DEPARTMENT OF NATURAL RESOURCES

Forests and Carbon in Minnesota: Opportunities for Mitigating Climate Change

A report to the Minnesota Legislature

1/15/2023

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This report fulfills requirements of Laws of Minnesota 2021, First Special Session chapter 6, Sec. 132:

> CARBON SEQUESTRATION IN FORESTS OF THE STATE; GOALS.
> The commissioner of natural resources must establish goals for increasing carbon sequestration in public and private forests in the state. To achieve the goals, the commissioner must identify sustainable forestry strategies that increase the ability of forests to sequester atmospheric carbon while enhancing other ecosystem services, such as improved soil and water quality. By January 15, 2023, the commissioner must submit a report with the goals and recommended forestry strategies to the chairs and ranking minority members of the legislative committees and divisions with jurisdiction over natural resources policy.

As requested by Minnesota Statute 3.197: This report cost approximately $152,318 to prepare, including staff time, printing and mailing expenses.

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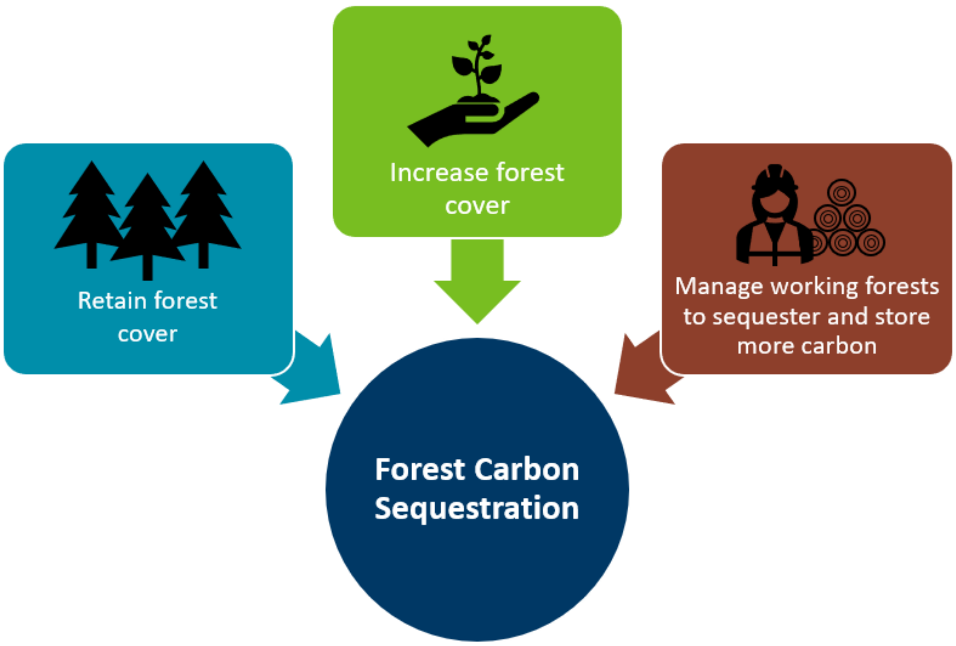
Contents

Executive summary

Well-managed forests provide multiple benefits such as wildlife habitat, recreation, water quality, timber and other forest products, and scenic beauty. They also help mitigate climate change by absorbing and storing carbon dioxide from the atmosphere when they grow.

There are three main pathways for increasing the role of Minnesota's forests in mitigating climate change: retain forest cover, increase forest cover, and manage working forests to sequester and store more carbon. These pathways are closely aligned with existing policies and programs that guide sustainable management practices on public and private forests in Minnesota.



Policymakers can accelerate these pathways with targeted investments and policies. Advancing the suite of goals and sustainable forestry strategies in this report will result in an increase in annual net forest carbon sequestration by up to 9 percent in 2048 compared to a baseline scenario. For reference, this increase is similar in quantity to emissions from nearly 244,000 gasoline-powered vehicles driven for one year.

The benefits provided by well-managed forests are strongly linked. Prioritizing one benefit can diminish other important benefits in the portfolio. Sustainable forest management aims to generate multiple benefits from forests over the long term. Professional forestry experts are well-suited to identify opportunities for balancing multiple benefits and avoiding unintended consequences.

Mitigating and adapting to climate change is a key policy priority for the state; it is also a strategic priority of the Minnesota Department of Natural Resources (DNR). *Minnesota's Climate Action Framework*—the state's plan for addressing climate change—describes a goal of reducing statewide net emissions to zero by 2050. This will be achieved through a combination of reducing emissions from major sources such as transportation, electricity generation, industry, and agriculture and increasing the amount of carbon dioxide absorbed and stored in forests, grasslands, and wetlands.

In 2021 the Minnesota Legislature directed the Minnesota Department of Natural Resources (DNR) as follows:

> CARBON SEQUESTRATION IN FORESTS OF THE STATE; GOALS.
> The commissioner of natural resources must establish goals for increasing carbon sequestration in public and private forests in the state. To achieve the goals, the commissioner must identify sustainable forestry strategies that increase the ability of forests to sequester atmospheric carbon while enhancing other ecosystem services, such as improved soil and water quality. By January 15, 2023, the commissioner must submit a report with the goals and recommended forestry strategies to the chairs and ranking minority members of the legislative committees and divisions with jurisdiction over natural resources policy.
>
> (Laws of Minnesota 2021, First Special Session chapter 6, Sec. 132)

The ensuing report presented here builds foundational knowledge about forest-based climate change mitigation pathways. It also defines goals and sustainable forestry strategies to guide governments, businesses, nonprofits, and individuals engaged in managing Minnesota's forests.

Overall, Minnesota's forests are a consistent carbon sink—absorbing more carbon dioxide from the atmosphere than they release over time due to harvest, natural disturbances (e.g., wildfire, pests, disease, and wind events), and conversion of forests to non-forest land uses. Forest carbon sequestration alone cannot completely offset statewide GHG emissions. However, maintaining and enhancing current trends in forest carbon sequestration is an important climate policy objective.

Taking steps today to increase the amount of carbon dioxide sequestered and stored by Minnesota's forests is essential for maintaining the strength of the state's forest carbon sink over the long term. The pathways, goals, and sustainable forestry strategies described in this report provide direction on how to accomplish this while maintaining a balanced portfolio of forest benefits and avoiding unintended consequences.

Retain forest cover

Goal: Reduce the rate of conversion of forests to non-forest land uses

Converting forests to other land uses results in an immediate loss of carbon storage in forests and diminished long-term sequestration potential. Around 30,000 acres of forest are converted to agriculture and development each year. Preventing forest conversion results in immediate climate mitigation benefits. Increasing efforts to retain forest cover today has the potential to increase annual forest carbon sequestration by up to 4% in 2048.

The DNR recommends the following sustainable forestry strategies for reducing conversions of forest to non-forest land uses:

1. **Enhance financial and technical assistance to private landowners**: Providing small private forest landowners with technical and financial assistance reduces the risk that forests are converted to agriculture or development.

2. **Increase the impact of forest land acquisition tools and easement programs**: Ingredients for successful land acquisition and conservation easement programs include strong partnerships and a commitment to streamlining administrative processes for acquiring forestland.
3. **Incentivize forest retention by strengthening markets for sustainably managed forest products**: A strong forest products market will encourage investment in forests, which reduces the risk of conversion to development or agriculture.
4. **Discourage fragmentation of private forests**: Policies that discourage the breaking up of large contiguous private forest parcels will help avoid conversion of these forests to other uses.

Increase forest cover

Goal: Facilitate and encourage tree planting where ecologically appropriate

Planting new forests increases the amount of atmospheric carbon sequestered and stored by forests in aggregate over time. There is ample opportunity for tree planting in Minnesota, ranging from 3 to nearly 8 million acres of formerly forested open lands where re-establishing forests is ecologically appropriate. Most of these acres are privately owned. The climate mitigation benefits of this pathway are not immediate as newly planted trees take several decades to reach peak carbon sequestration potential. Increasing the rate of tree planting today could increase annual net forest carbon sequestration by up to 5% in 2048.

The DNR recommends the following sustainable forestry strategies for accelerating tree planting:

1. **Increase in-state seedling production to support higher rates of tree planting:** Expanding in-state seedling production is a heavy lift that will require new investments in the seedling production supply chain and strong partnerships between public entities, Tribal governments, private businesses, and nonprofit organizations.
2. **Expand private landowner access to financial and technical assistance for tree planting:** Increasing the availability of state, federal, and nonprofit funding for sharing upfront costs will encourage more tree planting.
3. **Invest in protecting and expanding urban and community forests:** Maintaining carbon sequestration benefits from urban and community forests requires ongoing efforts to protect ash trees from the invasive emerald ash borer (EAB) insect and planting diverse species to efficiently replace current and expected mortality due to the pest.
4. **Develop a trained workforce for accelerating tree planting:** Meeting expected increases in demand for seedlings and tree planting will require a larger trained workforce who can collect more seeds, grow more seedlings, and plant more seedlings.
5. **Identify synergies between tree planting and agricultural practices:** Productive agricultural lands can also benefit from strategically planted trees.

Manage working forests to sequester and store more carbon

Goal: Expand active sustainable forest management to generate a balanced portfolio of forest benefits

There are two main approaches to enhancing carbon sequestration and storage on forests that are actively managed with timber harvest. One involves enhancing the amount of carbon stored within forest ecosystems over time. The other approach involves enhancing carbon storage in wood products and substituting wood products for more fossil-fuel intensive materials. While these approaches are not strictly mutually exclusive, they sometimes tradeoff with each other and with other social, conservation, and economic benefits forest provide. They also differ in terms of the timing of mitigation benefits. The Intergovernmental Panel on Climate Change (IPCC) states that sustainable forest management practices that balance these two approaches across landscapes generate the greatest long-term climate mitigation benefits.

Minnesota should continue to encourage the use of sustainable forest management practices and active management—including timber harvest—to generate a balanced portfolio of benefits at the landscape scale. As a parallel process, Minnesota should further explore the opportunities and tradeoffs of increasing carbon storage in forest ecosystems and increasing carbon storage and substitution via wood products.

The DNR recommends the following sustainable forestry strategies that will enhance opportunities to manage working forests to sequester and store more carbon:

1. **Enhance forest carbon measurement and accounting systems:** Increasing the quality and timeliness of data on forest carbon will improve understanding of baseline carbon storage and sequestration levels, provide a sense of what drives changes over time, and determine whether specific strategies produce desired results.
2. **Employ timber harvest as a tool of sustainable forest management on family forests:** Sustainable timber harvest plays an important role in climate mitigation as the primary means for creating younger faster growing forests.
3. **Support policies and incentives that strengthen and diversify wood products markets:** Targeted financial incentives can spur market development for in-state wood product production.
4. **Explore opportunities to increase in-forest carbon sequestration and storage:** The mitigation potential, tradeoffs, and uncertainties of increasing in-forest carbon sequestration and storage are sensitive to site-level factors and assumptions about future conditions.
5. **Evaluate the carbon storage and substitution benefits of producing short- and long-lived wood products:** More work is needed to understand the carbon storage and substitution benefits of wood products manufactured in Minnesota.
6. **Investigate planning tools for balancing approaches to mitigate climate at a landscape scale:** New modeling approaches are needed to analyze biological and economic impacts while accounting for multiple values at appropriate scales.

This report outlines goals and strategies for enhancing forest carbon sequestration on public and private forests in Minnesota. However, no individual entity can achieve these goals on their own. Making progress towards these goals will require strong partnerships among local, state, federal, and Tribal governments; nonprofit organizations; businesses; and private landowners. Within this larger community, the DNR can help lead the way by building broad support for these strategies and scaling up DNR activities to meet current and future needs.

Summary of pathways, goals, and strategies for increasing forest carbon sequestration in Minnesota

Pathways	*Goals*	*Sustainable Forestry Strategies*
Retain forest cover	Reduce the rate of conversion of forests to non-forest land uses	• Enhance financial and technical assistance to private landowners • Increase the impact of forest land acquisition tools and easement programs • Incentivize forest retention by strengthening markets for sustainably managed forest products • Discourage fragmentation of private forests
Increase forest cover	Facilitate and encourage tree planting where ecologically appropriate	• Increase in-state seedling production to support higher rates of tree planting • Expand private landowner access to financial and technical assistance for tree planting • Invest in protecting and expanding urban and community forests • Develop a trained workforce for accelerating tree planting • Identify synergies between tree planting and agricultural practices
Manage working forests to sequester and store more carbon	Expand active sustainable forest management to generate a balanced portfolio of forest benefits	• Enhance forest carbon measurement and accounting systems • Employ timber harvest as a tool of sustainable forest management on family forests • Support policies and incentives that strengthen and diversify wood products markets • Explore opportunities to increase in-forest carbon sequestration and storage • Evaluate the carbon storage and substitution benefits of producing short- and long-lived wood products • Investigate planning tools for balancing approaches to mitigate climate at a landscape scale

Introduction

The Intergovernmental Panel on Climate Change recently reported that avoiding the most severe and costly impacts of climate change—including significant shifts in weather and climate extremes—requires limiting global warming to 1.5 degrees Celsius (2.7 degrees Fahrenheit) above pre-industrial levels (Intergovernmental Panel on Climate Change, 2021). Global temperature increased nearly 1 degree Celsius since 1850 and is expected to increase beyond 1.5 degrees Celsius during the 21st century unless we make deep cuts in carbon dioxide and other greenhouse gas (GHG) emissions in the coming decades. Reducing emissions from major sectors such as electricity generation, transportation, and agriculture is a central priority to meeting this target. Bolstering the ability of natural systems such as forests, grasslands, and wetlands to remove and store carbon will also be required as part of a multi-faceted climate change mitigation approach.

Forests can play a prominent role among natural climate solutions. Forests remove large amounts of carbon dioxide from the atmosphere each year (U.S. Environmental Protection Agency, 2022a, Table ES-4). In addition, how we manage forests can directly influence carbon capture, storage and release (i.e., the forest carbon cycle). This report identifies goals and sustainable forestry strategies aimed at enhancing climate mitigation via forests. It also describes associated economic dimensions and long-term effects.

In 2021, the Minnesota Legislature directed the Minnesota Department of Natural Resources (DNR) to:

1) establish goals for increasing carbon sequestration in public and private forests in the state,
2) identify sustainable forestry strategies that increase the ability of forests to sequester atmospheric carbon while enhancing other ecosystem services, such as improved soil and water quality, and
3) submit a report with the goals and recommended forestry strategies to the Legislature by January 15, 2023.

(Laws of Minnesota 2021, First Special Session chapter 6, Sec. 132).

This ensuing report, *Forests and Carbon in Minnesota: Opportunities for Mitigating Climate Change*, supports and builds on the fact that implementing forest-based climate mitigation pathways, while also managing for forest products, water quality and flow, wildlife habitat, recreation, and other forest benefits, is an important way to mitigate climate change over the long term.

It is important to note that natural climate solutions—including increasing forest carbon sequestration—represent only a handful of the many pathways that have been identified, and are needed, to mitigate climate change and its effects on natural systems and Minnesota communities. Policymakers in Minnesota have also crafted laws and strategies to help reduce the state's GHG emissions. Implementation of energy-related statutes and policies such as the Renewable Energy Standard, Energy Efficiency Resource Standard, and Energy Conservation and Optimization Act has led to progress in decarbonizing energy systems. Other policies, like the Clean Cars Minnesota Rule, seek to reduce tailpipe emissions. The Next Generation Energy Act in 2007 established statutory goals for reducing statewide GHG emissions by 15% below 2005 levels by 2015, 30% below by 2025, and 80% below by 2050. In 2019, Governor Walz signed Executive Order 19-37 creating a Climate Change Subcabinet and Advisory Council to promote coordinated actions to reduce GHG emissions and enhance adaptation across Minnesota's economic sectors. Natural and working lands, which include public and private forests, are one of seven sectors included in the state's GHG emissions inventory (Minnesota Pollution Control Agency, 2021).

Most recently, *Minnesota's Climate Action Framework (Framework)* was completed in September 2022 via a collaborative process led by the Governor's Climate Change Subcabinet and Climate Change Advisory Committee. The *Framework* identifies climate mitigation and adaptation strategies across the major economic sectors: transportation, energy production, buildings, and natural and working lands such as agricultural lands, forests, grasslands, and wetlands (State of Minnesota, 2022). Climate-smart practices reduce GHG emissions from natural and working lands or increase accumulation (i.e., sequestration and storage) of carbon dioxide in plants, soils, and products. Implementing climate adaptation practices will buffer natural and working landscapes from the negative impacts of climate change and protect both accumulated carbon and future carbon sequestration potential.

This legislative report complements the *Framework* by providing additional depth on the opportunities and barriers related to forest-based climate mitigation pathways. This report also proposes a set of goals for increasing carbon sequestration in Minnesota's public and private forests, and sustainable forestry strategies for implementing those goals in Minnesota.

The first section provides important background on forest benefits, the forest carbon cycle, and Minnesota's forest carbon sink.

The second section outlines pathways for forest-based climate mitigation, along with goals and sustainable forestry strategies within each pathway. The three overarching pathways are: retain forest cover, increase forest cover, and manage working forests to sequester and store more carbon. This section also includes descriptions of mitigation potential, economic factors, connection to other forest benefits, barriers, and important knowledge sets that will help steer effective and efficient progress towards the goals proposed in this report.

The third section contextualizes the role of forest-based climate mitigation pathways as part of a multi-sector climate mitigation approach. It highlights important economic dimensions of various mitigation opportunities.

The fourth section concludes the report with a brief summary of findings. Appendices include explanations of methods used to calculate mitigation potential and background on current DNR forestry activities that contribute to climate mitigation. A Glossary provides definitions for terminology used throughout the report.

The DNR prepared this report by drawing from staff expertise and best available scientific literature on forest carbon, forest management, and climate policy topics. The DNR also conducted external technical review, stakeholder group discussion, and a Tribal coordination meeting to inform the content of this report. These engagements allowed the DNR to gather valuable perspectives on priorities and needs related to forest carbon sequestration. Feedback collected during these engagements enhanced the quality and comprehensiveness of the report. This report was also informed by inter-disciplinary discussion and feedback collected in the development of *Minnesota's Climate Action Framework.*

Section 1: An Overview of Forests and Carbon

What forests provide

Forests provide a portfolio of social, economic, and environmental benefits. The benefits in this portfolio are sometimes called "ecosystem services." Tangible forest products include energy, food, animal feed, wood products (e.g., lumber, paper), and medicinal, biochemical, and genetic resources. Forests provide habitat and regulate air quality, climate, and water quality and quantity. Forests also create opportunities for learning and inspiration that enhance a wide range of cultural values. Climate mitigation (sequestering and storing carbon) is one of these many forest benefits.

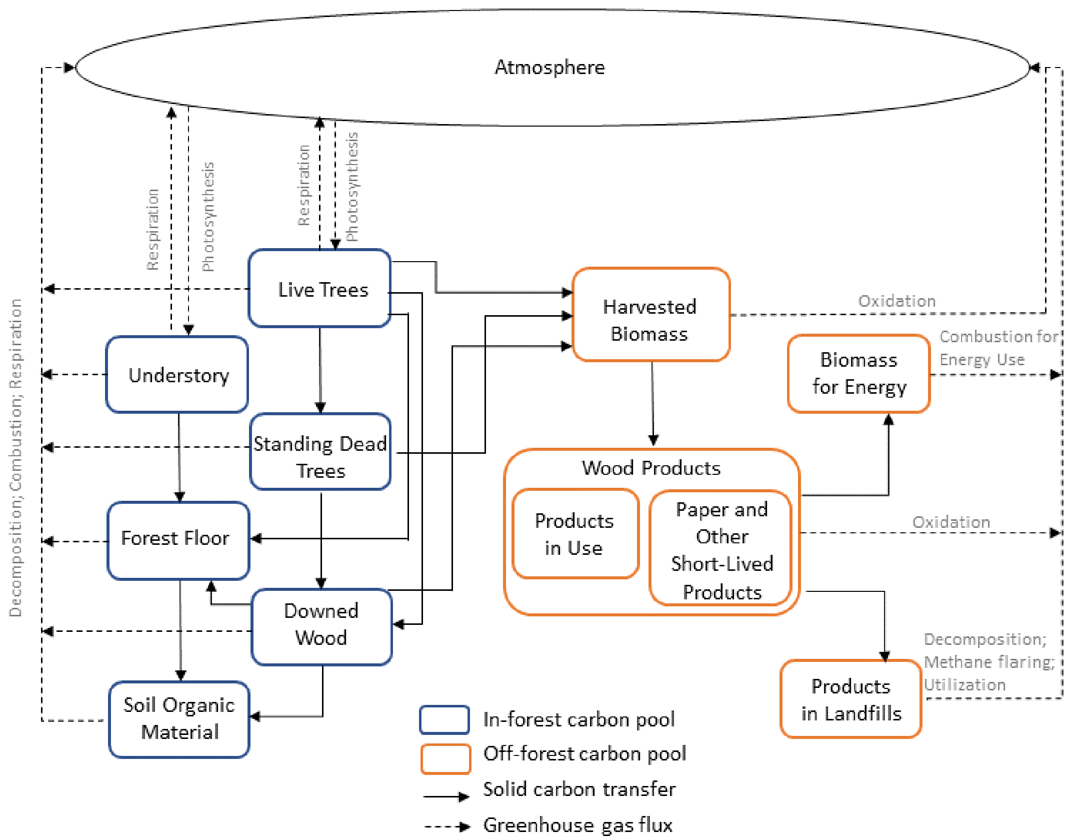
While every forest provides multiple benefits, every acre of forest cannot provide every benefit, and the relative emphasis of each benefit depends on the identified management objectives for a specific forest stand, area or landscape. For example, managers of publicly owned forests often strive to balance multiple benefits including diverse wildlife habitat, healthy watersheds, a robust forest products industry, and recreational opportunities, with the overall goal of reflecting and serving the diversity of values the public has regarding their forested lands. Tribal forest managers may emphasize additional culturally specific benefits such as traditional foods, medicines, and fibers, spiritual relationships, and protection of important cultural sites. In comparison, private industrial and non-industrial family forest owners may emphasize a smaller set of personal or business objectives in their forest management activities, such as timber production, wildlife enhancement, or recreation.

As noted above, forests have the potential to significantly contribute to climate mitigation efforts. Realizing this potential requires that forest managers consider climate mitigation benefits as part of a sustainable forest management approach and recognize that forest benefits are strongly linked. While increasing climate mitigation benefits can simultaneously enhance other forest benefits, tradeoffs can also occur.

The forest carbon cycle

Forests absorb atmospheric carbon dioxide as they grow—storing it as solid carbon in leaves, branches, roots, trunks, and soil. Stored carbon can persist in forests for several decades to centuries or longer. Most carbon stored in forest vegetation is ultimately released back into the atmosphere through decomposition, combustion, or respiration. When wood is harvested from the forest, carbon is transferred into wood products that are used over short and long timeframes (sometimes hundreds of years). These products are ultimately recycled, composted, disposed of in landfills, or burned. Barring major disturbance such as land conversion, carbon stored in forest soils can persist for millennia. This integrated system of carbon capture (sequestration), storage, and release is called the forest carbon cycle (Figure 1). Carbon accumulates within and moves between pools at different rates. The magnitude and timing of carbon released from these pools to the atmosphere vary depending on growth, land use patterns, forest management decisions, and wood product use and disposal.

Figure 1: Forest carbon cycle in a typical North American working forest



SOURCE: Adapted from Franklin et al. 2018.
NOTES: Indirect emissions (e.g., from transportation and processing) are not included in this discussion per IPCC guidance (Witi & Romano 2019, Table 8.2).

The forest carbon cycle illustrates the idea that forests are continuously exchanging GHGs with the atmosphere. The net result of that exchange over time describes the overall contribution of forests to climate mitigation. The following are key points for policymakers and forest managers to keep in mind regarding the forest carbon cycle and climate change mitigation:

- **The forest carbon cycle is measured in terms of "stock" and "flux":** Carbon stock is the amount of carbon stored in forest carbon pools (e.g., live trees, soil, wood products) at a single point in time. Carbon flux is the change in carbon stock over time. It is an estimate of the net amount of atmospheric carbon dioxide forests are sequestering (or emitting). Flux is expressed as a rate (e.g., tons of carbon per year) and is the most important metric describing the contribution of forests to climate mitigation.
- **Trends in forest carbon are clearest at larger scales**: The effect of forest management on carbon sequestration becomes most clear when viewed over long periods of time and over large numbers of acres. Individual forest stands range from a few acres to hundreds of acres, and stock and flux can change rapidly with timber harvest, land use conversions, or other disturbances like wildfire, pest

outbreaks, and disease. At larger scales, such as across landscapes, regions, or the state (thousands to millions of acres), forest carbon stock is relatively stable over time (Janowiak et al., 2017).

- **Carbon sequestration peaks in younger forests; carbon storage peaks in older forests**: Younger, rapidly growing forests sequester carbon at a higher rate compared to older slower-growing forests. However, older forests store more carbon compared to younger forests. Older forests can become a net source of emissions when the rate of natural mortality and decay exceeds the rate of growth. Studies suggest that allowing forests to advance into older age reduces the aggregate amount of carbon dioxide that forests sequester annually (Dugan et al., 2018; U.S. Department of Agriculture Forest Service, 2018). Maintaining a balance of forest ages—including younger forests—across the forest landscape promotes long-term forest carbon sequestration.
- **Carbon stored in wood products and emissions offset by using wood is less understood**: Technical understanding of the forest carbon cycle is strongest for in-forest carbon pools (e.g. live trees, litter). Comparatively less is known about the accumulation and release of carbon in wood products and the emissions avoided by using wood products in place of fossil fuel-intensive materials (e.g., concrete, steel, petroleum products). More data is needed.

Minnesota's forest carbon sink

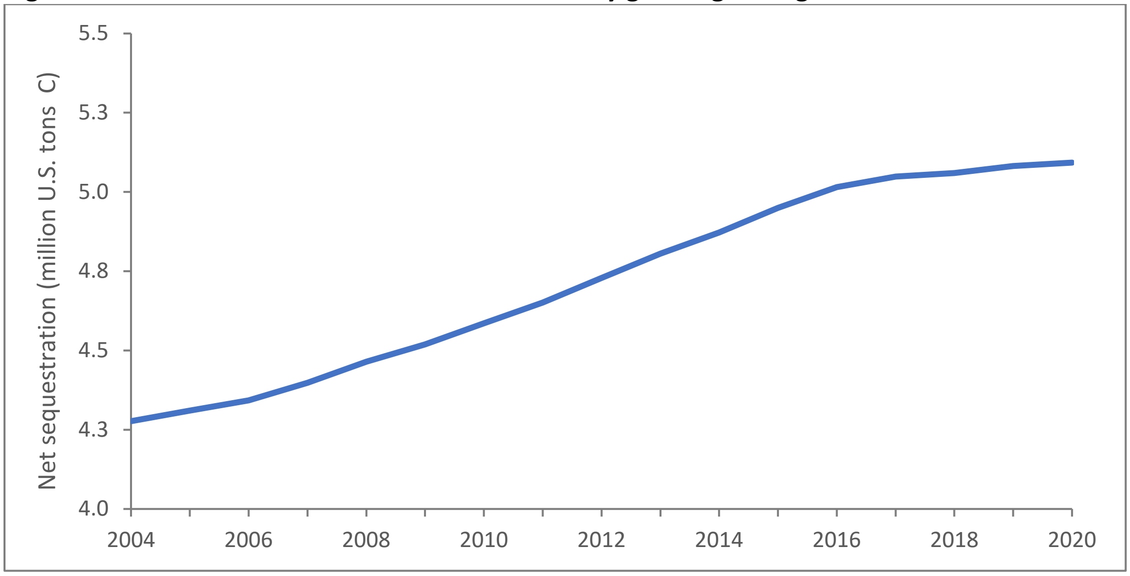
Minnesota's forests are a carbon sink, meaning they remove more carbon dioxide from the atmosphere overall than they release. Estimates of annual net carbon flux in forests between 1990 and 2020 suggest that during this period, Minnesota's forests sequestered more carbon dioxide from the atmosphere each year than was released from forests due to harvest, natural disturbances (e.g., wildfire, pests, disease, and wind events), and conversion of forests to non-forest land uses (Walters et al, 2022). In 2020, Minnesota's forests sequestered 5.1 million U.S. tons of net new carbon (18.7 million U.S. tons of CO_{2e})—representing a 20% increase since 2004 (Figure 2).

In 2020, most of the net new carbon sequestered in forests accumulated in existing forests (80%), with the remainder contributed by conversion of non-forest lands to forest lands (20%). Of the 80% that accumulated in existing forests, sequestration is attributable to:

- Net increase of carbon stocks in live vegetation such as trees, shrubs, and other types (64%)
- Net accumulation of carbon in dead wood (22%)
- Growth of fine and coarse roots (13%)
- Net accumulation of carbon in leaves and other small woody material on the forest floor (1%)
- Net increases in organic and mineral soil carbon (1%)

Minnesota's forest carbon sink is an asset in ongoing efforts to meet state GHG reduction goals. In 2018, forest regrowth in Minnesota offset around 5 percent of total gross GHG emissions from other sectors (Minnesota Pollution Control Agency, 2021). While this offset may seem small compared to the GHG reduction potential in other sectors (e.g., energy production, transportation), it is nonetheless significant, especially in light of the many other benefits that forests provide.

Figure 2: Minnesota's forest carbon sink is steadily growing stronger



SOURCE: DNR calculations using USDA Forest Inventory and Analysis data via Walters et al. (2022).
NOTES: Net carbon uptake on public and private forestlands combines net carbon flux of "Forests Remaining Forests" and "Land Converted to Forests." Flux is expressed in terms of net sequestration (e.g. negative net emissions). Estimates do not include carbon stored in wood products nor wood product substitution effects.

Section 2 includes analysis of how much more carbon dioxide Minnesota's forests might absorb in the future from implementing key forest carbon sequestration pathways.[1] Annual net forest carbon sequestration in the year 2048 (i.e., 25 years in the future) was used as the basis for comparing these pathways. Implementing two key pathways—retain forest cover and increase forest cover—could increase annual net forest carbon sequestration by up to 9 percent in 2048 compared to a baseline scenario.[2] For reference, this increase is similar in quantity to GHG emissions from nearly 244,000 gasoline-powered vehicles driven for one year.

Forest carbon sequestration alone cannot completely offset statewide GHG emissions. However, maintaining and enhancing current trends in forest carbon sequestration is an important climate policy objective. Taking steps today to increase the amount of carbon dioxide sequestered and stored by Minnesota's forests is essential for maintaining the strength of the state's forest carbon sink over the long term. The pathways, goals, and sustainable forestry strategies described in this report provide direction on how to accomplish this while maintaining a balanced portfolio of forest benefits and avoiding unintended consequences.

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[1] Mitigation potential was not estimated for the pathway "Managing working forests to sequester and store more carbon" due to the complexity of the pathway and lack of accessible modeling techniques.

[2] Mitigation potential is expressed as a percent increase in the amount of annual net carbon sequestration in the year 2048 compared to the amount of net carbon sequestration expected to occur in 2048 without deliberate efforts to enhance forest carbon sequestration (i.e., the baseline scenario).

Section 2: Goals and sustainable forestry strategies for mitigating climate change

This section describes three pathways and associated goals for enhancing climate mitigation benefits on public and private forest lands. These are: retain forest cover, increase forest cover, and manage working forests to sequester and store more carbon.

The DNR is responsible for providing expertise to understand, sustain, and manage Minnesota's trees, woodlands, and forests. As part of this charge, the agency strives to promote sustainable forest management strategies on public and private forest lands that generate multiple forest values, ecosystem services, and opportunities. Within each of the three pathways, we recommend goals and sustainable forestry strategies intended to enhance climate mitigation as well as other forest benefits.

Over the last several decades, technical experts have developed a large and evolving body of knowledge on pathways for increasing climate change mitigation benefits from forests. Three promising pathways—each with an associated goal and sustainable forestry strategies—emerge as applicable and effective in a wide range of ecological, social, and economic contexts (Table 1). The specific climate mitigation benefits from each approach will differ based on region and initial condition of the forest (Nabuurs et al., 2007).

The following subsections describe each pathway, along with the recommended goal for Minnesota and a list of high-priority sustainable forestry strategies for making progress towards each goal. The subsections also include estimates of mitigation potential (how much additional carbon sequestration each pathway can provide) and discussion of economic factors, connection with other forest benefits, barriers, and knowledge gaps.

Table 1: Forest-based climate mitigation pathways, goals, and sustainable forestry strategies

Pathway	*Goal*	*Sustainable Forestry Strategies*
Retain forest cover	Reduce the rate of conversion of forests to non-forest land uses	• Enhance financial and technical assistance to private landowners • Increase the impact of forest land acquisition tools and easement programs • Incentivize forest retention by strengthening markets for sustainably managed forest products • Discourage fragmentation of private forests

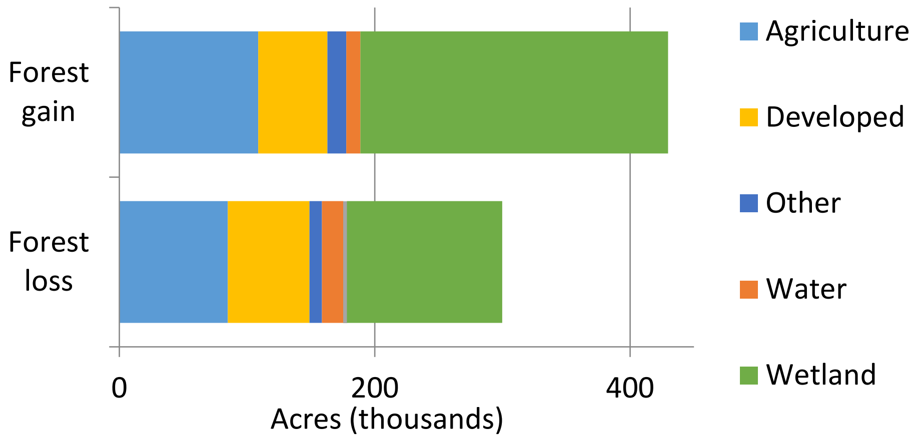
Increase forest cover	Facilitate and encourage tree planting where ecologically appropriate	• Increase in-state seedling production to support higher rates of tree planting • Expand private landowner access to financial and technical assistance for tree planting • Invest in protecting and expanding urban and community forests • Develop a trained workforce for accelerating tree planting • Identify synergies between tree planting and agricultural practices
Manage working forests to sequester and store more carbon	Expand active sustainable forest management to generate a balanced portfolio of forest benefits	• Enhance forest carbon measurement and accounting systems • Employ timber harvest as a tool of sustainable forest management on family forests • Support policies and incentives that strengthen and diversify wood products markets • Explore opportunities to increase in-forest carbon sequestration and storage • Evaluate the carbon storage and substitution benefits of producing short- and long-lived wood products • Investigate planning tools for balancing approaches to mitigate climate at a landscape scale

Pathway 1: Retain forest cover

Preventing the conversion of forest lands to non-forest land uses (e.g., agriculture, residential and commercial development, other infrastructure) is a core pathway for mitigating climate change (Intergovernmental Panel on Climate Change, 2018; Fargione et al., 2018; Grassi et al., 2017). When a forest is converted to a non-forest use, the result is an immediate loss of carbon storage in forests and diminished carbon sequestration capacity over the long term. Retaining forest cover is a cost-effective and high-impact way to increase climate mitigation benefits from Minnesota forests.

In Minnesota, forest conversion includes (1) recategorization of forests as wetlands due to minor shifts in tree canopy cover, (2) converting forests to agriculture, and (3) converting forests to development, which includes housing, roads, commercial and institutional buildings, and other infrastructure (Hillard et al., 2022). An estimated 60,000 acres of Minnesota forest are converted to other land uses each year—representing 0.35% of total forest cover (Hillard et al., 2022). However, forest conversions are currently outpaced by gains in forest cover due to intentional tree planting and natural regeneration, resulting in a net increase of 26,000 acres in forest cover per year (Figure 3). In terms of carbon, forest conversions to and from other uses resulted in the net sequestration of around 0.3 million U.S. tons of carbon (1 million U.S. tons of CO_{2e}) in Minnesota in 2020 (Walters et al., 2022).

Figure 3: Gain in Minnesota's forest cover outpaced loss by 130,000 acres from 2013 to 2018



SOURCE: Hillard et al. (2022).

Each year, more acres are converted from agricultural land and wetlands to forests than the other way around. However, more forested acres are converted to development than are gained from converting development back to forest each year—putting slight downward pressure on this overall increasing trend in forest cover. Conversion to development has steadily increased since the 1990s, reflecting population growth in the state.

The magnitude of carbon sequestration and storage loss due to conversion depends on the land use the forest is converted to, and is least for wetlands, more for agriculture, and most for development. Additionally, when forests are converted to development, losses of carbon stock and sequestration potential can be permanent. Converting to agricultural lands has a similar near-term effect but has greater potential for being converted back to forests in the future. Forest conversion to wetlands is a more fluid, mostly naturally occurring back-and-forth exchange that generally reflects small differences in carbon storage and sequestration.

Regional differences in economic drivers and land use pressures influence where forest conversion occurs. Conversion of forest to croplands tends to occur where forests border productive agricultural lands. In recent years, favorable agricultural markets have led to the clearing of areas of rare forest habitat types in the northwestern and north-central part of the state for crop production, representing a loss of particularly high-value forest (Marcotty, 2013; Ag Week, 2015). Forest fragmentation and conversion to residential development is a long-standing trend in the state and tends to occur at edges of urban and suburban settlements and other places where demand for housing is growing (Friesen, 2020; Minnesota Forest Resources Council, 2010).

Mitigation Goal: Reduce the rate of conversion of forests to non-forest land uses

Minnesota should strive to slow the rate of conversion of forests to other non-forest land uses such as development and agriculture. Taking this action will generate immediate climate mitigation benefits (Nabuurs et al., 2007; Williams et al., 2021). Family forests represent one-third of forest ownership in Minnesota and are at greater risk of conversion due to high technical and financial barriers to sustainable forest management (Friesen, 2020). To a lesser extent, conversion of industrial private and publicly managed forest lands also occurs.[3]

Sustainable forestry strategies for reducing the rate of forest conversion

There are several well-developed tools for reducing the rate of forest conversion, ranging from landowner assistance to land use planning. Targeted investments and policies that enhance the impact of these tools will meaningfully reduce the rate of forest conversion. The following high-priority sustainable forestry strategies provide actionable steps for achieving the goal of reducing forest conversion in Minnesota:

1. **Enhance financial and technical assistance to private landowners**: Publicly funded financial assistance programs (such as cost-share programs) can subsidize the cost to develop forest stewardship plans and manage forests according to such plans. Programs can also provide tax relief or other incentives to prevent forest owners from converting to non-forest uses or dividing or selling their land (Henke et al., 2012). Federal, state, local, and Tribal governments can help by increasing staff and funding for landowner assistance programs. For example, DNR Forestry provides technical and cost-share assistance as well as long-term incentives to prevent forest conversion (e.g., through the Sustainable Forest Incentive Act). Nonprofits can also provide incentives to landowners and link landowners to public technical and financial assistance opportunities. Updated estimates of landowner opportunity costs for retaining and investing in forests will help government and nonprofit entities design effective, targeted assistance programs.
2. **Increase the impact of forest land acquisition tools and easement programs**: Acquiring private forest land—through direct acquisition or conservation easements—can reduce forest fragmentation and conversion. Governments and nonprofits use land asset management strategies—including purchase, land exchange, and strategic divestment—to protect significant natural resources, create recreational opportunities, and consolidate land ownership. These land acquisition programs must be nimble in a fast-moving and competitive real estate market. Expanding the impact of conservation easement programs is another strategy for retaining forest cover. These programs allow private forest owners to enter into voluntary agreements that restrict converting their forest to non-forest uses. Easements may be purchased by qualified government agencies or nonprofits or donated by landowners to these entities. Ingredients for successful land acquisition and conservation easement programs include strong partnerships and a commitment to streamlining administrative processes for acquiring forestland.
3. **Incentivize forest retention by strengthening markets for sustainably managed forest products**: Forests can generate long-term revenues from timber harvest (Lubowski et al., 2008). Revenues incentivize landowners to keep forest as forest and generate other forest benefits such as scenic beauty, creating wildlife habitat, and protecting nature (Butler et al., 2021). Weak markets for forest products (such as building materials, paper, and fiber) reduce the economic value of forests and can lead to

[3] In recent decades, divestment in Minnesota's private industrial forest lands raised concerns about forest fragmentation and conversion of forests to other land uses. This concern is lower today as most of these holdings have already been sold or are being intentionally retained through nonprofit and public land conservation programs.

divestment and conversion to non-forest uses. In contrast, strong markets encourage investment in forests, which reduces the risk of conversion. Strong markets also stimulate active management of forests for multiple benefits. While generally less lucrative, some landowners harvest and sell non-timber products such as maple syrup or decorative materials.

4. **Discourage fragmentation of private forests**: Land use planning and zoning regulations can discourage fragmenting large forest lands into smaller parcels (Friesen, 2020). However, these tools may face obstacles at the local and regional level and have economic tradeoffs (Minnesota Forest Resources Council, 2010). Local policies that discourage the breaking up of large contiguous private forest parcels will help avoid conversion of these forests to other uses.

Expanding the impact of technical and financial landowner assistance programs will likely require increasing the amount and stability of funding to provide outreach, educate landowners, and administer resources using a targeted approach to meet individual landowner needs.

More direct mechanisms, such as conservation easements or targeted fee title acquisition offer more certainty that forests are retained as forests over the long term. However, they may take longer to implement and cost more per acre compared to providing technical or financial assistance to landowners. Taking a coordinated approach that recognizes this tradeoff, while using the right tool for the right job, would improve efficiency.

There are no timely and rigorous studies identifying low-cost and high-impact opportunities to retain forest cover in Minnesota. This knowledge would inform the strategic implementation of mechanisms like landowner technical assistance and financial incentives programs, conservation easements, and fee-title acquisitions.

It is not feasible to eliminate all forest conversion, which would create tradeoffs with other important needs and values. In certain circumstances, the social, economic, or environmental value of converting forests to residential or industrial properties, croplands, or other uses outweighs the climate mitigation and traditional benefits of retaining forests.

Retaining forest cover could annually sequester up to 4% more carbon

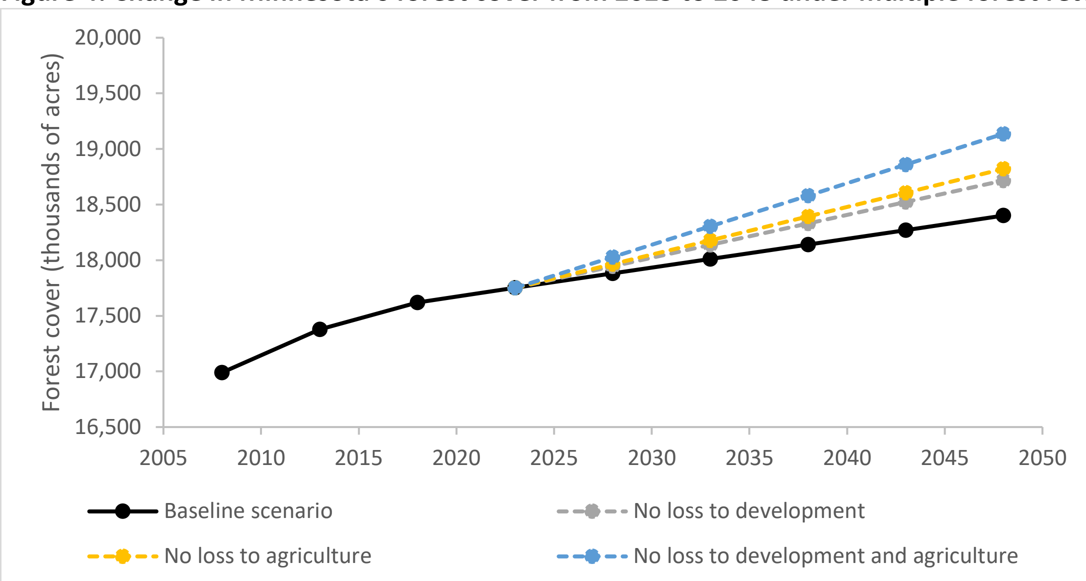
The mitigation potential of this pathway—an estimate of how much additional carbon could be sequestered in forests each year by enhancing efforts to retain forest cover—depends largely on the rate of forest conversion to other uses. In general, the slower the rate of forest conversion, the greater the potential to mitigate climate change over time. The following three avoided conversion scenarios could net sequester between 2% to 4% more carbon dioxide compared to the baseline scenario (Figure 4):

- <u>"No loss" to development</u>: This illustrates a scenario in which conversion of forests to development does not occur from 2023 to 2048. This scenario would result in avoided conversion of 12,600 acres of forest per year, which translates to 1.7% more annual net carbon sequestration in 2048 compared to the baseline scenario.
- <u>"No loss" to agriculture</u>: This illustrates a scenario in which conversion of forests to agriculture does not occur from 2023 to 2048. This scenario would result in avoided conversion of 16,800 acres of

forest per year, which translates to 2.3% more annual net carbon sequestration in 2048 compared to the baselines scenario.

- “No loss” to development and agriculture: This illustrates a scenario in which no forests are converted to development or agriculture from 2023 to 2048. This scenario would result in avoided conversion of 29,400 acres per year—generating a 4.0% increase in annual net carbon sequestration in 2048 compared to the baseline scenario. While it is doubtful that total avoidance of forest conversion to agriculture and development is politically, socially, or economically feasible, this scenario illustrates the upper limits of the climate mitigation potential for retaining forest cover.

Figure 4: Change in Minnesota’s forest cover from 2023 to 2048 under multiple forest retention scenarios



SOURCE: Author’s calculations based on current rates of forest gain and loss in Hillard et al. (2022).
NOTES: See Appendix 1 for additional discussion and summary table.

Discussion of economic factors

As previously mentioned, the owners of small family forests often encounter technical and financial barriers to managing their lands in an economically viable way. Surveys suggest that these owners retain and manage their forests for many reasons, foremost among those being for scenic beauty, wildlife habitat and protecting nature (Butler et al., 2021). Using forests to generate revenue tends to fall lower as a stated motivation for ownership. However, the costs of owning and managing forests—in addition to the potential economic value of converting forest to another non-forest land use—underly decision-making regardless of size or ownership type.

The risk that forests will be converted to other non-forest uses increases when the economic value of forests declines due to weak markets for wood products, technical barriers, or financial constraints. The risk is especially high when forest landowners also have opportunities to capture more economic value by changing their land use or selling their land to be developed into another use.

One of the primary drivers of opportunity cost in Minnesota is proximity to existing development. Minnesota’s urban footprint is growing—heightening the risk of forest conversion (Hillard et al., 2022). The economic return from converting forests to housing, commercial and industrial uses, and infrastructure increases as development encroaches. In other parts of the state, agricultural crop commodity prices and the distance to nearby mills and plants can influence decisions to convert forests to agricultural uses.

Cost-sharing, long-term incentives, and tax incentives can provide forest owners with enough additional economic value to make retaining forests more attractive. Additional analysis into the economic dimensions of forest ownership in Minnesota—especially opportunity costs—will improve the delivery and impact of these programs. This type of land use conversion modeling is common in predicting agricultural cropping decisions and has also been applied to understand reforestation potential in Minnesota (Turner et al., 2010).

Retain forest cover: connection with other forest benefits

Retaining forest cover by preventing conversion of forest to other uses is a long-standing practice for enhancing the social, conservation, and economic benefits forest provide. Preventing the fragmentation and conversion of forests ensures that forests will continue to generate these benefits over the long term. In addition to climate mitigation benefits, avoiding forest conversion promotes a wide range of ecosystem services including the provision of food and fiber to the regulation of climate and water. Overall, retaining forest cover does not result in major tradeoffs between forest benefits.

For many years, government entities and nonprofit organizations have focused their efforts on retaining larger and contiguous forests tracts. Larger tracts of forest have the capacity to generate a more robust portfolio of benefits compared to highly fragmented forests. This approach is a core feature of DNR's Strategic Land Asset Management program.

Barriers, constraints, and challenges to retaining forest cover

Although retaining forest cover is often viewed as "low hanging fruit" compared to other climate mitigation pathways, it can be challenging in practice. Many of the sustainable forestry strategies that promote retaining forest cover will encounter the following barriers, constraints, and challenges:

- **Family forest owners are diffuse and many are absentee.** Expanding the impact of public and nonprofit landowner assistance programs is challenged by the fact that family forest owners are not highly concentrated and cover a wide swath of the state. In addition, about half of family forest owners live more than one mile from their holding (also known as "absentee" owners).
- **Every parcel is unique.** The cost of retaining forest cover varies parcel-to-parcel based on landowner motivations and opportunity costs. Costs may be relatively low when landowners are personally motivated to retain forests or if opportunity costs are low. Costs can be much higher when landowners are not motivated and have higher opportunity costs. These factors will heavily influence the overall cost of property acquisition or conservation easement purchase.
- **Local buy-in is important for public land acquisition**. Local support is important for acquiring additional public lands, and it varies across the state. Some counties are concerned that public land acquisition may impact local property tax revenues or economic development potential, while others view

additional public lands as a helpful community asset. In all cases, DNR strives to work with local communities to develop public land acquisition strategies that meet both state and local goals.

- **Opportunity costs are tied to a global economy**. Economic factors that drive the decision to retain forests are difficult for government entities or nonprofits to directly influence. Market values for forest products, crops, forage, or real estate that determine the monetary value of keeping forests as forests are subject to regional and global economic forces.

Additional analysis to enhance delivery of benefits from retaining forest cover

Retaining forest cover is a "shovel ready" climate mitigation pathway that can be acted on now. However, taking steps to better understand where forests are at high risk of conversion and what factors are driving forest conversion in different parts of the state will enhance the impact of those actions. The following list of additional analyses will help direct a more effective and efficient approach to implementation:

- Quantifying the potential number of additional acres of forest that could be retained by enhancing investments in landowner assistance, conservation easements, and fee-title acquisition programs
- Estimating the number of acres of forest retained each year due to earned income from forest products
- Identifying existing or needed economic modeling tools that target low-cost and high-impact opportunities to retain forests through financial or technical assistance
- Evaluating opportunities to aggregate multiple family forest landowners into larger management areas and lower the per-acre cost of management
- Exploring the potential role of carbon markets in retaining forest cover

Pathway 2: Increase forest cover

Increasing forest cover by establishing new forests on previously forested (but currently unforested) lands is a core pathway for enhancing climate mitigation benefits (Griscom et al., 2017; Grassi et al., 2017). This pathway increases forest carbon stocks while providing long-term carbon sequestration benefits (Hodgman et al., 2012). Minnesota's current forest area of 17.6 million acres is just over half of pre-European forest cover, which was estimated at 31.5 million acres (Marschner, 1930). Many previously forested areas that were initially cleared for agriculture remain unforested and no longer support primary agricultural production. While it is not possible or desirable to restore all previous forest cover, many of these areas have potential for reforestation.

Recent analysis of Forest Inventory and Analysis (FIA) data in Hillard et al. (2022) provide several insights on changes in Minnesota's forest cover over time. In general, forest cover has increased around 7% since the late 1970s. An average of 86,000 acres of new forest are added each year, including both naturally seeded/regenerated and intentionally planted forests. Between 1990 and 2020, forest gain absorbed on average 1 million U.S. tons of carbon (3.7 million U.S. tons of CO_{2e}) per year (Walters et al., 2022). As previously described, forest gain outpaces forest loss and creates a net increase in forest cover of around 26,000 acres per year. Overall, the exchange of forest to and from other uses sequestered on average 0.3 million U.S. tons of net new carbon (1.1 million U.S. tons of CO_{2e}) per year between 1990 and 2020.

Most of the net increase in forest cover is the result of natural processes (e.g., tree cover fluctuations on wetlands) or unintentional side-effects of human land use decisions (e.g., wildfire suppression, agricultural land abandonment) rather than intentional tree planting. The amount of new forest created by intentionally planting seedlings on non-forested lands is likely a very small portion of overall annual forest gain; however, this is a critical research gap. Estimates based on the average number of seedlings planted in Minnesota from 2016 to 2020 suggest that around 1,400 acres of new forest are created each year by intentional forest planting.[4]

Over the last several decades, policymakers and forestry stakeholders proposed increasing the amount of tree planting to expand forest cover in Minnesota. In 2009, the Minnesota Climate Change Advisory Group proposed planting one million acres of new forest to mitigate GHG emissions (Minnesota Climate Change Advisory Group, 2008). In response to this proposal, several organizations developed estimates of the total in-state reforestation potential (non-forested acres on which new forests can feasibly be planted and maintained) based on a mixture of factors including site suitability, cost, and benefits.

A study commissioned by the Minnesota Forest Resources Council identified 7.6 million acres of non-forested lands with reforestation potential based on soil characteristics and assessment of historical forest cover (Turner et al., 2010). This study excluded lands that were native prairies prior to European settlement. Nearly all of the acres identified in this study were privately-owned croplands, grasslands, or pastures. A similar study in 2010 by Dovetail Partners, Inc. identified 5.4 million acres of reforestation potential (Stai et al., 2010). This study excludes a portion of formerly forested grasslands with high value to vulnerable grassland wildlife species. A more recent study by The Nature Conservancy identified 3.6 million acres of reforestation potential (Cook-Patton et al., 2021). Nearly 90% of acres identified by the study are located on private lands including pasture, floodplains, marginal cropland, and urban open spaces. Importantly, all three studies excluded primary croplands from the estimate of overall in-state reforestation potential to avoid tradeoffs with food security.

Mitigation Goal: Facilitate and encourage tree planting where ecologically appropriate

Minnesota should facilitate and encourage more tree planting, which will sequester and store more carbon while enhancing the portfolio of other benefits forests provide. There is ample opportunity for tree planting on formerly forested open lands where establishing new forests is ecologically appropriate. According to existing studies, most of this opportunity in Minnesota is on privately-owned opens lands not currently in forest use (Stai et al., 2010; Cook-Patton et al., 2021). Unlike retaining forest cover, the climate mitigation benefits of tree planting are not immediate and occur well after trees are initially planted. Climate mitigation efforts must account for this lag between implementation and maximum carbon sequestration benefit.

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[4] A recent survey of government entities and nonprofit organizations engaged in planting seedlings in Minnesota found that an average of 7.6 million seedlings are planted each year across the state (personal comm. Ashlee Lehner, Director of Forest Policy, Minnesota Forest Resources Council, 10/3/22). Assuming that seedlings are planted at an average density of 550 per acre and that 10 percent of acres planted each year are new forest acres results in the 1,400 acres/year estimate.

Sustainable forestry strategies for accelerating tree planting

Tree planting has long been a core component of sustainable forest management practices in Minnesota. However, the current rate of intentional tree planting for increasing forest cover is low. Targeted investments and policies that address key barriers to tree planting and enhance existing tools will result in meaningful increases in tree planting activity. The following list of high-priority sustainable forestry strategies provides a blueprint for achieving the overall goal of accelerating tree planting in Minnesota:

1. **Increase in-state seedling production to support higher rates of tree planting:** Expanding in-state seedling production will be a heavy lift that requires new investments in the seedling production supply chain and partnerships between public entities, Tribal governments, private businesses, and nonprofit organizations. Increasing investment in DNR's seedling production supply chain, such as procuring seeds and cones, improving state nursery buildings and equipment, expanding beyond current seedbeds, and allowing the State Forest Nursery to produce containerized seedlings will augment annual seedling production. In addition, supporting private investments in private nurseries and partnering with Tribal governments will boost seedling production while providing opportunities for local economic development. Nonprofit organizations play a key role by facilitating strong partnerships and directing technical and financial resources to where they are most needed.
2. **Expand private landowner access to financial and technical assistance for tree planting:** Upfront costs for purchasing and planting new trees on private lands can be a barrier to action. Increasing the availability of state, federal, and nonprofit funding for sharing these upfront costs will encourage more tree planting. Increased access to professional forestry advice and services can also help empower landowners to plant and manage trees sustainably. Public incentive programs play a major role in sharing the cost of tree planting, maintenance, and management with private landowners, including:
    - Conservation Reserve Program (federal)
    - Environmental Quality Incentives Program (federal)
    - Cost-share programs (Minnesota DNR and Soil and Water Conservation Districts)

   These programs vary by eligible practices and payment structure (Stai et al., 2010). Funding for programs is tied to the legislative budget process and can vary year to year depending on policy priorities. Staff to develop and assist with projects are also critical to putting incentive funds to work.
3. **Invest in protecting and expanding urban and community forests:** Urban and community landscapes offer an opportunity to expand tree planting. Though these areas represent a relatively small percentage of the acres available for reforestation, trees in residential areas sequester and store carbon and provide many additional social and economic benefits. Maintaining these benefits also requires ongoing efforts to protect ash trees from the invasive emerald ash borer (EAB) insect and planting diverse species to efficiently replace current and expected mortality due to the pest. The Minnesota Environmental Quality Board estimates that $8.5 million is needed annually to provide community grants to address planning and other technical assistance needs (Minnesota Environmental Quality Board, 2019).
4. **Develop a trained workforce for accelerating tree planting:** Meeting expected increases in demand for seedlings and tree planting activities will require a larger trained workforce that can collect more seeds and grow and plant more seedlings. Putting Minnesotans to work in these reforestation efforts could generate local jobs while increasing forests' ability to sequester and store more carbon.

5. **Identify synergies between tree planting and agricultural practices:** Productive agricultural lands can also benefit from strategically planted trees. For example, trees can provide wind breaks that protect agricultural crops from wind damage and shelter livestock. Integrating livestock and forest management through forested pastures (silvopasture) can create additional value for agricultural landowners.

Growing the right tree in the right location is an essential part of implementing these strategies successfully. Using locally appropriate seed and plant mixes in tree planting efforts ensures that new forests will thrive. There are also opportunities to promote climate adaptation through tree planting. For example, planting species that are projected to do well under changing climate conditions reduces the risk of major disturbance or loss in the future. These climate adaptation concepts should inform how seeds are collected, which species to grow in nurseries, and where seedlings are ultimately planted.[5]

In certain circumstances, re-establishing forest cover can conflict with efforts to promote grassland biodiversity values. Stai et al. (2010) note that the presence of trees in grasslands (or in the surrounding landscape) may have deleterious effects on nesting birds. More work is needed to define where tree planting is appropriate drawing from knowledge of where forest cover occurred historically and where planting trees conflicts with important grassland conservation values. From a carbon perspective, converting carbon-rich grasslands to forests may sequester less carbon than reforesting degraded agricultural lands (Franklin et al., 2018).

Increasing the rate of tree planting could sequester up to 5% more carbon

Increasing the rate of tree planting to establish forests on non-forested lands could result in an estimated <1% to 5% increase in annual net forest carbon sequestration in 2048 depending on the rate of tree planting. These estimates are based on a set of scenarios reflecting higher levels of tree planting from 2023 to 2048 (Figure 5). As additional acres of forests are planted, the overall footprint of Minnesota's forests expands. The larger the footprint, the more carbon dioxide forests can absorb and store. Smaller increases in the rate of tree planting results in lower mitigation potential in 2048 compared to larger increases.

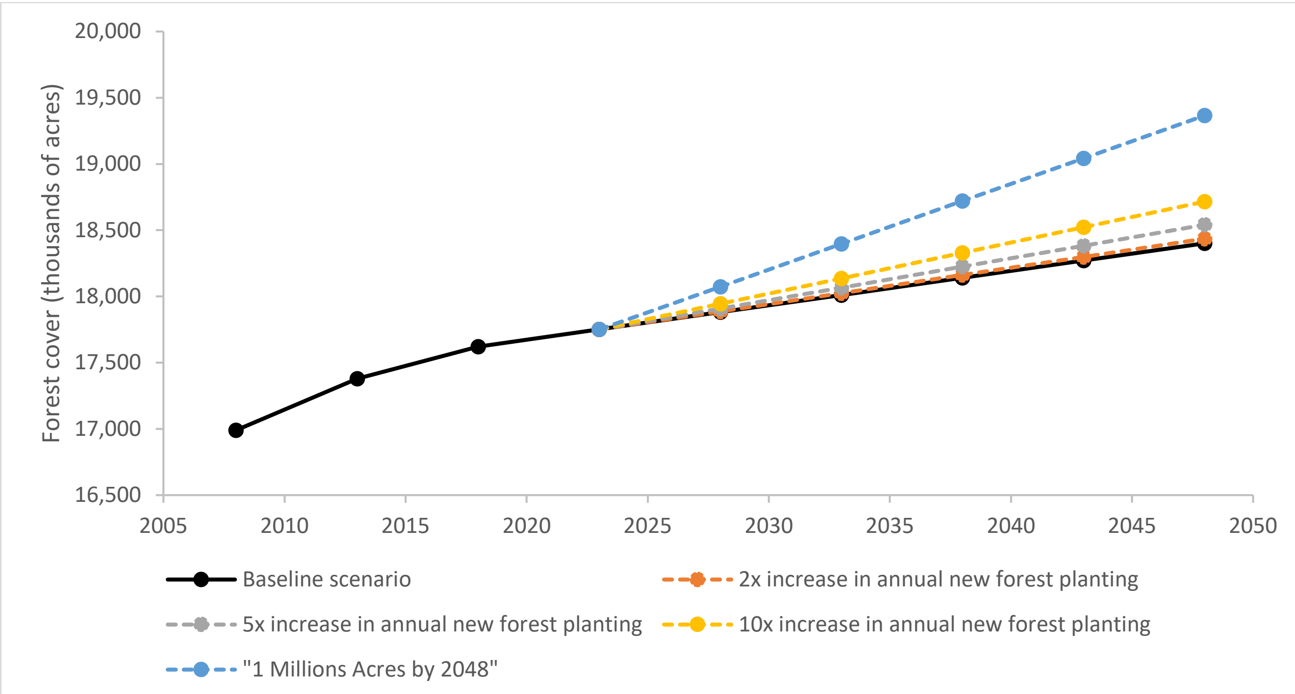
Doubling the annual rate of tree planting to 2,800 acres per year from 2023 to 2048 would result in a 0.19% increase in annual net sequestration in 2048 compared to the baseline scenario. A fivefold increase in the annual rate of tree planting (7,000 acres per year) from 2023 to 2048 would result in a 0.76% increase in annual net sequestration in 2048. A ten-fold increase in the annual rate of planting (14,000 per year) from 2023 to 2048 would result in a 1.71% increase in annual net sequestration in 2048.

The scenario "1 Million Acres by 2048" is the upper-bound scenario reflecting the ambitious proposal by The Nature Conservancy to reforest one million acres of historically forested area. To reach this goal over a 25-year timeframe, the annual rate of tree planting would need to reach 40,000 acres per year, a roughly 30-fold increase in the estimated current rate. In 2048, this scenario results in an estimated 5.24% increase in annual

[5] Tree planting can also result in negative feedbacks on climate mitigation. For example, conifer trees absorb more sunlight in winter than deciduous trees, which may exacerbate warming in far northern climates and dilute the carbon sequestration benefits of tree planting (Friesen, 2020).

net sequestration compared to a baseline scenario. Increasing the rate of tree planting to this level would be very challenging. Nevertheless, this estimate provides a sense of the upper limits of climate mitigation potential within this pathway.

Figure 5: Change in Minnesota's forest cover with accelerated tree planting from 2023 to 2048



SOURCE: Author's calculations using Hillard et al. (2022) (rate of forest gain and loss); see footnote 4 for description of sources for estimating annual rate of new forest planting statewide.
NOTES: See Appendix 2 for additional discussion and summary table.

Discussion of economic factors

Newly planted forests require many years to grow before income can be generated from their harvest. Landowners often face several competing opportunities on how to use their land, some producing greater near-term revenues compared to newly planted forests. Forest landowner surveys suggest that financial return ranks lower than access to scenic beauty and wildlife conservation as reasons for forest ownership (Butler et al., 2021). However, economic factors still play a strong role in the decisions that landowners make about their lands. Therefore, landowners and policymakers must consider both the costs and revenues of reforestation. This can be evaluated in terms of (1) the cost to plant and maintain new forest and (2) the cost to incentivize more landowners to convert to forest.

The costs to plant and maintain new forest is described by Turner et al. (2010). Reforestation costs include site preparation, seedling production and planting, and controlling competing vegetation. The overall cost of reforestation in 2010 ranged from $765 per acre for conifers to $875 per acre for hardwoods (in 2021 adjusted USD) (Turner et al., 2010) (Table 2). The overall cost today is estimated to have increased since 2010 (personal communication, Mike Reinikainen, DNR Silviculture Program Coordinator, 10/31/22). Recent increases in fuel costs and economy-wide inflation are also likely to increase reforestation costs for the near future.

Table 2: Reforestation costs in 2010 by tree species (adapted from Turner et al., 2010; in 2021 adjusted USD)

Activity	Hardwoods ($ per acre)	Conifers ($ per acre)
Site preparation	$121	$121
Seedlings	$307	$197
Planting	$254	$254
Control of competing vegetation	$193	$193
Total Cost	$875	$765

SOURCE: Turner et al. 2010 (estimates of reforestation activity costs), adjusted for inflation using U.S. Bureau of Labor Statistics CPI Inflation Calculator.

In addition to the upfront costs of tree planting, landowners also consider the long-term economic returns of converting to forests (Lubowski et al., 2008). When net returns (payments – costs) from planting and maintaining forests are greater than the returns from existing uses (e.g., crops, pasture, grasses), economic reasoning suggests that landowners will establish forest cover in lieu of existing uses. Given the fact that forests take many years to mature, the net returns from converting to forests are not always economical in the near term. Public policy tools such as incentive payments, tax relief, and market stimulus that enhance returns from forests can be used to further encourage more landowners to convert from existing uses.

Turner et al. (2010) developed an economic model specific to Minnesota for understanding the long-term economic returns of converting to forests from non-forest uses. The model estimates how many acres of non-forested lands landowners might hypothetically convert to forests in response to market conditions or policies that increase economic returns from forests.

One of the key outputs of Turner et al. (2010) is a mathematical expression predicting the amount of newly forested acres as a function of total annual payments to landowners. This model suggests that total annual payments of $138 per acre (in 2021 adjusted USD) could make tree planting economically feasible on 1 million acres of non-forested land. Lower annual payments would make tree planting economically feasible on fewer acres. For example, the model predicted that annual payments of $36 per acre (in 2021 adjusted USD) could make tree planting economically feasible on 34,000 acres of non-forested land.

Agricultural and forest product commodity prices modeled by Turner et al. (2010) have mostly decreased since 2010, which puts downward pressure on returns to both agricultural and forest landowners (University of Minnesota Extension, 2021; Minnesota Department of Natural Resources, 2021). However, production costs for agriculture have also decreased, while reforestation costs have increased.[6] Though more in-depth study is needed, these trends suggest that larger payments may be needed to induce the same amount of reforestation now than in 2010.

An update to Turner et al. (2010) based on current land uses, input costs, and commodity values compared to expected long-term gains would provide valuable information for designing effective reforestation incentives. This methodology could be expanded to consider landowner demographics and trends in tenure. Additional analysis will also help government agencies and policymakers estimate potential increases in tree planting on private lands according to different levels of investment in existing incentive programs (e.g., Conservation Reserve Program, Environmental Quality Incentives Program, state cost-share).

Increase forest cover: connection with other forest benefits

Increasing the rate of tree planting can maintain or increase forest benefits while enhancing the strength of the forest carbon sink. Expanding the footprint of forest cover can increase a wide range of benefits including timber production, wildlife habitat, water quality, flood control, air quality, and soil conservation (Stai et al., 2010; Cook-Patton et al., 2021). The scope and magnitude of benefits generated by reforestation depends heavily on where and which species are planted. It is important to consider ecological conditions during reforestation planning including matching forest types to local soils, hydrology, and climate to ensure that the right trees are planted in the right places.

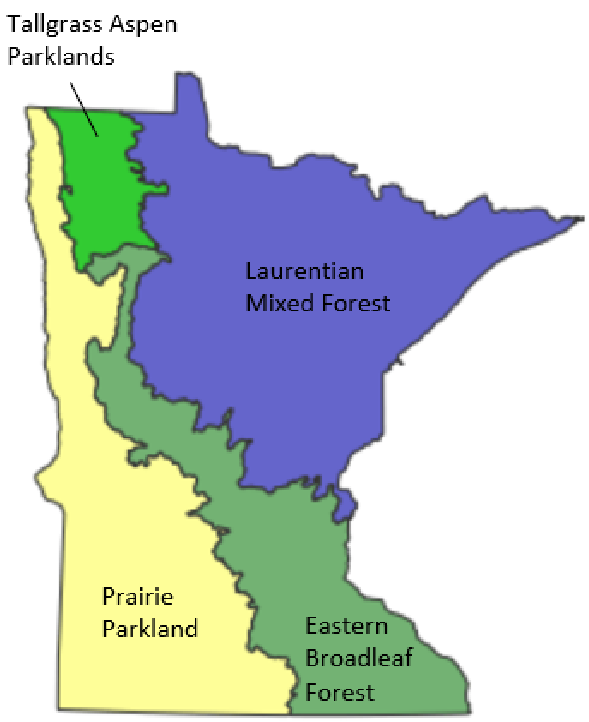
Not all areas are conducive for planting trees and careful planning is required when there is potential for conflicting values. Stai et al. (2010) investigated the potential wildlife benefits of reforestation in Minnesota. The study found that expanding forest cover in the heavily forested northeastern part of the state (the Laurentian Mixed Forest province) would likely generate wildlife benefits with few tradeoffs with other ecological values (Figure 6). Potential tradeoffs with prairie and grassland conservation values may occur in the prairie-forest transition zone where the Laurentian Mixed Forest and Eastern Broadleaf Forest provinces meet the Prairie Parkland region. Stai et al. (2010) found that tree planting in this transition zone would generate the most wildlife benefits when it complements the balance of other land types in the region such as savannas, shrublands, prairies, and grasslands.

Increasing forest cover on formerly forested open lands also enhances water quality, soil conservation, and flood control. As Stai et al. (2010) highlights, forests reduce sediment loss and keep pollutants and nutrients from reaching waterways. Forests also play an important role in absorption and regulation of water flow. Strategically planting forests along waterways can maximize this ecosystem service. Restoring forest cover in floodplains enhances the ability to store and convey flood water, which is increasingly important with heavier

[6] Personal communication, Mike Reinikainen, DNR Silviculture Program Coordinator, 1/28/22. Rising fuel prices and economy-wide inflation are likely putting upward pressure on both agricultural production and reforestation costs.

rainfall events expected in Minnesota's changing climate. Cook-Patton et al. (2021) identified nearly 200,000 acres of streamside land and over 500,000 acres of floodplain in Minnesota with high reforestation potential.

Figure 6: Ecological provinces of Minnesota



SOURCE: MNDNR, 2020 Ecological Classification System.

Increased tree planting has complex effects on the forest products sector. In the long term, more forest cover would increase the available wood supply and the amount of potential timber for harvest. This depends on alignment between the species of trees planted, the availability of that wood in the future, and markets for wood products. There is lag between when new forests are planted and when they are economically viable for harvest. In general, forests in Minnesota become merchantable after they exceed at least 40 years of age (Stai et al., 2010). Opportunities to harvest at even younger ages (e.g., to produce biofuels) or from treatments that occur before final harvest (e.g., forest thinning) could create value from younger forests.

Increasing forest cover also creates more opportunities for outdoor forest-based recreation—an important component of Minnesotans' health and wellbeing. Forests support a wide range of recreational activities including hiking, biking, hunting, camping, and foraging. Forest-based recreational activities can attract tourism that brings additional economic value to rural communities.

Barriers, constraints, and challenges to increasing forest cover

Reforestation has wide public appeal and presents fewer tradeoffs between climate mitigation and forest benefits compared to other forest-based climate mitigation pathways. However, barriers to implementing this goal and creating meaningful climate mitigation benefits include:

- **Low in-state seed and seedling supply**. In 2010, Turner et al. (2010) estimated that public and private nurseries had capacity to produce 22 million seedlings per year, which could support the planting of approximately 23,000 acres per year.[7] Over the last decade, total annual seedling production in Minnesota declined from nearly 15 million seedlings in 2012 to an estimated nearly 3 million seedlings in 2019 (Haase et al., 2021).[8] Contributing to this decline were the closure of two large private nurseries and one of two state forest tree nurseries, General Andrews State Forest Nursery. The state legislature provided funds in fiscal years 2022-2023 to increase seedling production at the State Forest Nursery in Badoura. Additional funding for procuring greater quantities of seeds, updating aging buildings and facilities, and developing a trained workforce is critical to sustained increases in seedling production. Strong partnerships between public entities, Tribal governments, private businesses, and nonprofit organizations will further enhance the state's seedling production supply chain while creating opportunities for local economic development.
- **Program funding variability**. Publicly funded programs that help private, local government, and Tribal landowners plant new forests are tied to variable legislative funding cycles and priorities. Uncertainty in the funding available for these programs—both direct funding and staff time to assist landowners to develop and carry out reforestation projects—can erode the efficiency and effectiveness of program delivery. Private funding from nonprofits can help fill gaps where appropriate.
- **Variable landowner opportunity costs**. Financial incentives to convert formerly forested open lands to forests must compete with potential economic value from other land uses. Factors driving opportunity cost include agricultural land value, crop commodity prices, agricultural production incentives, and value of residential or commercial development. Nimble and flexible incentive policies are needed to compete with these dynamic cost drivers.

Additional analysis for a targeted approach to increasing forest cover

Increasing forest cover through tree planting is an actionable pathway that can be implemented today. There are several components that need to be aligned in order to accelerate tree planting, including seeding

[7] Turner et al. (2010) estimated seedling production capacity in 2010 as 12 million seedlings per year from private nurseries plus 10 million seedlings per year from DNR Forestry's nurseries. The study found that 22 million seedlings planted at 950 seedlings per acre would result in around 23,000 acres of tree planting.

[8] Estimates of seedling production exclude Canadian imports—although imports can be a significant portion of seedlings planted in some years. Data on seedling production is collected in an annual voluntary survey of major nurseries in the United States conducted by USDA Forest Service in conjunction with academic collaborators (Haase et al., 2021).

production, technical and financial incentives for landowners, and an adequate workforce. Analytical efforts on the following topics can enhance the impact of this pathway:

- Quantifying the potential number of newly planted forest acres due to increasing resources for programs/policies that incentivize tree planting
- Identifying the role of both the private and public sectors in this effort and opportunities to maximize the contributions of both
- Identifying the prospects for increasing seedling production and policy changes needed to increase in-state public and private seedling production
- Assessing the relative influence of various drivers (e.g., seedling production, availability of landowner incentives) on the rate of tree planting
- Identifying where tree planting should take place in order to generate the greatest benefit at the lowest cost, and considering ecological appropriateness of available sites (e.g., historic land cover, expected climate changes)

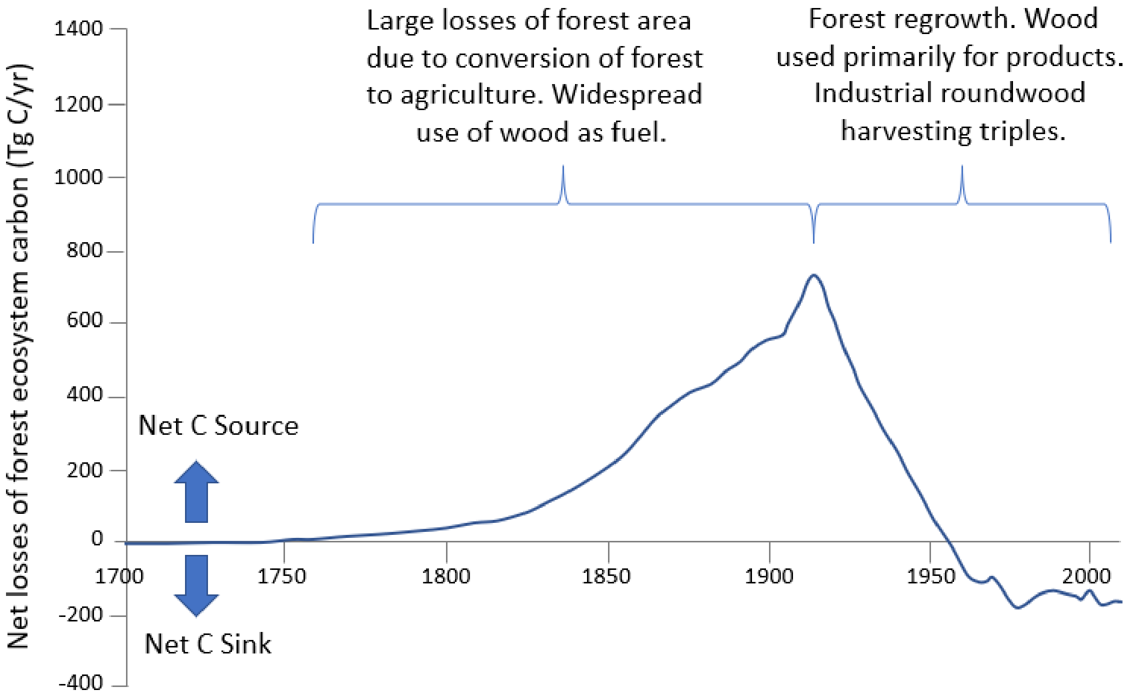
Pathway 3: Manage working forests to sequester and store more carbon

Working forests are forests that are actively managed with sustainable timber harvesting practices to produce a wide range of social, economic, and environmental benefits. One of the first things people tend to think of when the discussion turns to forest management and climate mitigation is the effects of timber harvest. Active management practices such as harvesting at sustainable levels, regenerating forests after harvest, maintaining forest health, increasing the vigor of existing trees, and minimizing harvest damages are essential to maintaining and bolstering the overall forest carbon sink (Kaarakka et al., 2021; Miner et al., 2014; Lippke et al., 2011).

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change states that long-term sustainable forest management that balances in-forest carbon storage and sustained yield of forest products will generate the greatest long-term climate mitigation benefit (Nabuurs et al., 2007). This is achieved by managing forests to maintain a mixture of forest ages and species at the landscape scale—a guiding approach for many forest managers in Minnesota.

The long-term trend in forest ecosystem carbon in the United States demonstrates the synergy between sustainably managed forests and climate mitigation (Figure 7). Major forest clearing for agriculture and unsustainable forest management practices throughout the 19th century resulted in large loss of forest area, making U.S. forests a net source of emissions. After the turn of the 20th century, forest regrowth and sustainable timber harvesting practices reversed this trend. During this time, forests transitioned to becoming a carbon sink while industrial timber harvesting activity tripled (Miner et al., 2014).

Figure 7: Forest regrowth and sustainable management contribute to the U.S. forest carbon sink



SOURCE: Miner et al., 2014.
NOTES: The analysis presented in this graph does not account for carbon stored in wood product carbon pools nor substitution benefits. One teragram (Tg) of C represents 1.1 million U.S. tons of C.

The influence of timber harvest on forest carbon stocks depends on spatial and temporal perspective (Bowyer et al., 2012; Janowiak et al., 2017). At the stand level, harvesting initially reduces carbon stored in forests while redistributing a portion of this carbon into wood products. Following harvest, forest carbon stocks rebound through natural regeneration or replanting of trees; carbon storage increases rapidly in the early stages of re-growth and slows down as the forest ages. This process restarts when timber is harvested again. While timber harvest certainly has an effect on carbon at the stand level over the short term, at the larger landscape scale and over a longer timeframe, carbon stocks in sustainably harvested forests are very stable (Figure 8).

Considering the urgent need to decrease global emissions in the next few decades, forest managers are evaluating opportunities to sequester and store more carbon *beyond* current baseline levels while also maintaining and enhancing other ecosystem services. These opportunities should be part of a sustainable forest management approach, while considering that:

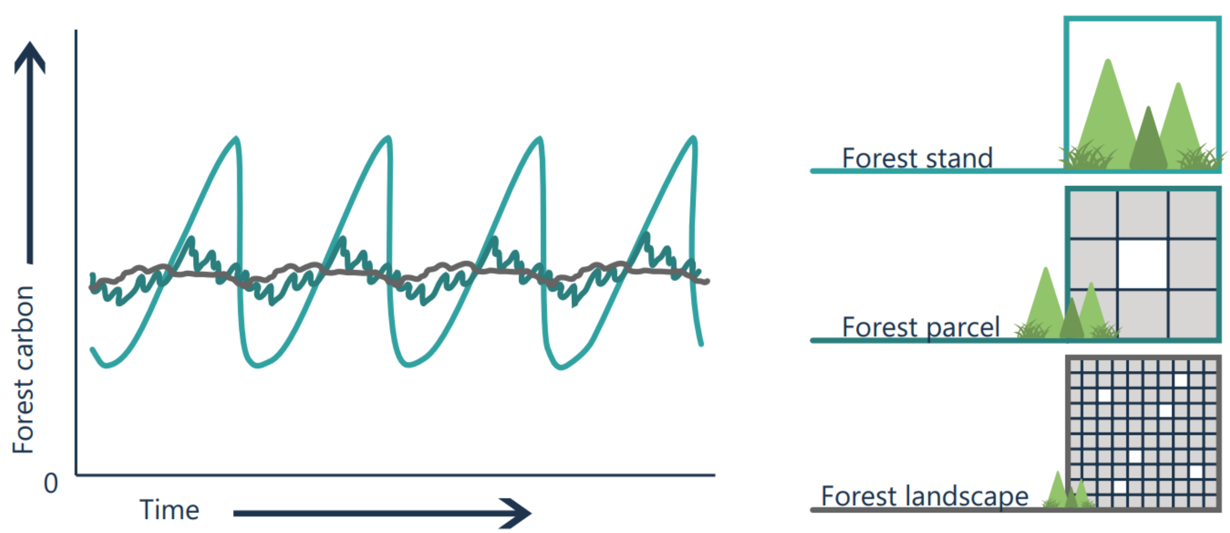
- **Carbon alone does not determine how forests are managed.** To be sustainable, forest management must provide wildlife habitat, healthy watersheds, forest products, and (on public lands) outdoor recreation. Managing forests for a single outcome can lead to the marginalization or loss of other ecosystem services (Franklin et al., 2018). Climate mitigation is one of several benefits that must be considered in efforts to balance these benefits at scale.
- **There are no "one-size-fits-all" carbon sequestration approaches for managing working forests.** Not all approaches described here are applicable to all forests in all circumstances. Each forest carbon strategy

must be evaluated in light of forest type, age, site productivity, management history, and market conditions (Nabuurs et al., 2007).

- **The impacts of management need to be evaluated at landscape scale and over long periods of time**. The impacts of forest management on carbon are difficult to discern when viewed at small spatial scales (e.g., forest stand or parcel) and short time horizons. This narrow perspective obscures the stability of forest carbon at the landscape scale. A broader perspective allows for a wider range of options.
- **Applying a systems-level approach enables more ways to enhance carbon sequestration and storage**. This includes accounting for the carbon implications of management decisions on both the forest ecosystem and harvested wood products, including the substitution benefits of using wood products in place of GHG-intensive materials and fuels (Nabuurs et al., 2007; Dugan et al., 2018; U.S. Department of Agriculture Forest Service, 2018).

The subsection that follows describes approaches to managing working forests to sequester and store more carbon. These approaches are part of an emerging body of technical and scientific knowledge. The forest carbon cycle—and changes in the cycle from timber harvesting and other management activities—is at the core of this exploratory work. As such, taking the next step from concept to planning and implementation requires engaging professional forestry expertise and using quantitative models. Models may be used to evaluate the climate mitigation benefits of specific practices and reduce unintended consequences. Professional forestry experts must set parameters and interpret results from these modeling exercises. These actions will help address critical information gaps related to managing working forests to sequester and store more carbon.

Figure 8: Carbon stocks in working forests are stable over time when viewed at the landscape scale



SOURCE: Janowiak et al. 2017.
NOTES: Adapted from Bowyer et al. 2012 and McKinley et al. 2011.

Managing working forests for carbon sequestration and storage: two approaches

The range of options within this pathway fall into two categories:

1. **Promote in-forest carbon storage:** Manage forests to maintain or increase the amount of carbon stored within forests (trees, soils, etc.).
2. **Promote off-forest carbon storage and substitution:** Manage forests to maintain or increase the amount of carbon stored in forest products. Enhance consumer use of forest products including those that substitute for other materials that emit more GHGs.

The following subsections describe how each approach mitigates climate change and highlights associated tradeoffs, differences, common ground, and unknowns. While neither approach can be fully maximized without reducing the mitigation potential of the other, these approaches are not mutually exclusive, especially at a landscape scale. Importantly, each approach focuses on climate mitigation opportunities in working forests where timber harvesting is the primary tool for sustainable forest management.

Approach 1: Promote in-forest carbon storage

As noted in Section 1 of this report, forest carbon stocks are the sum of carbon stored in live trees, organic soils, understory, forest floor, standing dead wood, and dead downed wood at a single point in time. Live trees and soils contain most of the carbon in a typical forest stand in Minnesota (Hillard et al., 2022). The amount of carbon stored in these in-forest pools over time depends on site productivity, species, soil type, site hydrology, and disturbances such as harvest, wildfire, diseases, pests, and animals that eat plants (Hoover et al., 2021; Ontl et al., 2020).

Though forest soils hold more carbon overall than other forest carbon pools, this pool is relatively stable over time. The live tree carbon pool (i.e., above- and below-ground biomass) is highly sensitive to management and therefore has received more attention for its potential to contribute to climate mitigation. It is also relatively easy to measure carbon stock and change in live trees compared to other in-forest carbon pools.[9]

Wildfire, wind events, drought/water stress, flooding, pests, disease, and invasive plants also influence in-forest carbon stores (Minnesota Forest Resources Council, 2020; Ontl et al., 2020). Changing temperature and precipitation due to climate change can exacerbate these stressors and are projected to increase over time. Proactive management in forests at high risk for climate impacts can reduce the risk of tree death, promote climate-adapted species, and encourage growth (Ontl et al., 2020).

[9] The scientific study of soil carbon and its relationship to management regimes is rapidly developing. One of the main challenges for operationalizing this approach is the enormous variety of soil types in Minnesota, which makes it difficult to establish "one size fits all" soil carbon enhancement practices (Nave et al. 2021). The other is that improvements in soil measurement technologies are needed to allow more cost-effective monitoring over time and across wider areas.

A growing body of evidence suggests that certain forest management techniques can maintain or incrementally increase in-forest carbon stores on working forest lands (Kaarakka et al., 2021). Each technique aligns closely with sustainable management values that Minnesota's forest managers have used for decades to maintain healthy and productive forests that can provide social, economic, and environmental benefits over a long timeframe. These management techniques include:

- Lengthening the time between harvests, reducing the amount of live or dead woody material removed in each harvest, and promoting a variety of tree species, ages, and forest structure through alternative harvesting practices (see Box 1)
- Helping forests resist or recover from disturbances (e.g., fire, windstorms) and stressors (e.g., browsing animals, insects) by removing hazardous fuels, controlling browsing animals, and removing invasive species and competing vegetation
- Increasing the number of trees per acre within forests to enhance in-forest carbon stocks

Box 1: Lengthening time between harvests and reducing timber removals: a note on tradeoffs

Reducing the frequency of timber harvest or the amount of wood removed as a technique to enhance carbon sequestration can have unintended consequences. While several studies show that this method quickly increases net carbon sequestration and can help meet near-term climate mitigation goals, this technique can also reduce available wood, impact local forest economies, and create a disincentive to keeping forested areas as forests (U.S. Department of Agriculture, 2018; Fargione et al., 2018; Franklin et al., 2018). Proposals to significantly scale this approach should be carefully evaluated according to forest cover type and tradeoffs with other forest benefits.

In the short term, this approach decreases the rate of carbon accumulation in off-forest harvested wood products and may lead consumers to increase their use of energy-intensive products like plastics, concrete, or steel. Over the long term, this technique could reduce the aggregate rate of net carbon sequestration as forests age and die naturally.

Less harvest can mean less revenue, which can ultimately result in reduced climate benefits. For example, if near-term wood supply decreases but demand for wood remains, wood may need to be harvested from other working forests (potentially out-of-state or beyond) negating near-term climate mitigation benefits. At a regional level, less harvest may also reduce aggregate demand for wood. This could diminish economic returns to forest owners, which could lead to the decision to convert forests to non-forest uses with higher economic values. This is more likely to happen if major forest product producers (e.g., mills, lumberyards, etc.) divested their operations and were slow to return.

These tradeoffs could negatively impact non-climate benefits as well, through lost forest ecosystem services and a decrease in economic viability of the forest products industry and communities that depend on harvested wood. Economic and community impacts must be carefully considered before implementing this approach.

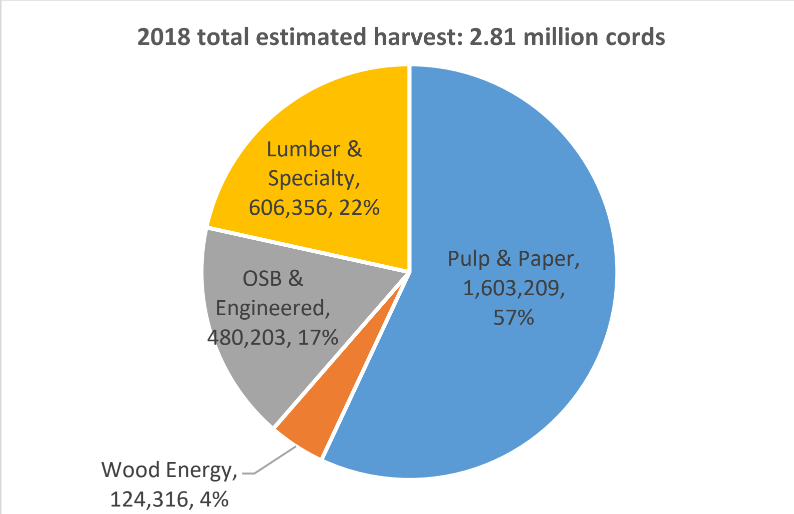
Approach 2: Promote off-forest carbon storage and substitution

Wood products generated through active forest management and sustainable timber harvest can contribute to carbon sequestration and storage (Lippke et al., 2011; Valsta et al., 2017; Janowiak et al., 2017). This is because wood products store carbon outside of forests—sometimes for long periods of time—and can provide lower-carbon alternatives for building materials, fuels, and other common products such as plastics, soil amendments, and some chemicals. Wood products generate substitution benefits when used in place of fossil fuels or fossil fuel-intensive materials such as concrete and steel, reducing overall GHG emissions (Sathre & O'Connor, 2010).

Understanding the opportunities, tradeoffs, and risks of this approach is technically challenging, and requires consideration of how harvested wood products are used. Decisions about the type, end-uses, and disposal of wood products influences their storage and release of carbon (Larson et al., 2012). Techniques for increasing the climate mitigation benefit of harvested wood products include:

- **Expand use of longer-lived wood products.** Longer-lived, durable wood products such as lumber and engineered wood store carbon for longer timeframes than shorter-lived products (Skog, 2008). Harvested wood products store carbon outside of forests, ranging on average from a few years (e.g., paper and paperboard; Skog & Nicholson 1998; Intergovernmental Panel on Climate Change 2006) to 100 years (e.g., wood used in housing; Skog & Nicholson 1998) depending on product type and disposal method. In some cases, products disposed in landfills may only partially decompose, retaining some amount of their carbon indefinitely (Congressional Research Service, 2020). Over half of the wood fiber generated from timber harvest in Minnesota is used as pulp and paper (Hillard et al., 2021) (Figure 9). Incorporating more longer-lived wood products such as lumber and engineered wood into this portfolio could increase the amount of net carbon sequestration in off-forest carbon pools over time and generate greater substitution benefits. For example, "mass timber" is a long-lived wood product sourced from smaller trees. This strong, lightweight wood can be used instead of concrete and steel in construction.
- **Use wood to replace fossil fuel-intensive materials ("bioeconomy applications").** Wood fiber can also replace fossil fuel-intensive materials in products such as chemicals, plastics, fuels, textiles, and soil amendments (Great Plains Institute, 2020). The net mitigation benefits depend on the rate of carbon emission of these wood products back to the atmosphere and the emissions avoided from using wood in lieu of other materials.
- **Use wood fiber to replace fossil fuel use in energy production ("bioenergy applications").** Using wood fiber to produce energy instead of fossil fuels can reduce GHG emissions over the long term. Already several areas around the world use wood biomass energy; however, there is robust debate about the timing and magnitude of mitigation benefits, as burning wood fiber as biofuel results in immediate and potentially large emissions (Franklin et al., 2018). The type of bioenergy, sourcing, production, and distribution significantly influences carbon mitigation benefits. Using bioenergy increases incentives to forest owners to retain or expand forest cover (Miner et al., 2014).

Figure 9: Estimated wood fiber use, in cords, from Minnesota timber harvest by primary industry sector (2018)



SOURCE: Hillard et al., 2021: *Minnesota's Forest Resources 2019*.
NOTES: Wood use data from Timber Product Output mill and fuelwood surveys conducted by the U.S. Forest Service Northern Research Station and the DNR.

Climate policy must consider near-term increases in GHG emissions due to wood combustion along with long-term net reductions. Near-term increases in emissions are expected to be paid back over time as forests regrow and substitution benefits accumulate. However, the exact length of this payback period—which can be several decades or more—depends on many factors and is a topic of discussion among experts and stakeholders. Other factors could offset these near-term emissions, including increased tree planting on low-density forests and expanding forests due to increased investment in forest management (Wear & Bartuska, 2020).

All working forests that generate harvested wood products are contributing to off-site forest carbon pools. However, measuring the climate mitigation benefits of wood products requires better understanding how consumers use and dispose wood products and how to quantify substitution benefits when wood replaces GHG-intensive materials. These complex measurements have frustrated efforts to develop standards for comparing the carbon footprint of wood products to other products. An active debate persists about the assumptions used to estimate the magnitude of emissions avoided by using wood products in place of other common materials (Franklin et al., 2018). Understanding how much carbon is stored in these pools now, and how they change over time in response to changes in practice or policy, is essential for illustrating the climate mitigation benefits of this approach (Russell et al., 2022).

Mitigation Goal: Expand active sustainable forest management to generate a balanced portfolio of forest benefits

The sustainable forest management practices used for decades by forest owners in Minnesota support long-term climate mitigation by keeping forests healthy and growing, harvesting at sustainable levels, regenerating forests after harvest, and protecting water and soil quality. When timber harvest is part of a sustainable forest management approach it promotes a mix of in- and off-forest carbon storage and substitution that collectively generate sustained climate mitigation benefits (Nabuurs et al., 2007).

Minnesota should continue to encourage the use of sustainable forest management practices and active management—including timber harvest—to generate climate mitigation benefits at the landscape scale. This is especially important for Minnesota's family forest lands where active management activity has been declining since the early 2000s (pers. comm. Mike Kilgore 10/7/2022). As a parallel process, forest managers in Minnesota should further investigate the potential benefits of in- and off-forest approaches to increasing carbon sequestration and storage via working forests. Additional analytical work will help identify "win-win" opportunities to enhance climate mitigation benefits among the many benefits forests provide.

Sustainable forestry strategies for managing working forests to sequester and store more carbon

Promoting active forest management is an actionable step that will generate a balanced portfolio of climate mitigation and other benefits over the long term. There is also a need for upfront work to better understand the scale of the opportunities and potential unintended consequences of emerging carbon-focused management concepts. Taking the next step towards this overall goal requires targeted investments and policies that support existing tools while paving the way for new approaches. The following list of high-priority sustainable forestry strategies describe the ingredients needed for managing working forests to sequester and store more carbon:

1. **Enhance forest carbon measurement and accounting systems:** Increasing the quality and timeliness of forest carbon data will improve understanding of baseline carbon storage and sequestration. This will also help identify what drives changes over time and whether specific strategies are effective. Ideally, measurement systems should encompass all land ownerships and track changes in forest carbon pools, wood products pools, land use changes, and emissions avoided due to substitution of wood products. This can be achieved with investment in remote sensing technology (e.g., lidar, aerial photography, and satellite imagery) and inventory methods that capture the full range of forest carbon pools.
2. **Employ timber harvest as a tool of sustainable forest management on family forests:** Sustainable timber harvest plays an important role in climate mitigation as the primary means for creating younger, faster growing forests. However, active management is declining on small privately-owned family forests in Minnesota. Due to a variety of factors, landowners may not be able to identify management objectives or write a management plan. In other cases, the high per-acre cost of management limits opportunities. In many cases, family forest owners are facing a combination of both barriers. Investing in landowner assistance programs for family forest owners will expand the footprint of active management on private lands by reducing common technical and financial barriers.
3. **Support policies and incentives that strengthen and diversify wood products markets**: Targeted financial incentives can spur market development for in-state wood product production. These incentives can be used to attract and retain a variety of traditional and innovative wood products businesses. In turn, strong markets for wood products encourage forest landowners of all sizes and ownerships to actively manage their lands. There are several different ways state policies can strengthen and diversify markets for wood products:
    - Incentivize businesses to use currently under-utilized tree species (e.g., balsam fir, birch, ash, tamarack) in harvested wood products
    - Incentivize wood product manufacturing, such as oriented strand board (a long-lived wood product)

- Enhance funding for the AGRI Bioincentive program to facilitate the use of wood biomass for energy and biochemicals
- Develop production incentives to attract and develop new markets and manufacturing in the state, such as mass timber, a long-lived wood product that is a lower-carbon alternative to concrete and steel

4. **Explore opportunities to increase in-forest carbon sequestration and storage:** Each forest management practice within this approach has different benefits and tradeoffs (Table 3). The mitigation potential, tradeoffs, and uncertainties associated with these management practices are sensitive to site-level factors and assumptions about future conditions. Professional foresters need to conduct additional quantitative analysis to illustrate potential outcomes and make effective decisions.

Table 3: Attributes of management practices for increasing in-forest carbon sequestration and storage

Management Practice	*Carbon Impact*	*Benefit Timeframe (Approximate)*	*Tradeoffs*
Reduce frequency of timber harvest or amount of timber harvested	Maintains existing in-forest carbon stores and sequestration potential	Near-term GHG benefits (immediate to 10 years)	Less wood available in near-term for forest products economy, consumers may use more fossil fuel-intensive products instead, reduced demand for wood may lead to forest conversion
Manage forests for greater diversity and growth through forest thinning, planting or seeding additional trees in low density forests, and managing forest stands for diverse species, ages, and structure	Increase carbon storage and sequestration capacity of forest	Mid-to-far term GHG benefits (20 to 50 years)	Fewer tradeoffs to wood production, but may include additional management expenses
Use climate adaptative forest management to sustain growth in the face of climate change	Prevent future loss of carbon storage and sequestration potential	Far-term GHG benefits (30 to 100 years)	Must anticipate future climate and make appropriate adaptations such as planting trees that are expected to do well in a changing climate

5. **Evaluate the carbon storage and substitution benefits of producing short- and long-lived wood products:** More work is needed to understand the carbon storage and substitution benefits of wood products manufactured in Minnesota. This will require evaluating the net effects of management on forest carbon stocks, accumulation of carbon in off-forest pools, and the emissions reductions from displacement of fossil fuel-intensive products.

6. **Investigate planning tools for balancing approaches to mitigate climate at a landscape scale:** Long-term forest management planning is essential to guide forest landowners on the extent, timing, frequency, and methods of vegetation management to help meet their objectives. Plans provide information about the forest, document landowner objectives, and help to translate goals into action. Landowners interested in forest carbon sequestration and storage may choose to include this in their management plan. New modeling tools are needed to analyze biological and economic impacts while accounting for multiple values at appropriate scales. Greater ability to quantify these implications would enable a more targeted discussion about opportunities to manage working forests to enhance climate mitigation benefits while avoiding negative impacts to other benefits forests provide.

Mitigation potential for managing working forests to sequester and store more carbon

Estimating mitigation potential from this pathway is a highly technical exercise that requires sophisticated modeling techniques and making important assumptions about the interaction of forest management practices, forests, wood products markets, and future climate conditions. A quantitative assessment of this scale is beyond the scope of this legislative report. At the statewide scale, it is currently not clear how much additional carbon can be practically gained through this pathway. Similarly, it is difficult at this time to quantitatively estimate the effects this pathway might have on other important forest values. The mitigation potential of each management practice varies according to forest type, forest age, site conditions, markets, and future changes in climate among other factors.

Quantitative modeling exercises guided by professional foresters can help determine how much additional climate mitigation benefit can be achieved by each practice (Kurz et al., 2015). Models can also be used to estimate the overall magnitude and timing of mitigation potential across a wide range of management approaches (Dugan et al., 2018, U.S. Department of Agriculture Forest Service, 2018). Ongoing research is evaluating the mitigation potential of forest management practices in Minnesota and Great Lakes states.

Discussion of economic factors

The economic benefits of working forests are driven by the value of harvested timber. Though not exclusively centered on timber harvest, the two approaches described above propose different ideas about how timber harvest can be modified to enhance climate benefits. Changes in the amount or frequency of timber harvest in aggregate will affect landowners, loggers, mills, and primary manufacturers in different ways.

Reducing the frequency and/or intensity of timber harvest to increase near-term carbon sequestration and storage can result in near-term losses of revenue to the forest products sector. The economic viability of this sector is driven in large part by the availability of reasonably priced, steady, predictable wood supply. When access to supply decreases, loggers and primary manufacturers may incur additional costs for shifting timber harvest to other parcels. The climate benefits of reducing the frequency and/or intensity of timber harvest are diminished when it results in the harvest taking place on another parcel. Enhancing in-forest carbon pools by forest thinning–which can support a wide range of values—often does not provide economic returns. Markets for verifiable forest carbon credits may play a role in offsetting landowner costs due to reduced harvest levels. It is unclear if or how strengthening markets for carbon credits will impact the economic viability of the forest products sector over the long term.

Minnesota's forest products sector is already promoting markets for wood products such as bioenergy and longer-lived wood products. Fostering new wood products markets that enhance climate mitigation will likely require up-front private sector investments in infrastructure. Policies that can stimulate demand for products can encourage private investment and participation. However, economic development strategies for inducing investment can be challenging. Effective policies to spur participation among public and private landowners to supply wood may involve public research and development grants, low interest loans, and subsidies to entice further private investment in wood product production. Finally, abatement cost estimates (the cost of mitigating one ton of GHG emissions) should include costs to the forest products sector.

Managing working forests to sequester and store more carbon: connection with other forest benefits

Climate change mitigation via sequestering and storing carbon is one benefit among many provided by working forests. As this subsection describes, there are several different ways to enhance climate mitigation benefits. Forest benefits are closely linked and driven by management decisions. Therefore, each of these opportunities (e.g. managing for in-forest carbon storage or off-forest carbon storage in wood products) will have different consequences for the provision of other forest benefits.

One of the ways this plays out is in terms of forest age. For example, practices such as increasing the time between harvest rotations will promote older forests, which provide habitat for animals like the red-shouldered hawk that prefer contiguous older forest. Older forests also have high recreational and aesthetic value. On the other hand, enhancing carbon storage in wood products through sustainable timber harvest promotes younger forest conditions that provide wildlife habitat benefits to species such as the ruffed grouse, that rely on young or mixed age-class forests. However, they may have lower recreational value compared to older forests.

Management practices also have different effects on the economic benefits forests provide. For example, broadly reducing the frequency or intensity of timber harvest to sequester and store more carbon can negatively affect incomes in the forest products sector and local and regional economies. On the other hand, private investments in the workforce and wood products infrastructure can increase carbon storage and substitution and generate long-term economic returns for the businesses and communities they support.

Forest managers do not expect to generate every benefit from every acre of forests. While tradeoffs are most acute at small spatial scale, there are opportunities to balance competing values at the landscape scale. For example, having a mix of forest ages and species across a landscape scale supports a broad array of forest benefits, including climate mitigation. As mentioned previously, forest management modeling tools are used to more precisely understand how benefits are related to each other and find opportunities to optimizes the delivery of these benefits across a landscape scale.

Barriers, constraints, and challenges to managing working forests to sequester and store more carbon

There are two main approaches to manage working forest to increase carbon sequestration storage. As described above, each of these approaches has specific tradeoffs and challenges. It is also important to highlight cross-cutting barriers to implementing this goal, including:

- **Intensive measurement and modeling needs**. Managing forests for multiple benefits, including carbon storage and sequestration, requires tools to accurately measure forest conditions and carbon pools and fluxes; model future outcomes; and evaluate tradeoffs and benefits. Measuring and modeling forest carbon changes to inform management requires significant resources. For the most part, the current tools for measuring and modeling are also imbalanced, as technical understanding of live tree carbon pools exceeds that of other in- and off-forest carbon pools.
- **Conflicting perspectives on forest management values**. There are differing views on how society should use forests and value various forest benefits (e.g., forest products, water quality and flow, wildlife habitat, recreation, and carbon storage and sequestration). Public land managers must balance a variety of benefits, which requires scientific evidence, quantitative assessment, and robust stakeholder engagement to identify tradeoffs and work towards "win-win" solutions. Private landowners are free to choose which values matter the most to them; providing sophisticated models and technical assistance can help landowners understand the tradeoffs of their decisions.
- **New management concepts are only slowly starting to incorporate future climate change impacts**. Technical guidance on managing working forests to sequester and store more carbon does not fully account for how climate change may impact forests' ability to sequester and store carbon in the future. Changes in forest type, productivity, or disturbances could alter Minnesota's forest carbon trajectory 50 or 100 years into the future. Keeping forests fully stocked with trees may become more difficult or expensive as the climate continues to change.
- **Key questions remain about a rapidly growing market for forest carbon credits**. Demand for forest carbon credits is growing and so is access to carbon credit markets for family forest landowners. This market-based approach can be used to incentivize a wide range of forest mitigation pathways. However, key questions about the risks and unintended consequences of scaling up production of these credits remain unanswered (see Box 2).

Additional analysis to inform managing working forests to sequester and store more carbon

Relative to retaining and increasing forest cover, managing working forests to sequester and store more carbon requires additional upfront capacity and knowledge building prior to action. There are several cross-cutting analysis needs. Building knowledge in the following areas will help ensure that this pathway remains viable while reducing unintended consequences for other forest values:

- Quantifying the climate mitigation potential and associated costs for in- and off-forest approaches to managing working forests for increased carbon storage and sequestration.

- Clarifying the social, environmental, and economic consequences of managing forests for climate mitigation benefits, and who carries those costs.
- Understanding how expanding markets for carbon credits may impact the economic viability of the forest products sector over the long term.
- Discerning the role of each interested partner and stakeholder in promoting practices that sequester and store more carbon in working forests. Interested partners and stakeholders can be government (municipal, county, state, federal, Tribal) and private (private forest landowners, forest products markets, carbon markets, etc.).

Box 2: Opportunities and challenges related to forest carbon credits

Carbon credits are a market-based approach for increasing climate mitigation benefits (Fernholz et al., 2021). Forest owners participate in this market by implementing practices that increase the amount of carbon accumulated on their land over time. Carbon credits represent the amount of carbon (expressed as carbon dioxide equivalent) accumulated on a landowner's land that exceeds the amount that would accumulate if these practices were not implemented. Credits generated from landowners are sold to corporate, individual, or government buyers seeking to offset GHG emissions. There are two main types of markets: compliance and voluntary (Russell et al., 2022).

Forest carbon credits can be generated by preventing a forest from being converted to a non-forest use (retaining forest cover) and establishing new forest (increasing forest cover). In the United States, a significant number of credits are generated by implementing forest management practices that increase in-forest carbon stocks on working lands by extending the length of time between harvests.

Extending the length of time between harvests can generate near-term increases in forest ecosystem carbon stocks. However, it may negatively impact local forest products economies by reducing available wood supply. It can also encourage the shifting of harvesting activity to nearby forests (or beyond state or national boundaries), which diminishes the overall climate mitigation benefits.

In Minnesota, opportunities to participate in forest carbon credit markets are increasing for family forest owners. Key unanswered questions about the risks and consequences of participation in forest carbon markets include:

- **Are forest carbon credits incentivizing sustainable forest management practices?** Opportunities for landowners to generate carbon credits should be aligned with sustainable forest management practices. They should also promote active forest management as a means for generating climate mitigation and other non-climate related benefits over the long term.
- **Have potential impacts on wood products economies, forest health, wildfire risk, and wildlife been properly understood and accounted for?** Prioritizing carbon sequestration and storage as a primary management objective for working forests risks diminishing other forest benefits. Scaling up the production of forest carbon credits may further amplify these risks. Careful implementation of carbon credit programs requires understanding and accounting for these tradeoffs.
- **Are forest carbon credits producing real climate mitigation benefits?** Scrutiny about the "additionality" of forest carbon credits—the extent to which credits represent real offsets of GHG emissions—is warranted. Methods for generating carbon credits should acknowledge the challenge of creating high-quality forest carbon credits and take steps to compensate for factors that compromise "additionality."

Section 3: Forestry pathways in a U.S. economy-wide climate mitigation approach

Avoiding the worst impacts of climate change will require significant reductions in GHG emissions across all economic sectors. But how much should each sector contribute to meeting GHG reduction goals? This depends in part on the feasibility of pathways for achieving emissions reductions in light of technological, economic, behavioral, and natural resource constraints.

Mitigation pathways vary in terms of the overall cost of implementation—such as the cost of new infrastructure, equipment, and labor—and the cost savings from greater efficiency or lower maintenance costs. Each pathway may also generate a suite of social, economic, and environmental benefits in addition to climate mitigation. The social cost of carbon—the monetary value of the net harm to society from emitting a ton of GHG to the atmosphere—provides another layer of cost and benefit for consideration in climate mitigation economics. Well-crafted climate policies promote cost-effective mitigation pathways that provide co-benefits and avoid unintended consequences.

A recent national-level study evaluated the array of pathways available for achieving net-zero GHG emissions by 2050 as part of the United States' long-term climate mitigation strategy (U.S. State Department of State & U.S. Executive Office of the President, 2021). The study found that implementing climate mitigation pathways on natural and working lands—including retaining and increasing forest cover—can contribute around 10% of net emissions reductions needed to achieve net-zero emissions by 2050 (See "Land Sink", Figure 10).[10]

Few studies have attempted to estimate economy-wide mitigation costs: the cost per unit of avoided carbon dioxide emissions or additional sequestration from implementing mitigation pathways.[11] A recent global study by Goldman Sachs Inc. illustrates that about half of abatable emissions can be achieved at a cost of less than \$100 per U.S. ton of CO_2e (Figure 11). A few pathways can create net revenues or savings (expressed as negative costs); while many pathways cost more than \$100 per U.S. ton of CO_2e—ranging up to \$1,000 per U.S. ton of CO_2e. The study provides a high-level comparison of mitigation potential and costs but simplifies the fact that these attributes can vary significantly based on local context, policy, and technological innovation (Friedmann et al., 2020).

Among pathways costing less than \$100 per U.S. ton of carbon dioxide equivalent (CO_2e), forest-based pathways appear to be relatively low to mid-range in cost. An analysis by Fargione et al. (2018) on forest-based pathways in the U.S. found that almost all of the potential for retaining forest cover (avoided conversion) in the U.S. could

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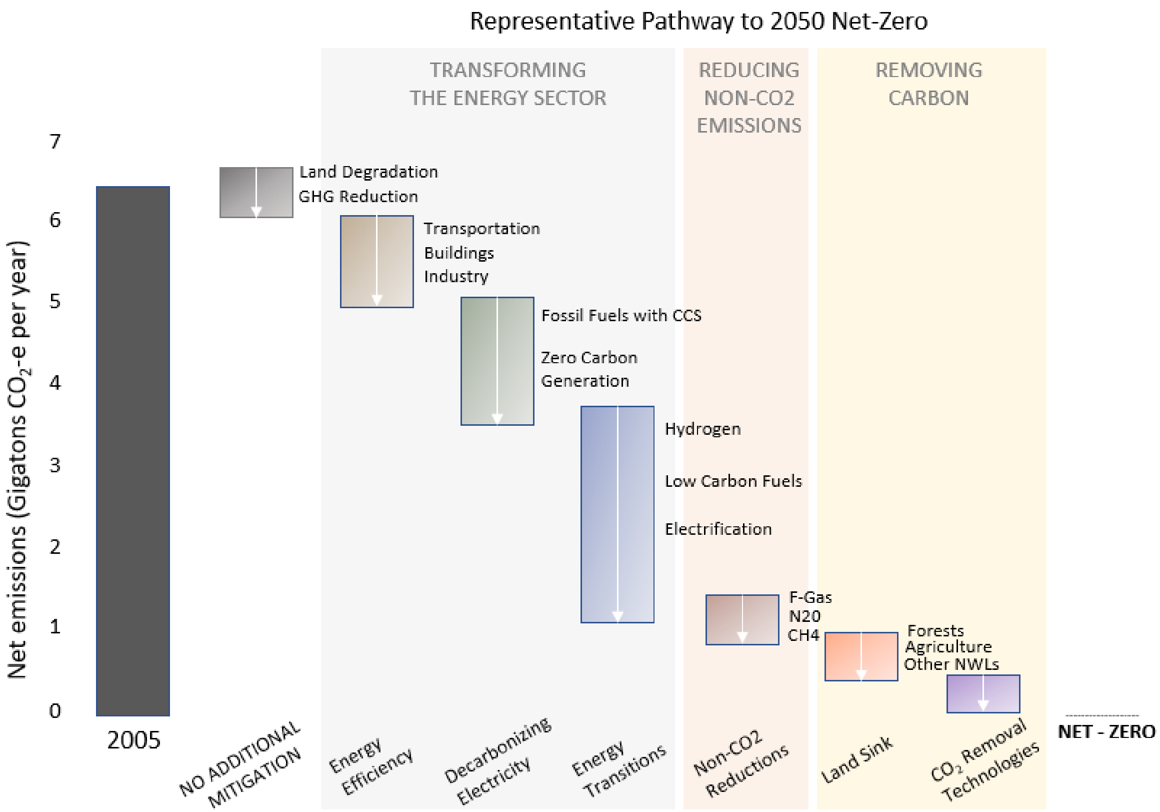
[10] Forests represent 95% of the carbon absorption capacity from the U.S. natural and working lands sector and currently offset 11% of national economy-wide GHG emissions each year (Domke, 2020).

[11] Examples of mitigation cost described in this section are not adjusted to reflect the social cost of carbon. However, the social cost of carbon is increasingly being incorporated into cost-benefit analyses to illustrate that many pathways are cost-neutral or cost negative when accounting for long-term societal impacts of GHG emissions (or avoided GHG emissions).

be achieved at under approximately $9 per U.S. ton of CO_2e. The same study found that around 80% of the climate mitigation potential from increasing forest cover (reforestation) could be achieved between $9 and $45 per U.S. ton of CO_2e. Another recent study of forest-based pathways in Maine suggests that most can be implemented at cost of $10-20 per U.S. ton of CO_2e (Daigneault et al., 2021). While these estimates do not specifically reflect climate mitigation costs of implementing pathways in Minnesota, they do provide a reasonable illustration of what these costs might be.

Figure 10: Achieving net-zero emissions across the U.S. economy will require contributions from all sectors

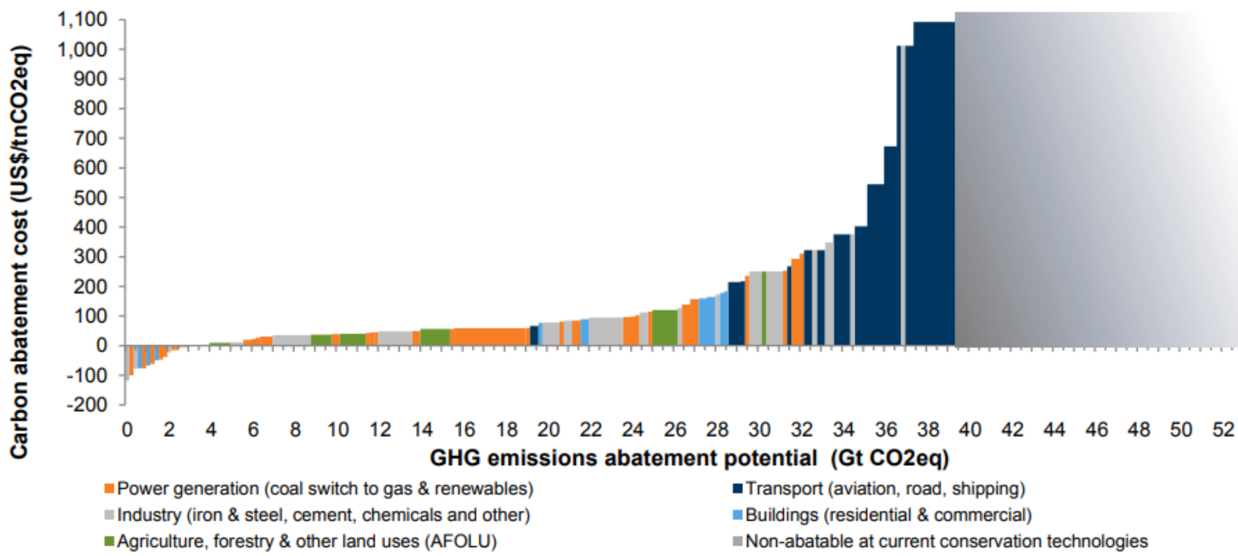


SOURCE: U.S. State Department of State and U.S. Executive Office of the President, 2021.
NOTES: This graph describes the potential emissions profile of the United States between now and 2050 based on assumptions made about technological costs, economic growth, and other drivers and constraints. Carbon units are expressed in terms of U.S. gigatons CO_2e per year.

In addition to likely being lower cost than many other mitigation pathways, retaining and increasing forest cover and managing working forests to increase carbon sequestration and storage can simultaneously enhance the unique economic (especially in rural economies), social, and environmental benefits that forests provide. These co-benefits increase the value of sequestering and storing forest carbon in ways that may not be fully captured by valuing emissions abatement alone.

As policymakers in Minnesota consider approaches to meet state GHG reduction targets, it is critical to identify the viability, mitigation potentials, and implementation and opportunity costs of each pathway. Existing studies at the global or national level (or from other states) provide high-level guidance but cannot be solely relied on to guide an effective economy-wide climate mitigation approach in Minnesota. In addition to understanding basic cost and benefits, it would also be beneficial to quantitatively estimate the value of co-benefits and tradeoffs across the full range of mitigation pathways. Providing an "apples to apples" comparison of economy-wide mitigation pathways will advance the statewide conversation on climate mitigation solutions among policymakers, public agencies, stakeholders, and the public.

Figure 11: About half of abatable global emissions can be achieved under $100 per U.S. ton CO_2e



SOURCE: Goldman Sachs Global Investment Research 2019.
NOTES: The analysis presented in this graph evaluated the cost of abatement among a range of pathways based on a near-term view of available technologies and commodity prices.

Section 4: Conclusion

Minnesota's forests contribute to mitigating climate change by absorbing carbon dioxide from the atmosphere when they grow and storing it in leaves, limbs, trunks, roots, soils, and wood products. For decades, these forests have absorbed more carbon dioxide from the atmosphere each year than is released from the forest due to timber harvest, dying and decaying trees, wildfire, disease, pests, and other natural processes (Domke et al., 2021).

Interest in the role of forests and forest management in climate mitigation is rapidly growing. Forest-based climate mitigation pathways will help the state meet its GHG reduction goals. However, implementation is challenged by economic and logistical barriers, potential tradeoffs with some other forest values, and uncertainties about the magnitude and timing of benefits.

This report identifies three goals to enhance climate mitigation benefits from forests: retain forest cover, increase forest cover, and manage working forests to sequester and store more carbon. Sustainable forest strategies for each goal are as follows:

Mitigation Goal 1: Reduce the rate of conversion of forests to non-forest land uses

<u>Strategies:</u>

1. Enhance financial and technical assistance to private landowners
2. Increase the impact of forest land acquisition tools and easement programs
3. Incentivize forest retention by strengthening markets for sustainably managed forest products
4. Discourage fragmentation of private forests

Mitigation Goal 2: Facilitate and encourage tree planting where ecologically appropriate

<u>Strategies:</u>

1. Increase in-state seedling production to support higher rates of tree planting
2. Expand private landowner access to financial and technical assistance for tree planting
3. Invest in protecting and expanding urban and community forests
4. Develop a trained workforce for accelerating tree planting
5. Identify synergies between tree planting and agricultural practices

Mitigation Goal 3: Expand active sustainable forest management to generate a balanced portfolio of forest benefits

<u>Strategies:</u>

1. Enhance forest carbon measurement and accounting systems
2. Employ timber harvest as a tool of sustainable forest management on family forests
3. Support policies and incentives that strengthen and diversify wood products markets
4. Explore opportunities to increase in-forest carbon sequestration and storage
5. Evaluate the carbon storage and substitution benefits of producing short- and long-lived wood products

6. Investigate planning tools for balancing approaches to mitigate climate at a landscape scale

This report builds foundational knowledge about forest-based climate mitigation goals and integrating climate mitigation into forest stewardship. The goals and sustainable forestry strategies are intended to provide high-level guidance to the broad array of entities engaged in managing Minnesota's forests. No single entity can achieve these goals on their own. Taking meaningful strides to implement these goals in Minnesota will require strong partnerships between local, state, federal, and Tribal governments, nonprofit organizations, and the forestry sector. Within this larger community, the DNR will help lead the way by building broad support for strategies and scaling up DNR activities that promote carbon sequestration and storage (Appendix 3).

Appendix 1: Explanation of forest conversion rates model

This report includes high-level estimates of how much more carbon dioxide Minnesota's forests might absorb in the next 25 years from implementing select climate mitigation goals (also known as mitigation potential). As described in Section 1, the contribution of Minnesota's forests to climate mitigation is generally measured as the net amount of carbon dioxide forests absorb in a single year (i.e. annual net forest carbon flux). Annual net forest carbon sequestration in the year 2048 (i.e., 25 years in the future) was used as the basis for comparing mitigation pathways to a baseline scenario. First, authors estimated how much forest cover there will be in 2048 in a baseline scenario (no intervention) and across a range of hypothetical scenarios. Then, the authors estimated the amount of carbon dioxide forests will absorb in 2048 in the baseline scenario and each hypothetical scenario. Mitigation potential is expressed as the percent increase in the amount of carbon dioxide absorbed under each hypothetical scenario compared to the baseline scenario in 2048.

These estimates of mitigation potential for retaining forest cover were developed using a basic spreadsheet modeling approach for determining overall statewide forest cover in 2048 based on a range of avoided conversion scenarios. The technical mitigation potential in 2048 (U.S. tons of CO_2e per year) is the product of the estimated forest cover in that year and the average sequestration rate of a typical forest stand in Minnesota (Table A 1.1). This required constructing scenarios with lower rates of gross forest loss compared to baseline levels (while holding the gross rate of forest gain constant). This approach produces approximate estimates of the additional amount of carbon dioxide that would be sequestered by forests in 2048 as the result of increasing the amount of forest retained as forests over time.

This modeling approach relies on assumptions that simplify a complex reality. One important assumption is that the rate of forest gain remains constant. This assumption was necessary to illustrate the effects specific to forest conversion. Another important assumption is that the average rate of sequestration by Minnesota's forests will remain constant. As some studies have found, forest aging can have a strong negative effect on the aggregate rate of sequestration (Dugan et al., 2018; U.S. Department of Agriculture Forest Service, 2018). Newly planted forests store less carbon but sequester carbon at a faster rate compared to older forests. Where forests are retained, what cover types (vegetation of a predominant species) are retained, and how retained forests are managed will also influence the rate of carbon sequestration. Similarly, where new forests are planted, what cover types are planted, and how they will be managed over time will influence the rate of carbon sequestration. This model assumes that forests retained represent average 50-year-old forests in Minnesota—which sequester carbon as a rate of 0.20 U.S. tons carbon/ac/year (0.73 U.S. tons CO_2/ac/year) based on Russell (2020)—and does not distinguish between cover types, productivity of sites, nor disturbance patterns.

This analysis does not account for carbon stored in harvested wood products nor emissions avoided through substitution of wood for alternatives that emit more GHGs. It also excludes indirect emissions related to forest management (e.g., from transportation and processing of wood products) in accordance with IPCC guidance to count these indirect emissions as part of the energy and industrial sectors (Witi & Romano 2019, Table 8.2).

Table A 1.1: Climate mitigation potential in Minnesota from avoided deforestation from 2023 to 2048

	Avoided conversion (1000s ac/yr)	Forest gain (1000s ac/yr)	Forest loss (1000s ac/yr)	Forest cover in 2048 (1000s ac)	Avg. C sequ. rate (U.S. tons CO_2e/ac/yr)	Mitigation potential (Million U.S. tons CO_2e/yr)	Change relative to baseline (U.S. tons CO_2e/yr)	% increase from baseline
Baseline scenario	-	86	60	18,401	0.734	13.5	-	-
No Loss to Development	12.6	86	47	18,716	0.734	13.7	231,210	1.71%
No Loss to Agriculture	16.8	86	43	18,821	0.734	13.8	308,280	2.28%
No Loss to Dev. And Agriculture	29.4	86	31	19,136	0.734	14.0	539,490	3.99%

SOURCE: Author's calculations using Hillard et al. (2022) (current rates of forest gain and loss) and Russell (2020) (sequestration rate of Minnesota's forests).

Appendix 2: Explanation of tree planting rates model

This report includes high-level estimates of how much more carbon dioxide Minnesota's forests might absorb in the future from implementing select climate mitigation goals (also known as mitigation potential). As described in Section 1, the contribution of Minnesota's forests to climate mitigation is generally measured as the net amount of carbon dioxide forests absorb in a single year (i.e. annual net forest carbon flux). Annual net forest carbon sequestration in the year 2048 (i.e., 25 years in the future) was used as the basis for comparing climate mitigation pathways to a baseline scenario. First, authors estimated how much forest cover there will be in 2048 in a baseline scenario (no intervention) and across a range of hypothetical scenarios. Then, the authors estimated the amount of carbon dioxide forests will absorb in 2048 in the baseline scenario and each hypothetical scenario. Mitigation potential is expressed as the percent increase in the amount of carbon dioxide absorbed under each hypothetical scenario compared to the baseline scenario in 2048.

These estimates of mitigation potential for increasing forest cover were developed using a spreadsheet model that estimates overall statewide forest cover in 2048 based on a range of tree planting scenarios. The technical mitigation potential in 2048 (U.S. tons CO_2e per year) is the product of the estimated forest cover in that year and the average sequestration rate of a typical forest stand in Minnesota (Table A 2.1). This required constructing scenarios with higher rates of forest gain (as a result of increasing tree planting activity) compared to baseline levels, while holding the gross rate of forest loss constant. This approach produces approximate estimates of the additional amount of carbon dioxide that would be sequestered by forests in 2048 as the result of increasing the amount of tree planting on non-forested lands.

This modeling approach assumes a constant rate of forest loss (to illustrate the effects solely due to increasing forest gain). This approach also assumes a constant average rate of sequestration by Minnesota's forests through 2048. Some studies have found that forest aging can have a strong negative effect on the aggregate rate of net sequestration (Dugan et al., 2018; U.S. Department of Agriculture Forest Service, 2018). Young forests will have a higher carbon sequestration rate compared to older forests. Russell (2020) found that on average, 10-year-old forests sequester 0.60 U.S. tons of carbon (2.2 U.S. tons of CO_{2e}) per acre per year (compared to 0.20 U.S. tons of carbon (0.7 U.S. tons of CO_{2e}) per acre per year for an average 50-year-old forest). This model estimates climate mitigation potential based on overall forest cover in 2048 and therefore uses the carbon sequestration rate of an average 50-year-old forest in Minnesota. Where trees are planted, and what cover types are planted will also influence the rate of sequestration. This model does not distinguish between cover types, stocking levels, productivity of sites, nor disturbance patterns.

This analysis does not account for carbon stored in harvested wood products nor emissions avoided through substitution of wood for alternatives that emit more GHGs. It also excludes indirect emissions related to forest management (e.g., from transportation and processing of wood products) in accordance with IPCC guidance to count these indirect emissions as part of the energy and industrial sectors (Witi & Romano 2019, Table 8.2).

Table A 2.1: Climate mitigation potential in 2048 from increasing rates of tree planting from 2023 to 2048

	Rate of tree planting (1000s ac/yr)	Overall forest gain (1000s ac/yr)	Overall forest loss (1000s ac/yr)	Forest cover in 2048 (1000s ac)	Avg. C sequ. rate (U.S. tons CO_2e/ac/yr)	Mitigation potential (Million U.S. tons CO_2e/yr)	Change relative to baseline (U.S. tons CO_2e/yr)	% increase from baseline
Baseline scenario	1.4	86	60	18,401	0.734	13.5	-	-
2x annual rate of planting	2.8	87	60	18,436	0.734	13.5	25,690	0.19%
5x annual rate of planting	7	92	60	18,541	0.734	13.6	102,760	0.76%
10x annual rate of planting	14	99	60	18,716	0.734	13.8	231,210	1.71%
"1 Million Acres by 2048"	40	125	60	19,366	0.734	14.4	708,310	5.24%

SOURCE: Author's calculations using Hillard et al. 2022 (rate of forest gain and loss); Russell 2020 (average rates of sequestration). See footnote 4 for description of sources for estimating annual rate of new forest planting statewide.
NOTES: The "overall forest gain" column reflects gross gain regardless of origin and includes natural regeneration in addition to intentional tree planting.

Appendix 3: DNR activities that promote climate mitigation

The Minnesota DNR is responsible for ensuring that forests and woodlands in the state are managed to generate a broad array of social, economic, and environmental benefits. As part of this charge, the DNR implements a wide array of forestry activities, many of which promote the climate mitigation goals and sustainable forestry strategies identified in this report. This appendix describes the link between these activities and climate mitigation. In doing so, it makes the case for investing in the DNR's work and thereby amplifying the climate mitigation benefits generated by Minnesota's forests. While DNR plays a lead role in these activities, many are implemented in partnership with other public, private, and nonprofit entities.

Forest land acquisition

The DNR helps retain forest cover by strategically acquiring conservation easements and fee title ownership of private forest lands. These land acquisition tools restrict development of forest land into other uses while providing a variety of important recreational, economic, and environmental benefits for the public. By keeping forests as forests, the DNR's land acquisition activities prevent the immediate loss of carbon stored in forests and long-term reduction in carbon sequestration potential. Avoiding conversion results in immediate climate mitigation benefits.

Conservation easement programs administered by DNR Forestry help forest owners protect their lands for future generations. Since 2000, these programs have generated $93 million from public and private sources and have protected 365,000 acres. Nearly all of these acres are open to the public for hunting, fishing, and other recreational uses. The DNR's objective is to purchase conservation easements on 530,000 acres of forest by 2034.

The DNR also directly acquires private forest land when there are opportunities to improve connectivity of public lands, where threats to forest conversion are high, or where parcels contain rare flora and fauna. For example, since 2015, the DNR has acquired approximately 2,600 acres of rare pineland sand forest habitat in north central Minnesota that is threatened by encroaching agricultural development. The DNR is also currently working with nonprofit partners to acquire former industrial forest lands to be conserved as working forests that support natural resource-based economies, provide clean air and water, and expand access to public lands.

Additional funding to purchase easements and properties is needed, including funding for staff to develop, implement, and monitor new acquisitions. Future opportunities for new acquisitions are primarily on small family forest lands. This poses several challenges. While acquiring small parcels tends to be more expensive per acre, time needed to process the acquisition is similar to that of larger parcels. Flexible funding sources that can be spent over longer times are better suited for land acquisition programs where acquiring a single easement or parcel can take several years.

Technical and financial assistance to private landowners

One-third of forest land in Minnesota is owned by nearly 206,000 family forest owners (Hillard et al., 2022). Approximately 83% of these landowners own 50 acres or less. Family forest owners face barriers to long-term stewardship including difficulty accessing technical expertise and high-per acre management costs. These barriers increase the risk that landowners will convert forests to other uses. The DNR helps landowners access forestry expertise by providing low-cost forest management planning services. DNR field foresters or private forest consultants can prepare a ten-year property-wide Woodland Stewardship Plan for landowners that describes long-term management options that meet multiple objectives. In 2021, nearly one million acres of private forest land had a plan, out of approximately 6.8 million acres of plan-eligible private land (Minnesota Department of Natural Resources, 2015). The DNR's long-term goal is to prepare plans for 150,000 acres of private forest annually (maintain 1.5 million active plans per ten-year cycle). The DNR works in close partnership with Soil and Water Conservation Districts and other partners to expand the reach of technical assistance.

The DNR also helps private landowners plant new forests on open lands by teaching them how to use trees to advance their property goals and providing federal and state financial cost-share incentives to plant trees. The DNR's cost-share dollars reduce the cost of tree planting by up to 75%.

Land planted in trees and included in a Woodland Stewardship Plan can be enrolled into one of two financial incentive programs to incentivize private forest owners to keep forest as forest. The DNR facilitates landowner enrollment in these programs by qualifying applications. Qualifying landowners can enroll to receive reduced property taxes for managed forests through the 2c Managed Forest Land designation or receive annual payments for keeping woodland areas undeveloped through the Sustainable Forest Incentive Act (SFIA). Financial assistance increases the value of forests for landowners relative to the opportunity costs.

State forest nursery

Each year, the DNR State Forest Nursery produces millions of high-quality seedlings to ensure successful regeneration after harvesting, retain forest cover, and establish new forests.

In a typical year, the Nursery grows 2 to 4 million bareroot seedlings. About half are used to replant state lands after harvesting. Nearly 1.5 million seedlings are sold to private landowners for tree planting efforts. The remainder are sold to counties, Tribal governments, and other public agencies. To ensure that seedings will thrive, the DNR matches seedlings to the same region ("seed zone") where the seed was collected. This improves survival rate and maintains local genetic diversity for our future forests.

As interest in using forests to mitigate and adapt to climate change grows, demand for seedlings from the Nursery and other private nurseries is also growing. However, Minnesota has experienced a long-term decline in in-state seedling production and workforce challenges related to the COVID-19 pandemic and other factors. Currently there are no large-scale conservation-grade seedling producers in the state, and only one major (out-of-state) containerized seedling producer. Funding from the state legislature in FY22-23 for new equipment to put unused planting beds back into production at the Nursery is helping to ramp up production capacity.

However, there are other funding needs including funding for procuring additional seeds, updating aging buildings and facilities, and developing a trained workforce that are critical to long-term, sustained increases in seedling production. The DNR is currently performing a study to estimate the costs of building and facility upgrades and replacements at the Nursery. These upgrades will benefit all landowners in the state by providing increased access to seedlings with proven seed sourcing at quantities large enough to carry out reforestation efforts.

Sustainable timber management

The DNR manages approximately 5 million acres of land according to sustainable forest management principles verified through third party certification; accounting for lands set aside by statute or policy and for lands that do not produce merchantable trees, 2.75 million of these acres are available for timber harvest in state forests, wildlife management areas, and certain aquatic management areas. Timber harvest is the primary tool for managing forests for balanced age distribution and diverse wildlife habitats across DNR-administered forest lands. Per statutory requirements, the DNR's long-term plans direct and guide management to ensure a sustainable supply of forest benefits (see Forest Planning below).

The DNR's forest management activities are certified by the Forest Stewardship Council and Sustainable Forest Initiative. These entities certify landowners who demonstrate that their practices meet rigorous sustainability standards. Certification ensures that forests are managed to provide environmental, social, and economic benefits. Maintaining certification requires annual independent audits to verify that forest management techniques continue to meet the high bar set by the certification bodies.

The DNR also adheres to the Minnesota Forest Resources Council's Site-Level Forest Management Guidelines (FMGs) and monitors their implementation across all forest lands (all ownerships) in the state. FMGs provide direction to loggers, forest managers, and landowners on best practices for maintaining site quality while harvesting timber (Minnesota Forest Resources Council, 2014). For example, FMGs provide guidance on planning, road building, erosion and water quality protection, wildlife, and biomass harvesting.

Sustainability is a strong overarching value in the DNR's approach to timber management. Additional analytical work is needed to quantify the specific climate mitigation benefits of this approach. However, the practices used to implement this approach are known to generate sustained climate mitigation benefits (Nabuurs et al., 2007). For example, harvesting at sustainable levels, replanting forests after harvest, and minimizing harvest damage support the long-term stability of carbon stocks at the landscape scale. Sustainably certified forest products offset the use of fossil fuel-intensive products and provide revenues that are reinvested into forests.

Healthy markets for forest products

The DNR promotes strong and diverse forest products markets that are critically important to sustainable forest management on all forest lands in the state. Markets provide economic incentives to actively manage forests and implement practices that enhance the contribution of working forests to climate mitigation. These economic returns increase the value of forests and incentivize private forest owners to keep forest as forests rather than convert to development or agriculture. Markets are also the vehicle for producing wood products that store carbon and substitute for more fossil fuel-intensive materials.

DNR Forestry's Utilization and Marketing Program supports the ongoing health of traditional markets and looks for opportunities to develop markets for new forest products. It does this by collaborating with researchers, lawmakers, businesses, communities, and environmental groups to expand the environmental and societal benefits of managed forests and underutilized wood (e.g., harvest by-products, small diameter trees, less marketable tree species). This includes collecting and analyzing data on the state's existing forest products industries, current utilization, and available forest resources and providing other business and economic development services. These services help key audiences make informed decisions about sustainable use of forests and opportunities for new industry developments.

The DNR will look to advance the use of forests and wood products as opportunities to enhance climate mitigation in addition to other forest benefits, including forest health. Providing markets for underutilized species provides more opportunities for forest management, which is especially important for at-risk forest types (e.g., ash forests threatened by emerald ash borer, tamarack forests threatened by eastern larch beetle, aging/dying paper birch forests along the North Shore of Lake Superior). This starts with identifying opportunities and assessing their contribution to climate mitigation. Common products with large carbon footprints can be replaced or hybridized with wood-based alternatives. Using mass timber in building construction is an example of substituting renewable wood products for materials with higher energy footprints such as steel and concrete. Wood-based derivatives can also be used as a substitute for petroleum-based fuels and a variety of other chemicals, reducing the GHG emissions associated with everyday products.

Forest data collection and analysis

The DNR regularly collects and analyzes data on the composition and condition of Minnesota's forests. These data are used by public and private forest managers for planning and implementation of practices that generate a broad range of traditional forest benefits. These data are also used for estimating how much carbon is stored in Minnesota's forests and how that storage changes over time. Collecting and analyzing these data plays an important role in evaluating the carbon implications for forest management decisions.

The DNR manages the collection of field data for the federal Forest Inventory and Analysis (FIA) program. The FIA program measures tree species, size, age, and health across all ownerships by sampling forested plots across the state. Professional forest managers rely on these datasets to provide a regional-to-statewide view of current forest conditions and changes over time. The FIA program also tracks forest ownership patterns and land conversions, and is the primary dataset for estimating forest carbon stocks and flows. By design, FIA data does not provide spatial detail for areas smaller than a county and requires five years of sampling to derive statistically accurate measurements for the entire state. The State of Minnesota invests in a more frequent and double intensity cycle compared to most other states, collecting FIA data with one plot for every 3,000 acres over the course of five years instead of one plot for every 6,000 acres over seven years. This investment was made to provide more timely information, improve data quality and precision, and to better inform management planning and monitoring of landscape scale forest changes over time.

The DNR also collects an even higher density of forest inventory field plots on all DNR-administered forest lands. In 2020, the DNR began transitioning from an exclusively field-based data collection method for summary-level inventory to an efficient, accurate, data-rich forest inventory method that combines a dense network of fixed radius field plots (plot-based forest inventory, or PBI) and high-density light detection and ranging (lidar) data. The PBI network has one plot for every 1,500 acres and is designed as a gridded network statewide across all forested lands. Compared to traditional methods, this new method is specifically designed to generate higher-resolution data on forest conditions at smaller spatial scales (e.g., 20 meter pixel). It can also be used to provide summary-level information at larger spatial scales and creates an opportunity for partners of other forest ownerships to participate.

Looking forward, continued investment in all forest measurement activities is needed because each activity makes a unique contribution to our overall understanding of Minnesota's forests. The DNR is also committed to enhancing the quality and timeliness of these data. This is accomplished by adopting new technology such as PBI and lidar as well as moving toward electronic data collection and development of modern data storage systems. Embracing new technologies can be costly in the short-term. However, enhancing forest inventory produces long-term cost-savings and other benefits for the agency, other public and private forest managers, and the public at large. In addition to improving forest management planning, continued investment in these datasets over time will also provide a clearer picture of how forests are contributing to climate mitigation by providing high-quality data for establishing a common baseline and consistent methods for measuring change in forest carbon across all ownerships.

Forest planning

The DNR's Forest Resources Management Plan ensures that DNR-administered forests are sustainably managed over the long term to balance multiple benefits, including wildlife habitat, timber production, biodiversity, forest health, and water protection. The plan defines goals for forest vegetation management and guides on-the-ground activities on the DNR's lands, consistent with their statutory purpose. Modeling informs the plan's strategic forest resource management direction. The model projects management under different scenarios for 100 years to assess sustainability and impacts on multiple values. The DNR determines its strategic forest management direction—including how much timber volume to offer from DNR-administered lands per year—from a combination of modeling results, stakeholder input, and statutory requirements. The DNR develops stand exam lists (lists of forest stands to examine for potential management) and narrative guidance for forest managers on how to incorporate values that meet the strategic direction. Together with other internal policy and direction to staff, the Forest Resources Management Plan's strategic direction, stand exam lists, and narrative management guidance ensure long-term sustainable management while meeting statutory requirements and balancing landscape-scale goals for multiple benefits.

Climate mitigation is emerging as a value of great importance to policymakers, stakeholders, and the public. As described in this report, integrating these values into an already intricate forest management system is technically complex, especially in managing working forests to enhance climate mitigation benefits. As such, proposals for climate mitigation through forest management on state lands must be routed through the DNR's holistic modeling, decision, and planning process to identify and appropriately analyze forest management opportunities and tradeoffs. Doing so will require further investment in modeling capacity, analyzing biological and economic impacts of different scenarios at the appropriate scales, and engaging stakeholders on any new strategic direction.

Forest health

Forests are susceptible to insects, diseases, and invasive plants that suppress growth and kill trees. These stressors impair the ability to generate a broad portfolio of benefits from forests—including climate mitigation benefits. For example, forests with high mortality due to these stressors can become near-term sources of GHG emissions due to decay. Resulting forests may be less dense, leading to less carbon sequestration as well. Experts suggest that anticipated changes in climate increase the potential for negative impacts from these stressors on forest health. The DNR promotes forest health through a combination of landowner education, monitoring for stressors, and treatment of invasive species.

Preventing the spread of insects, disease, and invasive plants is a key strategy for maintaining forest health. The DNR provides educational materials to landowners on reducing the spread of insects and disease. For example, educating landowners on identification and treatment of the pathogen oak wilt is a way to prevent more infection, which can be very costly to treat at large scale. The terrestrial invasive species program educates the public on ways to avoid introduction or expansion of invasive plants.

Quickly detecting insects, disease, and invasive plants is also important for identifying and treating negatively impacted forests. The forest health program actively monitors forests for signs of declining forest health through aerial survey. Information about the type and extent of impacts are incorporated into the DNR's management decisions and shared with other public, Tribal, and private land managers. The DNR uses this information to contain forest health issues and utilize wood products while still merchantable. Replanting after harvest is a key aspect of keeping forest as forests after severe forest health events.

The DNR also manages the spread of terrestrial invasive species (TIS) through a combination of reporting observations and treatments. DNR field staff report observations of invasive plants to a central database when they see them while doing other forestry activities. Tracking invasive plant observations allows foresters to prioritize sites for treatment as funding is available. Each year, the DNR implements chemical, mechanical, and biological treatments of invasive plants according to Area TIS Management Plans. The DNR also engages in outreach on TIS prevention to state forest users at events including the Minnesota State Fair.

Urban and community forests

Urban and community forests play a small but significant role in the contribution of Minnesota's forests to climate mitigation (Russell et al., 2022). Efforts to prevent the loss of urban trees, maintain urban forest health, and expand urban tree canopy through planting are important for generating long-term climate mitigation benefits. In addition to carbon capture and storage, urban trees reduce energy use by shading homes and buildings and provide a host of other social and health benefits to the public (Minnesota Department of Natural Resources, 2019).

The DNR supports urban forests by providing education, technical, and financial assistance to communities and homeowners. This assistance is used for identifying threats to trees—especially insects and diseases—and advising on treatments, and to reduce the cost of tree planning and management. As of May 2022, there are over 850 DNR-certified tree inspectors providing this service to more than 150 communities across the state. The DNR also recognizes communities that are taking steps to maintain and expand urban tree canopy through the Tree City USA program.

Currently, an invasive pest called emerald ash borer (EAB) (*Agrilus planipennis*) is a key threat to urban forests in Minnesota. Maintaining climate mitigation benefits from these forests require redoubling efforts to preserve urban ash trees, identify and contain EAB outbreaks, and plant diverse species to efficiently replace current and expected mortality due to the pest. Climate change is expected to increase heat and water stress to urban forests and potentially exacerbate insect and disease outbreaks. Creating climate adaptive forests will be key in avoiding impacts into the future. Urban forests also provide a nexus between climate mitigation and historically underserved communities. Directing resources to maintain urban canopies in these communities is a way to support climate mitigation benefits while addressing environmental justice concerns in urban areas.

Wildfire Prevention

Wildfire is a periodic occurrence in Minnesota—especially in the spring and fall when the combination of dry vegetation, low humidity, and high winds increase wildfire risk. Wildfire results in immediate emissions of carbon dioxide and other GHGs. The interaction of fires with forests is complex due to high variation in topography, vegetation structure, wind, and soil characteristics, among other factors. This variation makes it difficult to accurately estimate emissions from wildfires. In fire-adapted forests, wildfire generates near-term losses in forest carbon that are recovered when forests regrow over time.

The prevention and suppression of wildfire are core components of the DNR's mission. Minnesota experiences around 1,000 wildfires per year. The DNR adopted the national Firewise Program to work closely with partner agencies, municipalities, organizations, and homeowners to reduce wildfire risk. Across the state, more than 300 communities in high wildfire risk areas have a Community Wildfire Protection Plan (CWPP). The DNR also provides community assistance for wildfire mitigation practices such as hazardous fuel reduction in high-risk areas. The DNR plays a key role in the network of federal, state, local, and Tribal governments that are collectively responsible for preventing, preparing for, and responding to wildfire emergencies.

Glossary

Carbon dioxide (CO_2): A naturally occurring gas that is also produced by burning fossil fuels, burning biomass, land use changes, and industrial processes (e.g., cement production). It is the principal greenhouse gas produced by human activities that affects the Earth's radiative balance (State of Minnesota, 2022). Emissions are also sometimes expressed as carbon dioxide equivalent (CO_2e).

Carbon dioxide equivalent (CO_2e): A metric used to compare the emissions from various greenhouse gases based upon their global warming potential. Converting emissions from non-carbon dioxide GHGs (including methane, ozone, and nitrous oxide emissions) in common terms is a standard accounting practice.

Carbon flux: The measurement of change in forest carbon stock between two time periods (also called "net carbon flux"). Compared to carbon stock, flux is generally a smaller value and is expressed as a rate (e.g., U.S. tons of carbon per year). Flux is commonly measured by estimating the difference in forest carbon stock from year-to-year at large scale (e.g., landscape, region, state). When stocks are increasing year to year, flux is negative—an indication that forests are sequestering more carbon than they are releasing each year (also referred to as "net sequestration" or "sequestration"). In climate policy, flux indicates whether a forest is in aggregate removing GHGs from or emitting GHGs to the atmosphere. A comprehensive analysis of forest carbon flux incorporates all in- and off-forest carbon pools and substitution effects of using wood in place of fossil-fuel intensive products.

Carbon pool: A component of the forest carbon cycle where carbon accumulates. The forest carbon cycle has both in- and off-forest carbon pools. In-forest carbon pools include carbon stored in aboveground biomass, belowground biomass, soil, litter, and dead wood. Off-forest carbon pools include carbon stored in wood products that are either in use (e.g., wood-framed homes) or in landfills.

Carbon sequestration: The process of accumulating carbon dioxide in a carbon pool other than the atmosphere. For example, trees sequester carbon by using photosynthesis to convert carbon dioxide into plant biomass (Russell et al., 2022). In climate policy, this term is also used to refer to when forests in aggregate are absorbing more carbon dioxide than they are emitting each year (i.e. "net sequestration").

Carbon sink: Anything that removes more carbon dioxide from the atmosphere than it releases. Vegetation and oceans are two important natural carbon sinks. Forests are a carbon sink when they remove more carbon dioxide from the atmosphere each year than they emit through respiration, decomposition, and oxidation.

Carbon source: Anything that adds more carbon dioxide to the atmosphere than it absorbs. Forests can become a carbon source when the rate of carbon dioxide released from disturbance or natural mortality and decay exceeds the rate of carbon dioxide absorbed through new growth.

Carbon storage: A snapshot of the amount of carbon stored in a pool at a single point in time. This is also referred to as carbon stock: the quantity of carbon in a reservoir or system with the capacity to accumulate or release carbon (Russell et al., 2022).

Climate change: A change in the state or variability of the climate. Climate change is identified by variability in climate properties that persists for a prolonged period and can be identified (e.g., by using statistical tests). The United Nations Framework Convention on Climate Change (UNFCCC) distinguishes climate change from climate variability. Climate change is attributed directly or indirectly to human activity that alters the composition of the global atmosphere which is in addition to natural climate variability observed over comparable time periods (State of Minnesota, 2022).

Climate mitigation: A human intervention to reduce the sources or enhance the sinks of greenhouse gases (Intergovernmental Panel on Climate Change, 2014). The ultimate objective of climate mitigation is to stabilize greenhouse gas concentrations in the atmosphere at a level that prevents dangerous anthropogenic interference with the climate system. Also referred to as "climate change mitigation."

Climate mitigation benefits: The amount of GHG emissions reduced and/or removed from the atmosphere over time due to a specific practice or activity compared to a baseline scenario. Estimating the magnitude and timing of climate mitigation benefits is known as mitigation potential.

Ecosystem services: Benefits that people obtain from ecosystems. There are several types of ecosystem services. Food, water, and wood fiber are examples of provisioning services. Climate, flood control, and water quality are examples of regulating services. Recreational, aesthetic, and spiritual benefits are examples of cultural services. Soil formation and photosynthesis are examples of supporting services. The human species is fundamentally dependent on the flow of ecosystem services (Balloffet et al., 2012).

Family forests: Small privately-owned non-industrial forest lands. One-third of forest land in Minnesota is owned by nearly 206,000 family forest owners (Hillard et al., 2022). Approximately 80% of these landowners own 50 acres or less. Family forest owners face barriers to long-term stewardship including difficulty accessing technical expertise and high-per acre management costs.

Forest-based climate mitigation pathway: Practices that involve using forests and forest management to generate climate mitigation benefits. There are three main pathways: retain forest cover, increase forest cover, and manage working forests to sequester and store more carbon.

Forest carbon cycle: An integrated system of carbon capture, storage, and release that includes in-forest and off-forest carbon pools. Carbon accumulates within—and moves between—pools at different rates. The magnitude and timing of carbon released from these pools to the atmosphere also vary considerably. Forest growth, land use patterns, forest management decisions, and wood product use and disposal behavior all influence the rates of accumulation and release.

Greenhouse gas (GHG): Gases in the Earth's atmosphere (both natural and human-caused) that cause the greenhouse effect; amplification of the greenhouse effect by human-caused greenhouse gases is a driver of climate change. The four main types of GHGs are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_20), and fluorinated gases. Carbon dioxide accounts for nearly 80% of U.S. GHG emissions (U.S. Environmental Protection Agency, 2022b).

Greenhouse gas inventory: An inventory of the amount of heat-trapping GHGs released by human sources within a defined boundary over a discrete period of time. In Minnesota, common sources include energy generation, transportation, and agriculture. Inventories can also include "sinks" (e.g., forest regrowth) that offset a portion of overall annual emissions.

Landscape scale: Forest management actions can be viewed at a stand, parcel, and landscape scale. The stand is the smallest scale and generally represents an individual unit of management. A parcel may include several stands. The landscape scale encompasses many parcels (sometime with different ownerships) and can include different forest types.

Mitigation potential: Emissions reductions generated by implementing a specific action over time. In working forests, the mitigation potential of a specific management approach is the amount of carbon that accumulates in all forest carbon pools (including avoided emissions from using wood in place of other products) over time compared to a baseline scenario. Quantifying mitigation potential allows for "apples-to-apples" comparison of climate mitigation pathways across economic sectors.

Substitution: The reduction in fossil-based carbon dioxide emissions that occurs from using wood products rather than more energy-intensive alternatives. Emissions avoided by using wood instead of fossil fuel-intensive products are an important component of the climate mitigation benefits of managing forests.

Sustainable forest management: A long-term forest management approach for generating a portfolio of multiple forest benefits over time, including forest products, water quality and flow, wildlife habitat, recreation, and carbon sequestration and storage. This approach balances social, economic, and environmental benefits while acknowledging that not all forests can produce the same benefits (Lippke et al., 2011).

Sustainable timber harvest: A component of sustainable forest management that includes harvesting trees for commercial sale and manufacturing into wood products. To be sustainable, timber harvests are part of a long-term management plan, do not harvest more than is grown, balance age classes for even-aged forest cover types, and produce multiple benefits over time. Minimizing logging damages, replanting after harvest, and improving forest health are also elements of sustainable timber harvest.

Working forest: A forest that is actively managed with sustainable forestry practices to produce a variety of benefits, including forest products.

Legislative text

Laws of Minnesota 2021, First Special Session chapter 6, Sec. 132.

CARBON SEQUESTRATION IN FORESTS OF THE STATE; GOALS.

The commissioner of natural resources must establish goals for increasing carbon sequestration in public and private forests in the state. To achieve the goals, the commissioner must identify sustainable forestry strategies that increase the ability of forests to sequester atmospheric carbon while enhancing other ecosystem services, such as improved soil and water quality. By January 15, 2023, the commissioner must submit a report with the goals and recommended forestry strategies to the chairs and ranking minority members of the legislative committees and divisions with jurisdiction over natural resources policy.

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