resilience. For example, dependably cool and moist sites (e.g., north-facing slopes and low-laying areas) may provide resilient sanctuaries for boreal species as the climate warms, allowing the maintenance of these species on the landscape[122].

TRANSITION

Transition strategies are considered among the most proactive management options because they involve making intentional, directed changes to an ecosystem to guide it toward a desired, but different, future-oriented state[119]. These strategies aim to enable ecosystems to better respond to changing conditions while also preserving essential ecosystem functions and meeting management objectives. Because a transition strategy requires intentional change toward a different state, it may demand significant up-front investments of resources and effort; however, the necessary effort to maintain the adapted ecosystem may decrease over time as ecosystem adaptive capacity increases[119]. An example of a transition strategy may be the proactive planting of tree species that are better adapted to a warmer future climate than existing species. This may be most effective in regions where the native species provide essential ecosystem services that may be preserved should an appropriate replacement species be identified. For example, black ash plays a crucial role in moderating water levels and providing nutrients in northern Minnesota wetlands. Replacing black ash with a single or multiple replacement tree species that can fulfill these services – prior to the loss of ash from emerald ash borer (EAB) – may be essential.

MINNESOTA FOREST TYPES

Here, we review several important and iconic Minnesota forest cover types and assess whether a resistance, resilience or transition adaptive silvicultural strategy may be most effective in managing these forest types under a changing climate. These cover types were selected based on their relative abundance, importance to the forest products industry, and cultural or recreational significance. The cover types selected include: aspen, pine (including red, white, and jack pine), oak, northern hardwoods (e.g., maple, basswood), and lowland conifers (including black spruce, tamarack and northern white cedar).

ASPEN

Aspen forests compose the largest single category of forest cover in Minnesota, covering approximately 30 percent of the total timberland in the state at 4,620,822 acres[7]. These forests are also our most intensively managed, with over 1.5 million cords harvested on an annual basis[7]. Aspen, which tends to be fast-growing and short-lived, is an important component in engineered wood manufacturing as well as the pulp and paper industry, and many of the mills in Minnesota have been specifically designed to utilize our aspen resource[7]. Aspen forests by far are the most economically important to the state's forest industry, composing over 50 percent of volume harvested.

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TABLE 2 – SUMMARY RATING OF CLIMATE ADAPTABILITY AND PROPOSED SILVICULTURAL STRATEGY BY FOREST COVER TYPE.

Cover Type	Likely Climate Adaptability	Recommended Silvicultural Strategy
Aspen	Low	Resistance, Resilience, or Transition
Pine (Red, White, and Jack)	Medium	Resistance, Resilience, or Transition
Oak	High	Resilience
Northern Hardwoods	High	Resistance or Resilience
Lowland Conifers (Spruce and Tamarack)	Low	Resistance or Resilience

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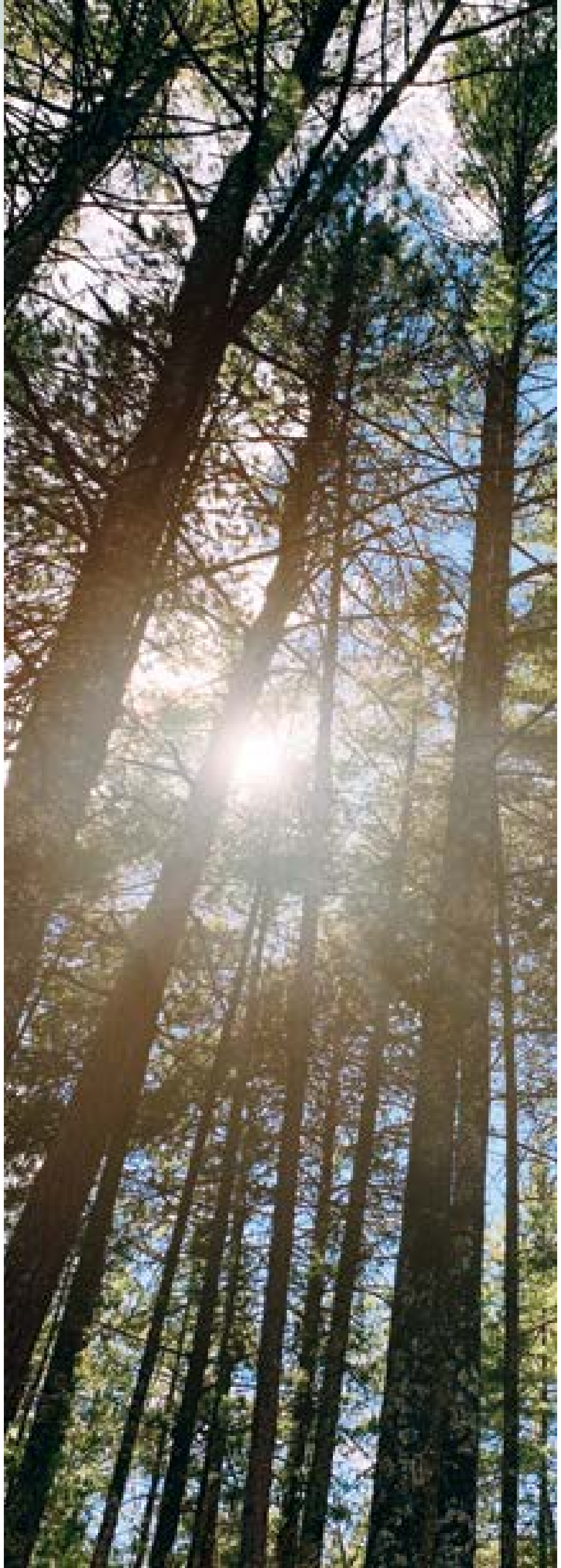
Key Challenges:
Aspen that is currently available for harvest is of lower quality and quantity than in past years; however, in the coming years, high-volume aspen will again reach harvest age[7]. This may lead to an over-abundance of available aspen, as markets slow due to the declining demand for pulpwood[7]. Aspen stands may also be susceptible to gypsy moth infestations and other native and invasive pests and pathogens because of their low diversity of tree species.

As a boreal species, quaking aspen (which compose over 60 percent of Minnesota's aspen resource) are near the southern edge of their native range in Minnesota[7]. This may make them particularly susceptible to the effects of climate change, especially the warmer temperatures that are expected throughout the region and the possible increase in drought conditions[16, 36, 123]. In some models, expected decreases in suitable aspen habitat resulting from climate change could be as high as 50 to 75 percent over the next century under various emissions scenarios[36]. In nearby Wisconsin, quaking aspen is expected to have a decrease in cover by around 25 percent, likely due to an initial lower quantity of aspen on the landscape[39].

Adaptation Strategies:
Native aspen forests, which are largely fire dependent, can be managed through resilience strategies such as prescribed burning or short-rotation harvest, similar to other fire-dependent forest types, such as pine[16]. Transition strategies that encourage the growth of other economically valuable species in place of or in tandem with aspen could be considered, particularly along the southern-most portions of the aspen range in Minnesota and in areas where aspen is less likely to be competitive in the future. Lastly, in regions which could be considered climate refuges (e.g., north-facing slopes), resistance strategies may be effective at maintaining aspen on the landscape.

PINE

Minnesota's pine forests are one of our most iconic landscapes – even our state tree is a pine (red, or Norway, pine, *Pinus resinosa*). These forests, which were once much more abundant in the state[124], are largely composed of red and jack pine with a smaller component of white pine, and currently cover over 1,057,500 acres, or around 6 percent, of Minnesota timberland[7]. Pine forests exist in both natural and managed states, with red pine plantations composing a large portion of the harvestable red pine in the state[7]. These plantations, while providing material for forest industry, tend to lack many of the other ecological components and biodiversity of natural pine stands. The annual harvest of red, white, and jack pine resources in the state is nearly 450,000 cords, or about 15 percent of volume harvested[7]. While some of this harvest is utilized in pulpwood operations, the vast majority of this resource is harvested for sawlog timber[7]. Because Minnesota's pine



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resources are largely used for long-lived forest products, such as dimensional lumber, the maintenance of these forests provides Minnesota with an important opportunity to maintain additional carbon on the landscape compared to those used primarily for pulp.

Key Challenges:
Jack pine harvest has decreased over the past several years, largely due to disease outbreaks such as jack pine budworm[7]. Mountain pine beetle also threatens to migrate eastward toward Minnesota as the climate warms; the arrival of this pest could have devastating consequences for Minnesota's pine forests. The effect of native and invasive bark beetles, as well as other pathogens, such as the fungi, Heterobasidion, on pine vitality may also be enhanced by drought or water stress, further reducing pine resources[7]. Regeneration of pine forests, particularly white pine, is hampered by herbivory from white-tailed deer, often requiring large investments in anti-herbivory measures.

Adaptation Strategies:
In natural pine forests, the mixture of native species aids in adaptive capacity for this forest type[16]. The adaptive capacity of these – and other forests historically managed by fire – may be encouraged through resilience strategies such as prescribed burns[16]. Resistance strategies that focus on maintaining the growth of pine forests in regions with dry, sandy soils may also be appropriate, as other species may be less likely to grow in these areas[16].

Managed pine plantations may be fairly resilient to climate change because they are generally drought-tolerant[16]. However, the low genetic and structural diversity of trees in managed plantations may make them more susceptible to pests and pathogens[16]. Resilience strategies such as thinning may increase adaptive capacity by limiting risk of drought-induced stress, dieback, and mortality, and if used to increase structural diversity, may further enhance resilience of pine forests[87, 90]. In addition, transition strategies that focus on the growth of more southern-adapted species, such as white pine, over less climate-hardy species such as jack pine, may be appropriate and maintain economic timber value on the landscape[35, 125]. A decline in white pine blister rust with a changing climate may also increase prospects for white pine growth and expansion in the state[7].

OAK

Minnesota's oak resource, which covers approximately 1,459,900 acres, or around 9 percent of timberland, is ecologically and economically important[7]. Over 146,000 cords of oak are harvested on an annual basis, largely for use as sawlogs or fuelwood[7]. In addition, many Minnesota wildlife species rely upon acorns as a food source and oak trees as den sites[7]. Oak forest can be found throughout the forested regions of the state but are most heavily concentrated in the central region of the state, across Pine, Kanabec, Aitkin, Mille Lacs, Crow Wing, Cass, Morrison,

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Wadena, Hubbard, Clearwater, and Becker counties[7]. The most abundant oak species in the state are red oak and bur oak, with smaller populations of northern pin oak, white oak, black oak, and swamp white oak[7].

Key Challenges:
Oak forests are threatened by gypsy moth infestations and oak wilt, both of which are already present in the state[7]. Sudden oak death represents a future threat to this resource[16, 126]. Additionally, oak regeneration is generally poor in areas where invasive woody shrubs (e.g., buckthorn) have become established[127].

Adaptation Strategies:
Oak forests may exhibit a high adaptive capacity to the effects of climate change in Minnesota. Bur oaks, which are both drought and fire-tolerant, may be one of the most climate-hardy tree species in the state[16, 38]. White oak and northern pin oak will likely experience increased growth in Minnesota under a warming climate[16, 128]. Resilience strategies, which encourage the maintenance of bur and white oak on the landscape but allow for some disturbance, may be most appropriate in managing for oak forests of the future. These strategies allow for prescribed burning, thinning, and other management of oak forests to encourage their adaptive capacity by reducing competition.

NORTHERN HARDWOODS

The northern hardwood cover type, which covers 1,445,015 acres, or 9 percent of forestland, in Minnesota, contains a diverse mixture of tree species. Over 50 percent of the volume in these forests tends to be composed of red and sugar maple and American basswood[7]. Northern red and bur oaks, along with quaking aspen, also make up a substantial portion of this cover type[7]. The ownership of our northern hardwood forests is largely in private hands[7]. This resource has been historically underutilized due to quality issues for forest products, unreliable markets, and the need for different logging equipment and intensity in order to conduct uneven-aged management and multiple entries into privately held lands[7]. However, the forest resources in the northern hardwood forests can be quite valuable. Some of the highest-quality basswood resources in the world can be found in Minnesota; this wood can be used for sawlog and veneer material, as well as craft wood[7]. The total maple and basswood harvest in Minnesota in 2017 was 217,500 cords[7].

Key Challenges:
Because northern hardwood forests have been historically underutilized, there may be an abundance of low-quality, over-mature stands. This is largely due to a lack of market demand and constraints in harvesting on private lands. There is also concern about the presence of gypsy moth in parts of northeastern Minnesota. This pest may threaten this forest type


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and further constrain its usability due to transport quarantines[7].

Adaptation Strategies:
While our northern hardwood forests certainly face challenges, there is the possibility for this forest type to expand into formerly boreal zones as the climate warms and more suitable habitat becomes available[16, 39, 57]. In particular, models of growth and tree species migration indicate that sugar maple is likely to experience an increase in growth and suitable habitat under warming climatic conditions and empirical data shown juveniles of this species to do well with warming[16, 33, 38, 57, 129]. This may be enhanced by the detrimental effects of climate change on balsam fir, which is a common understory species in northern hardwood forests and which is likely to experience decreases in growth and recruitment as the climate warms[16, 39, 57]. However, in the absence of disturbance – either natural or through harvest – to disturb ground needle cover and provide canopy openings, the ability of temperate species like sugar maple to rapidly expand their range into boreal zones will be constrained by conditions that are unfavorable to their establishment[42, 56].

Northern hardwood forests are likely to exhibit fairly high adaptive capacity due to their diversity in species composition and are likely to expand their range as temperatures warm. Because of this, resistance strategies that maintain growth and encourage the ability of northern hardwoods to migrate into desired regions may be appropriate. These strategies may involve intensive tending of regenerating forests to control quality and composition, as well as controlling herbivory and the spread of pests, such as gypsy moth and Asian longhorn beetle[16]. Management to increase diversity may be warranted on second-growth northern hardwood stands that have developed relatively low species diversity[130]. Resilience strategies, which allow for disturbance but ultimately result in the regrowth of this forest type, may also be appropriate given the likelihood that this forest can adapt and regenerate following harvest or other disturbance.

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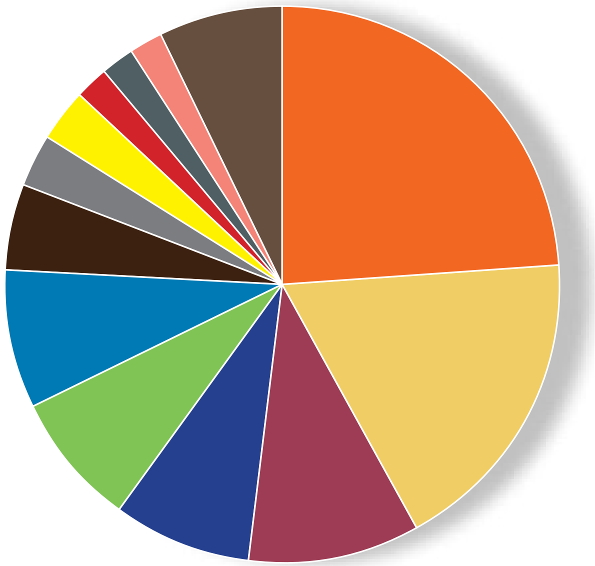

Sugar Maple 24%
American Basswood 18%
Red Maple 10%
Quaking Aspen 8%
Bur Oak 8%
Northern Red Oak 8%
Paper Birch 5%
Black Ash 3%
Elm 3%
Yellow Birch 2%
Green Ash 2%
Balsam Fir 2%
Misc. (1% each) 7%

Composition of Minnesota's Northern Hardwood Forest Type[7]

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LOWLAND CONIFERS

Lowland conifer forests, which are largely composed of black spruce, tamarack, and northern white cedar, cover approximately 3,477,000 acres, or around 21 percent, of Minnesota forestland[7]. These forests are largely found in peatlands, which are wetland areas where the soil is primarily composed of saturated, partially decayed plant matter[131]. Because of the organic plant matter that makes up their soils, lowland conifer forests store a large amount of carbon, making them an invaluable carbon reservoir[131]. Additionally, lowland conifers are often economically important. Approximately 260,500 cords of spruce and tamarack were harvested in 2016, largely for use as pulpwood (approximately 70 percent of harvest) or sawlogs[7]. These forests also provide important social and ecological services. Northern white cedar is an especially important cultural species to tribal communities in Minnesota, and cedar forests are gaining recognition as a stronghold for snowshoe hare populations.

Key Challenges:

Black spruce and tamarack in Minnesota are currently found near the southern edge of their suitable range, and a warming climate is likely to result in habitat changes that expose these species to greater stress and the potential for regeneration failure following death or disturbance[16]. Because these forests are highly dependent on the hydrologic regime in their soils, changes to the amount of precipitation or other factors which affect water levels (such as the development of roads or drainage ditches) can have a major impact on the health and vitality of lowland conifers like black spruce and tamarack[16].

In addition to challenges associated with a changing climate, Minnesota's tamarack resource is also under threat from a prolonged outbreak of the native pest, eastern larch beetle (ELB). As of 2019, the unprecedented two-decade long ELB outbreak in the state has resulted in an infestation of tamarack trees on hundreds of thousands of acres of Minnesota forestland.

Lastly, many of Minnesota's lowland conifer forests are aging. The majority of tamarack forest acreage is dominated by middle-age stands over 50 years old (and many stands greater than 90 years old). Most black spruce forests are older than 60 years old (with particularly large populations of spruce aged 60 to 80 and older than 100). The vast majority of northern white cedar acreage is dominated by forests over 100 years old[7]. These forests, which tend to be slow growing, will be hampered in their ability to regenerate as the climate warms. In addition, herbivory of northern white cedar seedlings has drastically impacted the natural regeneration of Minnesota's cedar forests, contributing to the lack of young cedar across the state.


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Adaptation Strategies:
Many lowland conifer forests have low adaptive capacity and are particularly vulnerable to climatic changes like alterations in the precipitation regime[16]. These forests provide important social, cultural, ecological, and economic value to the state, and are also highly important ecosystems due to the carbon storage capacity of their organic soils. Maintaining them on the landscape is likely to be a major management goal. Resistance strategies that focus on maintaining these ecosystems may be the only viable approach, but will also be expensive and only offer minor ability to adapt to changing conditions. Maintaining hydrologic integrity is critically important to increasing the resilience of these systems. This includes limiting and removing ditches, maintaining culvert systems, and developing other strategies for keeping and enhancing hydrologic connectivity[132].

These ecosystems may have some inherent resilience to a changing climate. The acid soils found in many lowland conifer peatlands may prevent other, more southern-adapted species, from encroaching on the habitat for black spruce and tamarack in these areas, and low-laying areas may be able to retain the necessary hydrologic and climatic conditions for these ecosystems to continue on the Minnesota landscape[16]. Resilience strategies that focus on increasing diversity in sites that are capable of supporting more than one species may also be effective for these forests. For example, artificially introducing species such as black spruce or cedar to a tamarack stand could increase resilience in those forest stands.

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SUMMARY & CONCLUSION

Management strategies that focus on the creation of healthy, resilient forests are essential to the ability of Minnesota's forests to continue to thrive under a changing climate. Adaptive silvicultural strategies, which are categorized as resistance, resilience, and transition strategies, can provide a framework for understanding and establishing how to manage Minnesota's forests. This section focused on five main forest cover types and potential adaptation management strategies for each:

- **Aspen:** Minnesota has a vast aspen resource that is economically important to the state. Because this resource is found near the southern edge of its range in Minnesota, strategies that increase resilience and/or transition these forests to other economically viable species may be most appropriate. Resistance measures may also be appropriate in areas that may provide climate refuges for this species.
- **Pine:** Pine forests are important economically, as well as culturally, to the state of Minnesota. Not only is our state tree a red pine, but pine forests offer an opportunity to store large amounts of carbon on the landscape and within long-lived timber products. These forests, which are adapted to wildfire, may benefit from a resilience strategy which returns fire to the landscape. In addition, transition strategies which focus on the growth of more southern-adapted white pine may also be appropriate.
- **Oak:** Our oak forests are thought to be some of the most climate-resilient landscapes in the state, due to their drought- and fire-hardiness. These forests would benefit from resilience strategies which provide the necessary disturbance to the landscape through fire and removal of undergrowth to ensure the continued growth and regeneration of many of our oak species.
- **Northern Hardwoods:** The northern hardwood forests are composed of a more diverse array of tree species than our other forests; this diversity is likely to make them resistant to many expected climate change effects in the state. In addition, because many of the species found in northern hardwood forests are currently at or near their northern species limit, a warming climate may increase the range of this forest type on the landscape. Resistance strategies that focus on maintaining high-quality northern hardwoods and resilience strategies which allow for some disturbance would both likely be appropriate for these forests.
- **Lowland Conifers:** Our lowland conifer forests, which are largely found in peatland areas and are composed almost entirely of black spruce, tamarack, and northern white cedar are extremely ecologically, economically, and culturally valuable to the state for their carbon storage and importance to the pulpwood and paper industries. Maintaining this forest type will require that resistance strategies be implemented, particularly to ensure that these forests continue to sequester and store vast amounts of carbon in the peatland soils. Resilience strategies that aim to increase species diversity in certain stands may also be effective at increasing climate resilience in certain cases.

In order to maintain our forests on the landscape, it is crucial that we understand what management practices and silvicultural strategies are necessary to increase the adaptability of our diverse forest types. Additional research is necessary to better understand which strategies might provide the best possible outcomes for maintaining our forest cover and the essential services they provide.

KEY RESEARCH NEEDS

The following research needs and questions were developed by the Research Advisory Committee based on their relevance to the topics reviewed in this section and importance to developing effective forest management strategies.

RESISTANCE – RESILIENCE – TRANSITION

- Expand research on genetic variation and associated adaptive response of tree species and forest types to changing conditions, esp. black ash replacement species, tamarack regeneration, and selection potentials for conifers and hardwoods.
- Expand research on silvicultural techniques that may foster resistance, resilience, and adaptation.

MINNESOTA FOREST TYPES

- Improve our understanding and planning for successional species and genetic populations that may or may not need to be encouraged by human intervention (e.g., native Minnesota species and non-native species through assisted migration).
- Expand research on native tree species response potentials for adaptation, including genetic selection and assisted gene migration.
- Examine the adequacy of existing tree seed zones and seed transfer guidelines.

SECTION 4
KNOWLEDGE GAPS AND NEXT STEPS FOR MINNESOTA

SUMMARY

As governments around the world – from the local to national level – wrestle with how to address climate change in their communities, Minnesota is positioned to be at the forefront of addressing the effects of a changing climate. This paper reviewed the scientific literature relating to climate change projections, impacts and resilience of our trees and forests, the role of forests and forest management in mitigating certain outcomes, and potential market opportunities that may further enable climate-positive futures for the diverse Minnesota landscape. Specifically, we have identified the importance of forests in:

- Providing essential ecological, social, and economic services;
- Sequestering and storing carbon and its potential use in an emission mitigation strategy; and
- Adapting to the climate threat through existing and innovative forest management techniques and strategies.

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KEY MESSAGES

1. Climate change threatens Minnesota's forests and the goods and services those forests provide to families, communities, businesses who depend on them, and all residents of the state (*Section 1*).

2. One of the most important services that forests provide is carbon sequestration: the absorption of atmospheric carbon dioxide and storage of carbon in trees' woody biomass and in forest soils. We have an opportunity in Minnesota to boost carbon sequestration through specific forest management strategies, thereby contributing to our state's carbon emissions reduction goals and mitigating climate change (*Section 2*).

3. We also have an opportunity to design and implement forest management strategies that help family forest owners, tribes, public land managers, and the forest products industry adapt to the adverse effects of climate change on forest goods and services (*Section 3*).

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RESEARCH NEEDS & OPPORTUNITIES

Research has played and will continue to play a critical role in filling knowledge gaps relating to the impacts of climate change on Minnesotan forests and the importance of our forestland in the face of a changing climate. The review of existing practices and scientific research presented in this paper indicates that we must increase the emphasis on mitigating and adapting to climate change in managing our forests. Doing so will aid in overall forest health and the preservation of the crucial services that our forests provide. To achieve this, maintaining and conducting new research related to climate change and forest management is needed to develop best management practices. The specific research questions in each section of this paper are a starting point to address information needs related to climate change and forest management. In addition, the Research Advisory Committee (RAC) of the MFRC published a report, "Priority Research to Sustain Minnesota's Forest Resources," in 2019 that includes related research topics for addressing climate change and forests[133]. Here, we address the broad areas of study that are necessary to provide Minnesota with the tools and understanding we need to address the very real challenges and opportunities associated with climate change. In this case, the broad areas for research are:

- **How might our changing climate and the unique attributes of Minnesota's forests affect our ability to manage forests to ensure a continuation of the essential ecological, sociological, and economic services on which we depend?**
  (See Section 1 research needs).
- **How can we maximize carbon storage in our forests and forest products, and how large a role can the sequestration of carbon in forestlands play in an emissions reduction strategy?**
  (See Section 2 research needs).
- **Can we improve the adaptive capacity of our forests to increase their resilience in the face of a changing climate?**
  (See Section 3 research needs).

POTENTIAL POLICY ACTIONS & FUNDING PRIORITIES

There are a number of actions which may be undertaken in the immediate future to help Minnesota prepare for future climate change impacts on our forests and associated forest management challenges and opportunities.

KEEPING FORESTS FORESTED

Support should be given to policies and proposals that help protect and conserve our existing forest area. This may include the use of conservation easements, tax policy, landowner incentives, or zoning restrictions that limit parcelization of forest cover, as well as novel approaches to maintaining forest cover. Conserving our existing forestland is integral to any carbon storage and emissions-mitigation strategy the state might pursue.

INCREASE NURSERY CAPACITY

Minnesota's tree nurseries produce around 22 million seedlings per year, which is sufficient to plant around 23,000 acres of trees. This stock is in high-demand, and there are generally few seedlings available for expanded planting opportunities such as increased stocking, afforestation, and reforestation strategies[81]. Increasing the capacity of Minnesota's state-run or private nurseries should be encouraged in order to provide the quantity and quality of seedlings needed for afforestation, reforestation, increased stocking of forests, and adaptation of forests to conditions more resilient to a changing climate. Additionally, nursery capacity should expand to include a more diverse suite of species and provide adequate information on seed provenance to ensure planting stock will be well adapted to changing conditions.

UPDATING THE MILLION ACRE REPORT

Under the direction of the Legislature, in 2008, the Minnesota Forest Resources Council conducted a review of the Minnesota Climate Change Advisory Group's recommendation to plant 1,000,000 acres of trees to increase carbon sequestration in our forests. This culminated in the 2010 publication of the Turner et al. report, "Assessing Forestation Opportunities for Carbon Sequestration in Minnesota," colloquially known as the Million Acre Report[81]. One decade later, it is time to revisit and update this report. In the past decade, there have been numerous updates in the science and understanding of climate change outcomes in Minnesota and how best we might meet those challenges. An update to the Million Acre Report would also be an important tool in assessing how, where, and what would need to be implemented for an effective reforestation and afforestation strategy in Minnesota.

ENHANCED COLLABORATION

Climate change does not recognize borders and affects all of our lands, regardless of ownership. This crisis provides an incentive for increased collaboration across agencies, organizations, states, and even countries, in developing effective management plans and strategies. The U.S. Forest Service's Shared Stewardship initiative is an example of how this collaboration may look; development of regional forestry-based research cooperatives provide another such opportunity. Enhancing collaboration must necessarily involve increased communication amongst various stakeholder groups, particularly in a state with varied ownership like Minnesota. The focus of these collaborative efforts should be on developing stand- to- landscape-level solutions to the pressing issue of climate change.

BIOENERGY FEEDSTOCKS – MARKET DEVELOPMENT FOR FOREST RESIDUALS

The use of forest harvest residuals and residuals from the primary industry as a feedstock for the production of value-added biofuels is generally considered to be the most cost-effective and eco-friendly method of generating bioenergy[101, 106]. The MFRC has developed guidelines for the maintenance of a certain amount of residuals on the landscape following harvest in order to preserve ecological function and prevent erosion. Other residual woody material could be used for bioenergy production if incentives and markets were developed for its use. Utilization of forest residuals for bioenergy production could provide both economic and forest health benefits.

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LONG-LIVED WOODY PRODUCTS & OTHER NOVEL CARBON PRODUCTS

Minnesota should encourage the development of markets for long-lived woody products that have the potential for storing carbon long after harvest. These include traditional lumber, as well as novel products such as engineered wood products (e.g., laminated veneer lumber, cross laminated timber) and thermally modified timber. These engineered products may be of particular interest in Minnesota because of their ability to utilize softwoods and small-diameter stock. Increasingly, the construction industry is seeking materials that have demonstrated high dimensional stability, tolerances, performance, and environmental impacts. The use of engineered wood products has the potential to dramatically increase in the coming years, and Minnesota should be at the forefront of this technology.

Of course, Minnesota-based mills must compete in a global economy. An update to the MFRC's 2014 report, "Report on the Competitiveness of Minnesota's Primary Forest Products Industry" may provide an opportunity to review ways to improve industry competitiveness nationally and internationally and address issues leading to reduced industry competitiveness.

MINNESOTA CARBON MARKET

One way in which carbon markets may become a feasible revenue stream for Minnesota landowners is through the development of a Minnesota-specific market for carbon offsets. Creating a Minnesota-specific cap-and-trade system (or one that covered the wider Midwest region) could create opportunities for Minnesota forest landowners, by increasing demand and price for Minnesota forest offsets. Currently, some Minnesota industries purchase offsets, but they do so voluntarily, and they often invest in credits generated in other states. Creating a Minnesota market would have an additional advantage in that the forest-offset methodology could be tailored to the forest types/management regimes/ownership patterns of the state, rather than being tailored to the California regulatory market.

In addition to a cap-and-trade market (or as an alternative to it), the state could also play a role in creating a voluntary market for forest offsets in Minnesota which specifically incentivizes the purchase of local carbon offsets by Minnesota-based companies. A policy like this could, for instance, encourage emitters to voluntarily report and offset their emissions, without actually requiring it. A cost-benefit analysis of the development of such markets in Minnesota would provide additional information into the feasibility of this market opportunity for Minnesota landowners and public land managers.

REFER REPORT TO PIC FOR DEVELOPMENT OF POLICY & COMMUNICATIONS STRATEGY

Upon publication of this paper, the Research Advisory Committee (RAC) of the MFRC recommends that it be referred to the MFRC's Policy and Information Committee (PIC). The role of the PIC is "identifying and prioritizing emerging issues related to the Sustainable Forest Resources Act, in particular in fulfilling [the MFRC's] statutory mandate to 'advise the Governor and federal, state, county, and local governments on sustainable forest resource policies and practices'," according to Minnesota Statutes, Chapter 89A.03. In this capacity, the PIC should review the recommendations of this paper to identify and prioritize strategic issues, generate appropriate policy recommendations, and bring any such recommendations to the full Council for approval.

CONCLUSION AND CALL TO ACTION

Climate change represents a real and imminent threat to global and local ecosystems. In Minnesota, our forestlands provide numerous benefits to the state – from ecological services, including improving water, air, and soil quality and providing crucial wildlife habitat, to economic and cultural services, including supporting our rural and tribal communities. Climate change impacts on our forests will present our state with challenges as we work to increase the resiliency and adaptability of these essential systems. However, we will also be presented with some potential opportunities to improve the quality and quantity of our forest cover, mitigating carbon emissions and counteracting their effect on the climate.

In this paper, we reviewed the unique attributes of Minnesota's forestland, identified the most likely outcomes of climate change in our state, and assessed how those outcomes might affect our forests and our ability to manage them (*Section 1*). We also reviewed how Minnesota can increase carbon on our landscape through enhancing and expanding our forest cover, managing our forests to maximize carbon storage, and utilizing innovative market solutions to fund and facilitate carbon-positive forest management (*Section 2*). Further, we assessed five common and important Minnesota forest types for their likely resilience to a changing climate, as well as strategies that may be utilized in managing these forests for increased climate adaptability (*Section 3*).

We stress the importance of increasing and expanding research in the topics of climate change and Minnesota's forests by supplying key research needs and questions at the end of each section of this paper. The role of research in developing appropriate and effective management strategies for Minnesota's forests in the face of climate change cannot be overstated.

Lastly, we suggest a number of actions that Minnesota can and should promptly take to prepare our state for our climate future and its impacts on our forests. These actions include steps that are necessary for maintaining and increasing carbon on the Minnesota landscape and mitigating or reducing our fossil fuel emissions. In addition to the actions listed here, it is important to recognize that forest management in Minnesota is conducted largely through partnerships with forest industry. Advancing our capability for managing Minnesota's forest composition and overall forest health may require growing industry capacity and increasing DNR and other agency staffing and expertise to attract investment in new products, processes, and facilities.

Minnesota has the opportunity to develop a comprehensive climate change strategy that not only helps to mitigate the effects of climate change and reduce fossil fuel emissions, but also enhances our forests and the crucial ecological, sociological, and economic services they provide. This opportunity is achievable if we act now and work together to find solutions for the many challenges we face under a changing climate.

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