MANAGING FORESTS FOR CARBON IN MASSACHUSETTS

Contents

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INTRODUCTION

Foresters and natural resource professionals are taking a greater interest in forest management actions for providing carbon benefits to mitigate a changing climate. Climate mitigation actions work to reduce the atmospheric carbon dioxide and other greenhouse gases responsible for climate change. Inclusion of carbon-related goals in forest management planning is becoming common with the increasing recognition of the climate regulation benefits our forests provide through their ability to sequester and store carbon. This guide assists foresters who are interested in integrating carbon management into the plans they write and projects they implement. The guide supports the development of forest management and stewardship plans that intentionally consider climate change impacts and informs the identification of management actions that support landowners' carbon goals for their property.

The first section of this guide introduces key carbon terminology as it relates to typical forestry practices and summarizes carbon dynamics over different spatial and temporal scales.

The second section of this guide outlines how foresters can integrate carbon management into forest management planning, including Forest Stewardship Plans, by assessing risks to carbon and evaluating opportunities to enhance carbon within the context of landowner goals and objectives. This section presents overarching principles of carbon management, examples of carbon-beneficial actions that relate to common management concerns, and considerations when communicating with landowners about frequently asked topics involving forestry and carbon.

Any time you are working in the woods, you are surrounded by carbon in its many different forms: from the organic matter in soils, roots, and the litter of the forest floor beneath your feet to the tree biomass in the mid- and overstory above your head. These are some of the main types of biomass that contain carbon as it flows through ecosystems, most of it to be ultimately released back to the atmosphere. To understand how carbon moves within a forest, as well as make the process of estimating the total amount of carbon in a forest a feasible task, we group these categories of carbon-containing materials into "pools".

According to the U.S EPA and international guidelines for carbon measurement and reporting[1], ecosystem carbon pools are defined as:

Aboveground biomass: living biomass above the soil, trees (> 1 inch diameter) including bark, stumps, branches and tops, and foliage. This pool also includes understory and ground layer vegetation.

Belowground biomass: all living root biomass of trees or understory plants (coarse roots).

Dead wood: all dead woody biomass either standing, on the ground, or in the soil.

Forest floor: the leaves, needles, twigs (less than 3 inches diameter), and all other dead biomass on the ground that has not yet become part of the soil.

Soil: mineral and organic soils, including fine roots, to a depth of one meter.

Several additional carbon pools occur outside of the forest ecosystem and include *harvested wood products in use* and *harvested wood products in solid waste disposal sites*. Like carbon within a forest, carbon has a residence time within these pools before it is released back to the atmosphere either from combustion or decomposition. Carbon pools in harvested wood are critical for accurate carbon accounting at a state or national scale and for carbon offsets projects to give a complete accounting of the effects of forest management on the carbon sequestered or emitted to the atmosphere. However, carbon within wood products is considered carbon that has been removed from the forest ecosystem and so is not included as part of the total forest ecosystem carbon stock.

The amount of carbon within a particular pool can be estimated by taking measurements or collecting samples, and repeated measurements can be used to calculate the amount and rate of change over time. Quantification of carbon pools requires intensive data collection, especially when a high degree of accuracy is desired. Permanent plots are often established and remeasured to detect change over time. This level of detail is not strictly necessary for incorporation into forest management plans, but understanding how different forest carbon pools are measured may be helpful for foresters (see Box 1).

BOX 1 | *Measuring Forest Carbon Pools*

Estimation of forest carbon pools often begins with delineating forest stands of similar forest type and condition (e.g., age class, site productivity) to stratify data collection.

Procedures for measuring carbon pools include[2,3]:

Aboveground biomass: Forest inventory data is collected using either a basal area prism or tree d.b.h. (diameter at breast height) and estimated heights from fixed area plots are recorded. Allometric equations are then used to calculate the total aboveground biomass. Stand-level carbon is estimated by scaling up from the plot to the entire forest stand. Understory and ground layer vegetation is a small proportion of this pool and may not be quantified in carbon pool measurements.

Belowground biomass: Direct measurement of this pool is not only time- and labor-intensive, but can also be destructive for forest soils, so this pool is typically estimated using regression models representing belowground biomass as a proportion of aboveground biomass.

Dead wood: Dead wood volume is measured within plots and then the carbon content of dead wood is estimated based on its degree of decomposition. Down dead wood is typically sampled with one line intersect per plot, with the diameter and decay or density class of wood recorded. Standing dead wood is typically recorded as part of the tree inventory, and an allometric equation is used to estimate the mass minus a percentage loss estimate based on the degree of crown breakage.

Forest floor: Estimation of this pool is often through direct harvesting down to the upper surface of the mineral soil within subplots. Live herbaceous biomass is excluded from the sample. Samples are dried and weighed. A sample of material is analyzed for carbon concentration to determine the amount of carbon in the sample.

Soil: The amount of carbon in soil is a function of the concentration of carbon, the density of the soil, and the depth of measurement. Carbon concentrations are measured through laboratory analysis (e.g., dry-combustion, elemental analyzer, or chemical oxidation methods). It is important that sample volume is accurately estimated to determine a precise estimate of soil bulk density. Sample collection is often to a fixed depth or the depth to refusal (e.g. the depth at which the probe can no longer be inserted). Due to the high variability in soil carbon levels at fine scales, many soil samples per plot are taken to estimate the size of this pool.

Carbon pools that are most affected by forest management activities include aboveground and belowground biomass and dead wood. Measurement of these pools provides a snapshot of how a particular forest stand or property compares with other similar stands within Massachusetts. A method for estimating these pools using basal area measurements can be found in *Climate Forestry Assessment: A Guide to Integrating Resilience and Carbon Data into a Massachusetts Forest Inventory.* These estimates, along with additional information found within this guide, can help inform possible management actions with the potential to increase carbon sequestration rates and storage within forest carbon pools in the coming decades.

Carbon Flux Through Forests

Most carbon enters the forest ecosystem through the process of photosynthesis, where plants use sunlight to turn carbon dioxide into sugars which are then used for plant growth and metabolism. This process of forming biomass from atmospheric carbon dioxide (CO_2) is known as sequestration. Unlike carbon pools, which are often visible and easily apparent, sequestration is a process where the accumulation (or uptake) of carbon in the ecosystem is only apparent over time. The rate of CO_2 conversion into forest biomass is controlled by many environmental factors such as temperature, moisture, and soil nutrient status, but is typically limited by the amount of leaf area that is present in the forest: the greater the leaf area, the higher the potential sequestration rate if all other environmental factors are the same. As forests mature and competition for available resources such as water and nutrients change, leaf area becomes only one of many factors that influence sequestration rates. As forests age, species composition or forest health may play a larger role in determining the rate of carbon accumulation in a stand.

Although many people think of carbon being "locked away" in trees and soils, the carbon contained within forest pools is far from static, but rather flows through the ecosystem over time. Carbon dioxide fixed into sugars through photosynthesis can be used to power a plant cell and be released back into the air over the course of days, or be turned into leaf tissue, wood, or roots. The allocation of carbon to these different parts of the plant can have an important influence on the expected residence time of that carbon in the ecosystem before it returns to the atmosphere:

- When the leaves fall to the ground in October, much of their carbon may be released into the atmosphere through decomposition within weeks to a few years.
- Carbon that was turned into stem wood can last as long as a tree's life span, which can range from decades to hundreds of years, or be dropped to the forest floor within a branch broken in a March nor'easter. Once the tree or branch dies, the carbon in dead wood may remain in that form for years to decades or more before eventually being decomposed and emitted back to the atmosphere as CO_2.
- Carbon finds its way into soils through many routes, including root growth and death and leaf litterfall. The residence time of carbon within the soil is highly variable: plant roots release carbon compounds into the surrounding soil (called the rhizosphere) and are consumed by soil bacteria and fungi within hours to days. Fine roots may die and decompose over the course of months to years. Many trees have symbiotic relationships with specialized fungi called mycorrhizal fungi, where the plants provide carbon in the form of sugars in exchange for the fungal-derived nutrients. Regardless of where they originate, carbon-containing materials in soil are digested by microbes, and some carbon is emitted back to the atmosphere as CO_2 while some carbon becomes chemically bound to soil particles and can persist anywhere from decades to thousands of years.

These are some of the various ways that carbon is transferred from one pool to the next within the forest ecosystem, ultimately returning to the atmosphere as a result of these ecological processes. These processes are affected by climate, disturbance, human activities, and other factors which determine not only the amount of carbon within each pool of the forest ecosystem, but also the longevity of carbon within the ecosystem.

Disturbances often shape forest ecosystem structure and composition, and in doing so can have a large impact on carbon: from losses of carbon to the atmosphere, transfers of carbon from one pool to another, and effects on post-disturbance carbon sequestration rates. Natural disturbance events such as windstorms and ice loading cause tree mortality that transfers carbon to dead wood, while tree damage that can reduce sequestration capacity from reduced leaf area for a period of years or longer. Chronic stressors such as invasive plants, insect pests, and tree diseases can also cause tree mortality, often over the course of years. Disturbance from forest harvest removes carbon from the ecosystem by transferring carbon from merchantable stems into wood products while tops and branches are often left as slash, going into the dead wood carbon pool. Disturbances can result in carbon loss from the soil pool as roots decompose and the carbon inputs from root growth dramatically decline in the years following cutting. The magnitude of impacts to live tree biomass and soil carbon pools directly relate to the size and intensity of the disturbance. Following a disturbance, carbon sequestration rates may be reduced until leaf area recovers, which depends on rates of tree recovery. In other instances, sequestration rates may increase if enough advanced regeneration is present and able to respond quickly to the available light.

Carbon Dynamics Over Time

The total amount of carbon in a stand, as well as in individual pools within the forest, is the result of many interacting factors, most importantly: stand age, tree density, disturbance history, forest type, and site quality. Carbon stock changes over time are primarily influenced by the rate of tree growth since this is the main source of carbon input into the system. Following a disturbance such as a clearcut harvest, there is an initial period during stand re-initiation when live tree carbon does not show much accumulation in the first 1-5 years, after which the live tree pool begins accumulating carbon more quickly as young trees grow (10-40 years). During this time of initially slow and then increasing sequestration, trees are creating the branches, foliage, and roots needed to capture light, compete for soil nutrients, and sequester carbon dioxide. During the stem exclusion or self-thinning phase, the rate of stand-level sequestration begins to slow down as individual trees increasingly compete for limited resources in the forest. As trees grow larger, they use a greater percentage of their carbon fixed through photosynthesis to maintain their biomass (beyond 50 years). Throughout the development from young to mature forest, the other carbon pools, such as dead wood and the forest floor, are slowly increasing as carbon is transferred from live trees to these pools (Fig. 1). Although the amount of carbon in dead wood and forest floor increases over time, most of the carbon within a typical forest in Massachusetts is found in live tree biomass and soil. Across all forest types, live trees and soil constitute 74% (44% and 31%, respectively) of the total forest carbon (Fig. 2). Additionally, a typical 80-year-old forest stand in the Commonwealth sequesters carbon at a rate of 0.5 tons of carbon per acre annually.

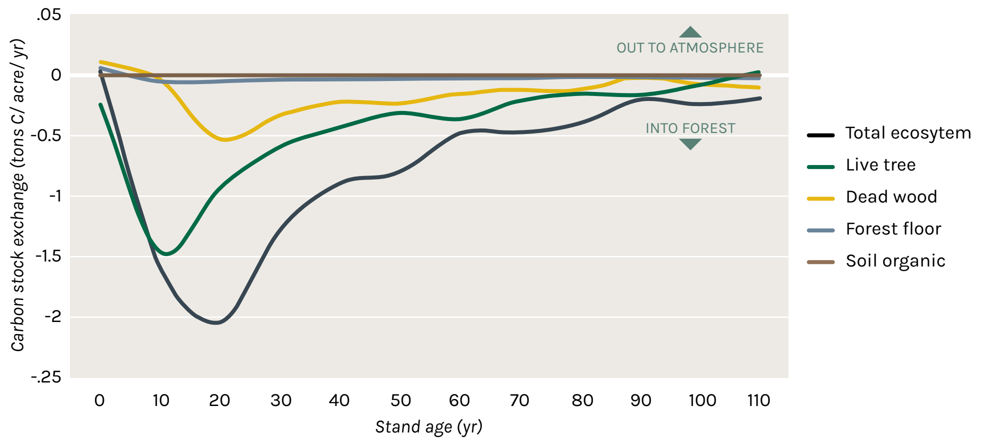

Figure 1. Carbon stock change by pool over 110 years following clear-cut harvest in Northeast Oak-hickory stands.[4]

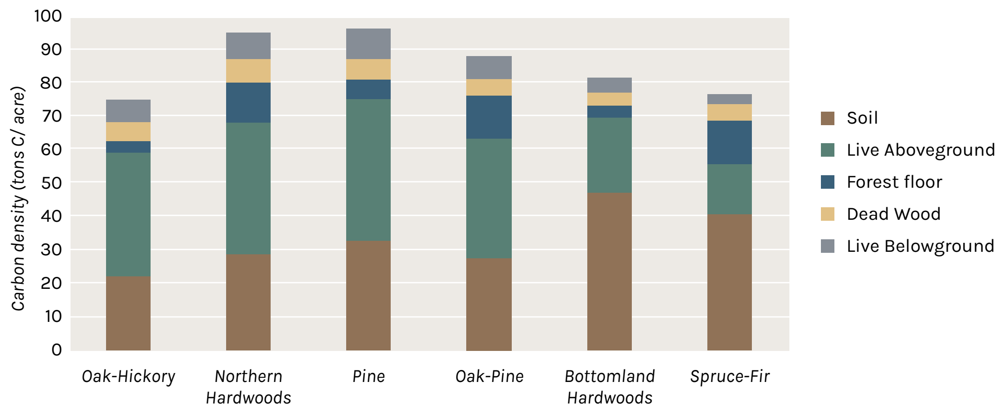

Figure 2. Carbon pool by forest type group in MA. (Data source: USDA Forest Service, Forest Inventory and Analysis)

Severe impacts from disturbances or invasive plants, such as tree girdling from oriental bittersweet, can reduce a forest stand's carbon sequestration rate.

Sequestration & Storage in Forest Stands

The dynamics of carbon over time from young to older forest stands do not necessarily describe how carbon sequestration rates of an individual tree might change over time. This presents what often seems to be conflicting information on sequestration rates reported in mature stands compared to rates observed in mature trees. Understanding the importance of spatial scale in measuring and describing sequestration rates is key to the apparent contradiction.

In young regenerating stands, trees are generally similar in size and competition for light is low, so stand-scale sequestration may be close to the sum of the growth rates of all the trees within that stand. Under these conditions, sequestrations rates (e.g. metric tons of carbon per acre per year) are at their highest point in stand development. In older closed-canopy forests there is strong competition for light, soil moisture, and nutrients, especially where there is vertical layering of the tree canopy. This competition results in decreasing stand-scale sequestration, despite individual large trees potentially sustaining high rates of carbon sequestration[5]. For example, several eastern white pines in western Massachusetts were found to gain the greatest biomass volume between 100-150 years old[6]. The simple explanation for this apparent paradox between the high rates of sequestration in some older, large-diameter trees and the relatively slower rates of older forest stands is due to the decrease in tree density of large trees in a stand over time from mortality. As a stand matures and uneven-aged conditions develop, the stand has fewer large trees that can support higher sequestration rates, and a greater number of smaller-diameter trees in the understory whose growth are suppressed.

Taken together, the abundance of small, light-limited trees that are growing slowly, few healthy large trees sustaining high sequestration, and some large trees in declining health with low rates of sequestration, results in lower sequestration rates on a per-acre basis. Similarly, large-diameter trees can also account disproportionately for stand-scale carbon storage in uneven-aged stands. One global dataset[7] suggests that trees approximately 24 inches d.b.h. account for 41% of the carbon stored within a forest, while a study from the Pacific Northwest[8] showed that trees > 21 inches d.b.h. or larger held 42% of total aboveground carbon despite representing 3% of the stems. In contrast, young stands with many small-diameter trees have lower biomass and so store less carbon relative to older stands. While the significance of large-diameter trees on sustaining sequestration and maintaining stored carbon highlights their importance to forest stand carbon, these benefits to climate mitigation are often countered by processes that impact older trees that result in greater carbon loss from stands.

Carbon Balance and Forest Disturbance

The amount of carbon coming into a forest relative to the amount being lost is known as the carbon balance. If not impacted by stressors or disturbances, healthy forests can remain carbon sinks for long periods of time, typically well beyond the age of their maximum economic value. In reality, most forest stands experience some level of periodic disturbance from events like high winds or insect pest outbreaks which can reduce carbon sequestration rates, if not also carbon stocks. As long as these disturbances are minor in severity, short in duration, and do not result in stand mortality, the forest will remain a carbon sink or quickly recover to one after the disturbance. As forests age and sequestration rates slow, low- to moderate-severity disturbances create opportunities for tree regeneration that are important for sustaining the system as a net sink while also maintaining high carbon storage[9]. When carbon emissions from the forest (e.g., release of CO_2 from plants, decomposers, and fire) are greater than inputs from plant productivity, the system becomes a net carbon source. For example, hemlock stands at Harvard Forest began to show declines in annual carbon sequestration from hemlock woolly adelgid in 2013. Tree growth declined to the point that carbon emissions were greater than inputs, and these stands became a carbon source to the atmosphere by 2015[10]. Forest health impacts from insect pests are just one example of how natural disturbances can affect carbon balance in a forest and turn a once healthy, mature stand from a carbon sink into a carbon source.

Climate Change Impacts on Carbon

Changing climatic conditions are increasingly impacting forests in New England, and many of the impacts are anticipated to have negative consequences for forest carbon stocks and carbon sink capacity into the future. These impacts include increased frequency and severity of disturbance and greater impacts of existing stressors in addition to the arrival of new stressors. Refer to *Managing Forests for Climate Change in Massachusetts* for a summary of climate impacts to forests in Massachusetts and management options to reduce climate risks.

Climate Impact	*Effects*	*Carbon connection*
Longer growing season	• Longer period for tree growth • Longer period for decomposer activity	• Increased net carbon sequestration from enhanced growth
Shorter, warmer winters; reduced snowpack depth and duration	• Increased freeze-thaw cycles, frost heaving/soil freezing damage to tree roots • Greater potential for damage to sensitive soils during forest harvest operations • Expanding populations of insect pests	• Reduced sequestration from tree mortality • Soil carbon loss from erosion or soil disturbance
More frequent and intense weather events (e.g., extreme precipitation events)	• Increased flooding and soil erosion • More frequent wind damage • Enhanced disturbance frequency and intensity	• Soil carbon loss from erosion • Reduced sequestration from tree mortality
Greater risk of growing season drought conditions	• Reduced tree productivity and forest health • More damage to trees from insects • Enhanced risk of wildfire	• Greater risk of carbon loss from wildfire • Reduced sequestration from tree mortality • Decreased rate of tree growth
Increased insect pest and pathogen outbreaks	• Reduced forest health • More damage to trees from insects	• Reduced sequestration from tree mortality • Decreased rate of tree growth
Increases in non-native invasive plant species	• Reduced tree regeneration • Enhanced tree mortality	• Lower carbon stocks from reduced regeneration or stocking • Reduced sequestration from tree mortality
Projected decline in suitable habitat for many northern tree species	• Reduced tree regeneration • Enhanced tree mortality	• Lower carbon stocks from reduced regeneration and stocking • Reduced sequestration from tree mortality
Conditions may become more favorable for some southern tree species	• Enhanced tree growth or regeneration of climate-adapted species	• Higher carbon sequestration • Reduced risk of disturbance-induced carbon loss where climate-adapted species are abundant

Climate change and its impacts will affect different parts of the landscape in unique ways. Tree species may vary in their responses to warming temperatures, changing precipitation, or greater pressure from insect pests, while different sites may vary in how drought-prone their soils are or their susceptibility to extreme weather events such as windthrow, flooding, or ice damage. Species composition, as well as site characteristics such as soil type, elevation, aspect, and landscape position can alter the vulnerability of a species or forest type on a particular site to these various climate impacts. More information on the vulnerability of common forest types to climate impacts is summarized in the *New England and Northern New York Forest Ecosystem Vulnerability Assessment and Synthesis* and the *Climate Change and Massachusetts Fish and Wildlife* reports (see Resources).

The greater the vulnerability to climate impacts, the more climate change is anticipated to threaten the carbon stored on those sites, or the capacity of the forest in those locations to sequester carbon in the coming decades. Greater vulnerability to climate impacts that threaten a forest's capacity to be a carbon sink may signal a need to integrate an assessment of climate risks to maintaining carbon benefits, as well to a landowner's other goals, into management plans.

Effective management of natural and working lands for carbon benefits is often included in planning for climate mitigation. These actions, often called "natural climate solutions", begin with considering carbon goals in land management planning[11]. While there is no silver bullet or one-size-fits-all strategy for the management of forests for carbon benefits, carbon mitigation options generally fall into three categories:

- *Avoid forest loss* through conversion to other land uses, such as residential or commercial development or agriculture, or failure to regenerate after severe disturbances.
- *Reduce forest ecosystem carbon emissions* from wildfire, drought, pests and pathogens, tree mortality caused by disturbance or other climate-related stressors, and unsustainable forest harvesting practices that reduce tree growth or increase tree mortality.
- *Enhance forest carbon sequestration rates* through actions that increase tree growth or the transfer of carbon into long-term stable forest carbon pools.
- *Ensure prompt and successful regeneration* to a diverse and fully stocked stand.

Just as the site conditions and management goals and objectives differ between forest stands, so do the considerations and options for integrating carbon into forest management or stewardship plans. Key considerations include how carbon goals might align or conflict with other landowner goals, how actions might impact all carbon pools within the ecosystem (not just the live tree carbon pool), and how management—including harvesting trees or reducing harvests, or the many other activities that fit into forest management—might impact carbon sequestration into the future. Ideally, management options and implications for carbon sequestration, storage, and other management goals are discussed with landowners over a range of timescales from short-term (<10 to 20 years) to long-term (20+ years), in order to identify how co-benefits and tradeoffs might emerge over time.

Principles for Managing Forest Carbon

Carbon dynamics in forest ecosystems are complex and may feel overwhelming to landowners, foresters, and scientists alike. The following principles can serve as a starting point for integrating carbon and climate change into forest management plans:

Keep forests healthy

Foresters routinely consider the risks that disturbances and forest health issues pose to the production of timber, enhancement of wildlife habitat, and other management goals. Responding to disturbance and forest health threats, which create an unintended loss of carbon storage or carbon sequestration capacity in a stand, is often a starting point for carbon management. Best management practices to protect soils and waterways may not only reduce negative impacts to forest growth and aquatic ecosystems, but can also help retain soil carbon. Recognizing that soils accumulate carbon very slowly over time yet play a critical role in carbon storage within the ecosystem highlights the importance of protecting soils from disturbance such as erosion and compaction.

Address climate risks and forest vulnerabilities

A changing climate is increasing the risks to forests from many existing stressors, such as increased pressure from insect pests, invasive species, and storm damage to trees. Climate change is also changing patterns of precipitation, often increasing the intensity and frequency of both floods and drought. These climate change impacts are beyond the natural range of variation experienced by present-day northeastern forests and may result in the decline of health and productivity of some tree species and forest types into the future. Identifying which climate impacts are most important for a particular site as part of an adaptation planning process can inform effective actions for maintaining or increasing its carbon storage or sequestration. For example, if drought-related tree mortality is an impact of concern, thinning overly-dense stands might be a priority management action for reducing carbon loss on a property. Refer to *Managing Forests for Climate Change in Massachusetts* for additional information on climate impacts, forest vulnerability, and adaptation planning.

Recognize tradeoffs between management goals

Landowners often have many goals for their forests, and it is not always possible to achieve every goal on every acre. Considering carbon goals often requires an understanding of where and how carbon management actions can support other goals, and where tradeoffs may exist. For example, creating areas of young or early successional forests may be important for landowners with goals for enhancing wildlife diversity by creating habitat for species that require more open canopy conditions. Harvests to meet these objectives reduce carbon storage in the impacted areas and likely result in carbon emissions. Although the young forest will likely sequester carbon quickly if trees regenerate, the overall impact may be less carbon than if the management did not occur. The recognition of these potential tradeoffs helps landowners understand the carbon consequences of their management decisions, to enable prioritizing their goals for their forest.

Anticipate the timing of carbon benefits

Practices such as regeneration harvests, thinnings, or allowing a stand to continue to grow without intervention may all have carbon benefits, but these benefits may be realized over different timescales. Depending on the prescription or management action implemented, the benefits for carbon may occur in the relative near-term or be realized in the decades following treatments. For example, allowing for longer rotations can provide immediate carbon benefits as carbon loss from harvest is delayed and stored carbon continues to accrue. In contrast, thinning treatments can provide near-term (~20-30 years) benefits to carbon as tree growth is enhanced from reduced competition, although at the cost of an immediate (0-20 years) loss in carbon storage. Adaptation-focused actions such as regeneration harvests are intended to shift species composition to better align with future climate conditions like hotter and drier summers. It might take many more decades before carbon benefits become apparent following this type of treatment, but ultimately the abundance of better-adapted tree species will sustain growth rates that can provide for greater carbon sequestration and storage compared to the existing trees. Long-term carbon benefits from adaptation actions are most often due to anticipated mortality or reduced growth of the existing trees when those species are expected to be at greater risk of impacts into the future.

For more information on how to consider forest health, climate impacts, trade-offs, and timing of carbon responses interact for individual management actions, see Healthy Forests for Our Future: A Management Guide to Increase Carbon Storage in Northeast Forests.

BOX 2 | Carbon Benefits of Wood After Forest Harvest

Carbon is removed from a forest when trees are harvested, but this does not necessarily mean that this carbon is emitted back to the atmosphere. Wood products and bioenergy provide additional ways carbon can be stored or emissions from burning fossil fuels can be reduced.

Wood Products - The carbon storage value of any given wood product depends on how the product is made, the useful lifetime of the product, and what happens to the wood after the product has reached the end of its life. Carbon storage in products is maximized when the amount of waste produced during processing is minimized and when products have a long lifespan. For example, wood that goes into single-family home construction has a duration of 80-100 years compared to an average 6-year lifespan for paper products[12].
In order to fully understand the carbon storage value of a product, understanding the full lifecycle of a product is needed. This means knowing what happens to the product after its lifespan has ended (such as recycling compared to landfill disposal). Wood products take less energy to produce than energy-intensive materials such as concrete or steel, so there are carbon benefits when wood is used instead of these products, plus the additional benefit of the carbon stored in the wood itself. Forest management that emphasizes the production of long-lived, durable wood products, such as silvicultural practices that influence the species or size of trees available for timber production, can increase the carbon mitigation benefits of wood products.

Bioenergy – Wood can be used to produce electricity, heat, and even transportation fuels. Sources of bioenergy can include harvesting firewood, utilization of harvest residues, wood chips from sawmills, municipal solid waste, or by-products from pulp production. While firewood and harvest residues can offset the burning of fossil fuels for energy production, these practices could also reduce carbon in dead wood pools in the ecosystem and the many benefits that snags or down woody material can provide. Sites where excessive fuel loads present an elevated concern for wildfire risk could be targeted for utilization of harvest residues. The use of small diameter or low-grade wood for bioenergy can provide opportunities for improving forest health, such as removing diseased or vulnerable species that can provide future carbon benefits for the ecosystem. Like the use of harvest residues, these actions present a tradeoff with the loss of carbon from the ecosystem and the greatest benefit for carbon may be realized in sites where there are concerns for forest health, such as overstocked, vulnerable, or degraded stands.

Integrating Carbon Goals into Forest Management

Many forest management actions that help landowners manage their property for healthy forests, diverse habitats that support wildlife, or stands that grow wood quickly also align with goals for carbon. Common sustainable forestry practices, such as removing populations of invasive species and protecting soil and water resources during management, provide both immediate and long-term carbon benefits. At the same time, there can be times where goals are not compatible. For example, creating areas of early-successional habitat for certain wildlife[13] may be at odds with a landowner's goals of maintaining large carbon stocks in mature, well-stocked stands. As with the creation of any forest management plan, working with a landowner to clearly identify the goals for their property is important. Refer to *Caring For Your Woods: Setting Goals* for helping landowners identify and prioritize goals for their woodlands that reflect their interests and enable well-informed management decisions.

Having the necessary resources and knowledge helps foresters to not only recognize actions that reduce the risk of carbon loss in the future or identify opportunities to enhance carbon sequestration, but also to feel comfortable talking to landowners about integrating carbon into management plans. A first step in planning for carbon goals includes ensuring a forest is healthy and is not at risk of carbon losses. A climate-informed forest management plan that intentionally considers climate change impacts on carbon storage and sequestration, as well as associated management actions, as described in the *Managing Forests for Climate Change in Massachusetts* guide, is a great place to start. When integrating carbon goals into forest management and stewardship plans, it is helpful to discuss the various management concerns that could impact forest health and the ability to maintain carbon stocks and sequestration capacity, or options for potentially enhancing carbon stocks or increasing sequestration rates in their stands. A "menu" of potential climate change adaptation actions for a variety of topics, including forest carbon[14], can be browsed online at *adaptationworkbook.org/strategies*.

Management Impacts on Carbon Dynamics

Forest management involves a range of practices that can influence carbon storage and sequestration in forests, from short to long timeframes. Specific management decisions and actions influence the amount of carbon removed from the ecosystem, which can alter the trajectory of future carbon storage. Management also influences stand structure and composition, which can alter the potential for climate change impacts and stressors that could impact carbon sequestration or storage in the decades to follow. Climate-related disturbance and stressors are anticipated to increase in the future, but the vulnerability of stands to these impacts is not the same in every forest. The decision on whether to actively manage to reduce risks of undesirable climate impacts, where to implement management, and the specific actions taken will likely influence the risks to carbon mitigation capacity or the ability to achieve carbon-related goals. The following scenarios provide some examples of how climate change vulnerability and management choices may influence forest carbon in Massachusetts forests.

Low Vulnerability | Passive Management

TIME 1 *TIME 2*

Passively managed stands that have low risk from disturbance and stressors will continue to age and accumulate carbon in the absence of harvest. Stand complexity often increases as trees grow larger and the forest develops more structural complexity. Species composition may shift to include more shade-tolerant species in the mid-canopy or understory. Over time, most carbon pools increase: the increase in carbon is primarily in the live aboveground and belowground biomass pools as trees grow larger; dead wood pools often increase as well.

Low Vulnerability | Active Management

TIME 1 *TIME 2*

Some forest stands can be actively managed to accelerate the development of late-successional stand characteristics using practices that mimic low-severity natural disturbances. These management practices can include reduced harvest, enhancements of vertical structure, elevated quantities of dead wood (including both snags and down dead wood), and the creation of variable spacing among trees. These are more likely to have intended carbon benefits where risks of carbon losses are low. Application of a variety of practices can allow for regeneration while also releasing the crowns of the largest trees. These practices seek to balance carbon storage and sequestration, maintaining higher levels of stored carbon relative to practices that remove greater biomass, such as regeneration harvests using gaps, while potentially enhancing sequestration rates more than passive management[18]. The intentional increase in stored carbon through greater stand complexity may additionally enhance the stability of stored carbon through the further reduction in climate risk that comes with greater forest diversity.

High Vulnerability | Passive Management

TIME 1

TIME 2

Forest stands may be considered high vulnerability due to many different stand conditions. These include the presence of species susceptible to changes in climate such as warmer/ drier conditions or forest health issues such as insect pests, or site conditions that increase the exposure to climate impacts like drought or extreme weather. Passively managed stands that are at high risk of disturbance or impacts from stressors may lose carbon over time due to elevated tree mortality. Carbon stocks may be reduced in live aboveground and belowground biomass, while more carbon may be present as dead wood, particularly snags and downed dead wood. Fewer large-diameter trees will remain, resulting in lower carbon stocks compared to low-vulnerability forests allowed to grow without forest harvest. Carbon loss from increased natural disturbance frequency and severity has the potential to reduce carbon storage more than timber harvesting activities on highly vulnerable sites[15]. The types of disturbance, including their severity and frequency, will affect how carbon is redistributed between live and dead wood pools in these vulnerable forests. Carbon transferred to dead wood pools is not immediately lost from the system but is typically emitted back to the atmosphere slowly over time, while the reductions in aboveground live tree biomass lower the capacity for sequestration.

High Vulnerability | Active Management

TIME 1

TIME 2

Active management may reduce the vulnerability of forests to climate change, thereby sustaining forest carbon storage and sequestration. Over time, high-vulnerability stands actively managed for adaptation are likely to have greater carbon stocks and sequestration rates compared to high-vulnerability stands not managed with a focus on adaptation. Management to reduce climate risks can result in enhanced age-class diversity, greater species diversity from regeneration of shade-intolerant species, and more structural heterogeneity. Collectively, this can decrease carbon loss from natural disturbances[16]. Additional carbon benefits may come from higher growth rates of residual trees that are well-adapted to changing climate conditions, as well as enhanced regeneration, especially if regeneration includes climate-adapted species[17,18]. Although active management to adapt forests to changing conditions removes carbon from a stand in the near-term, the carbon benefits result from reduced risk of severe disturbance improves long-term, stable carbon storage and enhanced capacity for lasting carbon sequestration. Production of wood products may provide an additional climate benefit if products are long-lived or substitute for more carbon-intensive products.

Examples of carbon management actions that address common forestry concerns

Management Concern	*Potential Carbon Management Actions*	
Young forest stands (stand initiation - stem exclusion)		
Stand stocking: Is the stand sufficiently stocked with a diversity of species, including low-risk or future-adapted species?	• Enrichment planting with a variety of native species that are expected to do well under future conditions	• Implement practices to increase protection of regeneration from herbivory, such as increasing hunting, constructing deer exclosures, or using tree tubes
Tree competition or mortality: Is the stand at risk of excessive competition that might increase risk from drought or forest health issues?	• Release of future-adapted species ordesired growing stock (such as precommercial thinning)	• Implement weeding or brush removal to release desired growing stock from competition
Mature forest stands		
Stand stocking: Is the overstory sufficiently stocked, including low-risk or future-adapted species?	• Enrichment planting with a variety of native species that are expected to do well under future conditions	• Implement practices to increase protection from herbivory, such as increasing hunting, constructing deer exclosures, or using tree tubes
Tree health: Is there damage from insect pests or diseases, or excessive competition that might increase risk from drought or forest health issues?	• Consider prescriptions to increase species diversity or regenerate future-adapted species	• Thin around crop trees, retaining existing healthy, full-crowned trees with good form while improving sequestration through enhanced growth. Carbon benefits are enhanced by thinning from below and retaining a diversity of future-adapted species
Stand complexity: Is the development of coarse woody debris or snags sufficient?	• Implement practices that enhance structural complexity in living and dead wood, such as retaining low-quality timber on site for down dead wood (such as chop-and-drop) and retaining slash, tree tops, and existing snags when present	• Designate reserves and/or legacy trees, such as trees in declining condition (as long as no serious diseases or pathogens are present), to retain as eventual snags or downed wood
Soil functioning: Are there actions that can help maintain or add to soil carbon?	• On wet sites, fell or redistribute residues to areas prone to saturation where decomposition will be slow	• Broadcast residues, such as chipped wood, on impacted sites such as forwarder trails, decking and landing areas, and haul roads
Carbon stocking: Is the stand considered low-vulnerability to impacts from climate and other stressors?	• Increase the time between harvests by extending rotations (even-aged stands) or delaying harvest entry (multi-aged stands) to allow for additional tree growth	• Create or enhance no-cut areas on or adjacent to sites where harvest may impact soils (slopes, wet sites, sensitive soils), or other actions that increase the amount of retention during harvest actions

Management Concern	Potential Carbon Management Actions	
All forest conditions		
Maintaining soil carbon during active management: Are there sites with soil conditions more prone to carbon loss such as wetlands and erodible soils?	• Use slash mats, tracked or wide-tired machines, or minimize entries to reduce mineral soil exposure, compaction, and rutting.	• Minimize the footprint of skid trails used by machinery and conduct mechanized harvests during intermediate moisture, frozen, or snow-covered conditions
Post-disturbance forest recovery: Are there risks to forest recovery following disturbance?	• Monitor for establishment of invasive species that may limit tree regeneration or impact remaining mature stems (e.g., invasive vines)	• Create suitable conditions for regeneration through site preparation or plant larger seedling sizes of future-adapted species to help increase survival

Increasing the retention of healthy trees and dead wood within the stand—while not increasing stand vulnerability and still meeting the intended silvicultural objectives—is likely to provide the most effective action for *near-term* carbon benefits during active forest management. Optimizing retention, especially of trees expected to be aligned with future climate conditions and with high crown ratios and density, improves carbon benefits, since the existing photosynthetic capacity drives sequestration in the immediate future. As noted previously, the decision to manage for higher retention and near-term carbon benefits is often determined by considering the combination of landowner goals besides carbon and the anticipated vulnerability of the forest.

This guide intends to provide information to bolster natural resource professionals' understanding and build confidence in their existing knowledge of forest carbon. After all, much of carbon management is about what foresters already know: how forests grow. To help foresters offer guidance on incorporating carbon into forest management, this section provides information on questions landowners might be interested in discussing. An overview of forest carbon in landowner-friendly language is provided in Caring for Your Woods-Managing for Forest Carbon.

How could carbon management work with other goals for my property?

There are many goals that often work well with maintaining high carbon stocks within stands, such as management for wildlife habitat, aesthetics, and recreation. For example, goals centered around recreation, such as hunting or maple sugaring, typically focus on actions that maintain a well-stocked and healthy forest that align with carbon goals. In these instances, tailoring forest management planning for non-carbon objectives in ways that best support the overall goal of managing carbon may be the best option. Not all goals align with carbon goals. For example, maintaining high carbon stocks may not be compatible with large openings for birds, or creating a viewshed. Landowners interested in generating income from timber or creating early successional habitat for wildlife species that depend on those conditions may be able to align management plans with young forest conditions that sequester carbon quickly, recognizing that these goals reduce forest carbon storage in the near term. For landowners who have a diverse set of objectives for their properties, carbon may align with some but not all goals. Foresters can assist landowners in assessing trade-offs and optimizing management plans by zoning management activities to alleviate potential conflicts, such as establishing open habitats in areas of lower productivity and setting aside sites with more productive areas as either reserves or stands emphasizing active management for tree growth. This approach of balancing multiple objectives to optimize carbon benefits based on the set of values a landowner has for their woods is likely to be more common than a single objective of maximizing carbon at the expense of everything else.

Does eliminating harvest provide the biggest carbon benefit?

Among the many messages heard regarding forests as a natural climate solution, one of the most prevalent messages relates to eliminating forest harvest and allowing forests to grow old and maximize their climate mitigation potential. Reducing or eliminating harvesting activities on many sites will increase forest carbon in the near term, however active management provides carbon benefits as well.

- Sequestration and storage: the rate of sequestration of additional carbon diminishes as forests mature. Maintaining low- to moderate-levels of disturbance, either through natural or intentional processes, can maintain both high carbon stocks while sustaining high rates of sequestration by creating structurally complex forests[20].
- Maintaining a healthy forest is important for preventing the release of CO_2 back to the atmosphere. Forests vulnerable to climate impacts, disturbance, or forest health issues are at risk of carbon loss. Active management in these situations can reduce risk, improving the longevity of carbon on the land and the ability to sequester additional carbon.

Old-growth forests (forests that were never cleared following European settlement) in the Northeast are rare and valued places that are protected for their unique ecological value. It is important to recognize that these systems developed over long periods of time, largely under conditions different from our current climate and the climate of the future. Many of our current forests—even mature forests a century or more old—are recovering from past clearing, agricultural abandonment, and multiple harvests over the past century and a half. This legacy often results in very different stand conditions from an old growth forest. These forests are often lacking in species diversity and structural complexity, which combined with climate and other stressors make them more vulnerable to carbon loss. Assuming all mature and old-growth forests will store additional carbon into the coming decades (or longer) by eliminating harvest is not supported by our current scientific understanding of climate vulnerability, so assessing site vulnerability is critical.

How do harvest and disturbance affect forest carbon?
The effects of harvest on ecosystem carbon storage are directly proportional to the amount of biomass removed from the system (refer to the description of carbon benefits of wood products, BOX 2). The impacts on future tree growth and sequestration are influenced by which trees are retained and how they are distributed. For example, trees retained in aggregated reserves may grow more slowly due to competition for light compared to retained trees in a dispersed arrangement following a thinning treatment. However, natural disturbances impact forest carbon in other ways. Disturbance from storm damage (e.g. wind and ice) or tree mortality from insect pests or tree pathogens may not have an immediate impact on carbon stocks, as the biomass of damaged trees remain in the ecosystem and only slowly decompose. Generally, post-disturbance sequestration rates are low for a period of time but as tree cover increases, so does carbon sequestration. However, sequestration rates might not recover fully if remaining trees are damaged and prone to further health issues. Depending on the nature and scale of impact, this recovery may take years to many decades.

Can carbon benefits be maintained given the impacts of insect pests such as emerald ash borer and hemlock woolly adelgid?
The benefits of proactive management to reduce the risk of impacts from insect pests or pathogens are likely to be similar whether your goals are for carbon benefits or something else, such as timber income or forest habitat for wildlife. Reducing stand densities can decrease risks from drought, and potentially improve the health of trees vulnerable to certain insect pests such as hemlock woolly adelgid. Management such as thinning can also aim to shift species composition by focusing on retaining tree species expected to do well into the future, either because these species are anticipated to grow well under future climate conditions or because they currently have fewer pest and disease concerns. These are a few examples of the many climate adaptation actions that can provide carbon benefits. See the *Managing Forests for Climate Change in Massachusetts* guide for more adaptation examples that can reduce risk of carbon loss from insect pests.

Are forest stewardship climate plans compatible with carbon offset projects?
The Massachusetts Forest Stewardship Program is compatible with the creation of carbon offset projects. In fact, many forest carbon programs require landowners to have a forest management plan and forest stewardship plans can often fulfill this need (it's always wise to ask individual programs about their requirements). A landowner sells carbon when enrolled in a carbon offset program, which will likely limit the forest management options available. Management practices undertaken must generate additional stored forest carbon compared to the regional baseline to generate carbon credits. Selling carbon credits does not invalidate a forest management plan, although landowners should be encouraged to assess compatibility of offset program requirements with planned activities and Chapter 61 programs if enrolled. More information for landowners on forest carbon markets can be found at the *Securing Northeast Forest Carbon Program*, as well as in the Carbon Resources section at the end of this guide.

Staff with NIACS and the Forest Service talk about the impacts to carbon from forest management and disturbance at a field tour on the Green Mountain National Forest.

Adaptation
Adjustments, both planned and unplanned, in natural and human systems in response to climatic changes and subsequent effects. Ecosystem-based adaptation activities use a range of opportunities for sustainable management, conservation, and restoration.

Biomass
The mass of living organic matter (plant and animal) in an ecosystem. Biomass also refers to organic matter (living and dead) available on a renewable basis for use as a fuel; biomass includes trees and plants (both terrestrial and aquatic), agricultural crops and wastes, wood and wood wastes, forest and mill residues, animal wastes, livestock operation residues, and some municipal and industrial wastes.

Carbon offset/carbon credit
Standard, tradeable unit used to represent the removal of one ton of carbon dioxide from the atmosphere. 1 carbon offset/credit = the amount of carbon in 1 metric ton of carbon dioxide.

Carbon pool
Different types of biomass found within forests. The amount of carbon stored in pools changes over time and in response to various factors. Pools can be defined in several ways, but generally include the following: live aboveground biomass (trees, shrubs, herbs, grasses), live belowground biomass (roots), dead wood (standing dead trees, stumps, logs), forest floor (leaves, small branches), and soil organic matter.

Carbon sequestration
The process of plants using sunlight to capture CO_2 from the air and convert it into plant biomass, including wood, leaves, and roots.

Carbon stocks
The quantity of carbon contained or stored within various pools in an ecosystem.

Carbon storage
Carbon that is retained long-term within the forest, contained within various “pools”, and quantified in “stocks” (see definitions above).

Climate change
A change in the state of the climate that can be identified (such as by using statistical tests) by changes in the average and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external factors, or to persistent human-caused changes in the composition of the atmosphere or in land use.

Disturbance
Stresses and destructive agents such as invasive species, diseases, and fire; changes in climate and serious weather events such as hurricanes and ice storms; pollution of the air, water, and soil; real estate development of forest lands; and timber harvest. Some of these are caused by humans, in part or entirely; others are not.

Diversity
The variety and abundance of life forms, processes, functions, and structures of plants, animals, and other living organisms, including the relative complexity of species, communities, gene pools, and ecosystems at spatial scales that range from local through regional to global. There are commonly five levels of diversity: (a) genetic diversity, referring to the genetic variation within a species; (b) species diversity, referring to the variety of species in an area; (c) community or ecosystem diversity, referring to the variety of communities or ecosystems in an area; (d) landscape diversity, referring to the variety of ecosystems across a landscape; and (e) regional diversity, referring to the variety of species, communities, ecosystems, or landscapes within a specific geographic region.

Fluxes
The amount of carbon exchanged between land, oceans, atmosphere, and individual carbon pools over a specified period of time.

Mitigation
In the context of climate change, actions that reduce the amount of heat-trapping greenhouse gases, such as CO_2, in the atmosphere to minimize changes in the earth’s climate. Actions can include avoiding or reducing emissions of greenhouse gases into the atmosphere, as well as removing greenhouse gases that are already present in the atmosphere.

Resilience
In ecology, resilience is the capacity of an ecosystem to respond to a perturbation or disturbance by resisting damage and recovering quickly.

Structural diversity
The amount of three-dimensional variation within a forest stand. This is influenced by a combination of plant species diversity, height classes (vertical structure), and standing and downed dead wood, is often used as an indicator for biodiversity of forest ecosystems.

Vulnerability
The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the impacts and adaptive capacity of a system. A system may be considered to be vulnerable if it is at risk of a composition change leading to a new identity, or if the system is anticipated to suffer substantial declines in health or productivity.

RESOURCES

Massachusetts Department of Conservation and Recreation – Climate Forestry www.mass.gov/guides/climate-forestry

Climate Change Adaptation Resources

- *Forest adaptation resources: Climate change tools and approaches for land managers, 2nd edition.* www.nrs.fs.usda.gov/pubs/52760

- *New England and northern New York forest ecosystem vulnerability assessment and synthesis* www.nrs.fs.usda.gov/pubs/55635

- *Adaptation strategies and approaches for different topics* www.adaptationworkbook.org/strategies

- *Resilient MA: Climate Change Clearinghouse for the Commonwealth* Resilientma.org

- *Climate Change and Massachusetts Fish and Wildlife:*

  Volume 1-Introduction and Background www.mass.gov/doc/climate-change-and-ma-fish-and-wildlife-vol1-introduction-and-background/download

  Volume 2-Habitat and Species Vulnerability www.mass.gov/doc/climate-change-and-ma-fish-and-wildlife-vol2-habitat-and-species-vulnerability/download

  Volume 3-Habitat Management https://www.manomet.org/wp-content/uploads/old-files/Climate%20Change%20and%20Massachusetts%20Fisheries%20and%20Wildlife%20Reports,%20Vol.%203%20April%202010.pdf

Forest Carbon Resources

- *Massachusetts Department of Conservation and Recreation: Caring For Your Woods-Managing For Forest Carbon* www.mass.gov/doc/caring-for-your-woods-managing-for-forest-carbon/download

- *USDA Forest Service: Considering Forest and Grassland Carbon in Land Management* https://www.fs.usda.gov/research/publications/gtr/gtr_wo95.pdf

- *Northern Institute of Applied Climate Science: Forest Carbon Management* www.forestadaptation.org/focus/forest-carbon-management

- *Mass Audubon and Massachusetts Department of Conservation and Recreation: Forest Carbon Market Solutions: A Guide for Massachusetts Municipalities* www.mass.gov/doc/forest-carbon-market-solutions-a-guide-for-municipalities/download

- *New England Forestry Foundation: Exemplary Forestry standards for Southern New England's Central and Transition Hardwood forests* www.newenglandforestry.org/wp-content/uploads/2021/12/EFHardwoods-one-page-metrics-and-standards-Final-v3.pdf

- *The Nature Conservancy and Northern Institute of Applied Climate Science, Healthy Forests for our Future: A management guide to increase carbon storage in Northeast forests* www.nrs.fs.usda.gov/pubs/63533

- *Pennsylvania State University Extension: Forest Owner Carbon and Climate Education (FOCCE)* www.sites.psu.edu/focce/

- *Securing Northeast Forest Carbon Program* www.northeastforestcarbon.org

- *MassWoods (UMassAmherst): Forest Carbon: An Essential natural Solution to Climate Change* masswoods.org/sites/masswoods.org/files/Forest-Carbon-web_1.pdf

Other

- *MassWoods (UMassAmherst): Restoring Old-Growth Characteristics to New England's and New York's Forests* https://masswoods.org/sites/default/files/pdf-doc-ppt/Restoring-Old-Growth-Characteristics.pdf

- *Society of American Foresters: Addressing Proforestation on Public Lands* https://www.eforester.org/Main/SAF_News/2022/SAF-Develops-Resource-on-Proforestation.aspx

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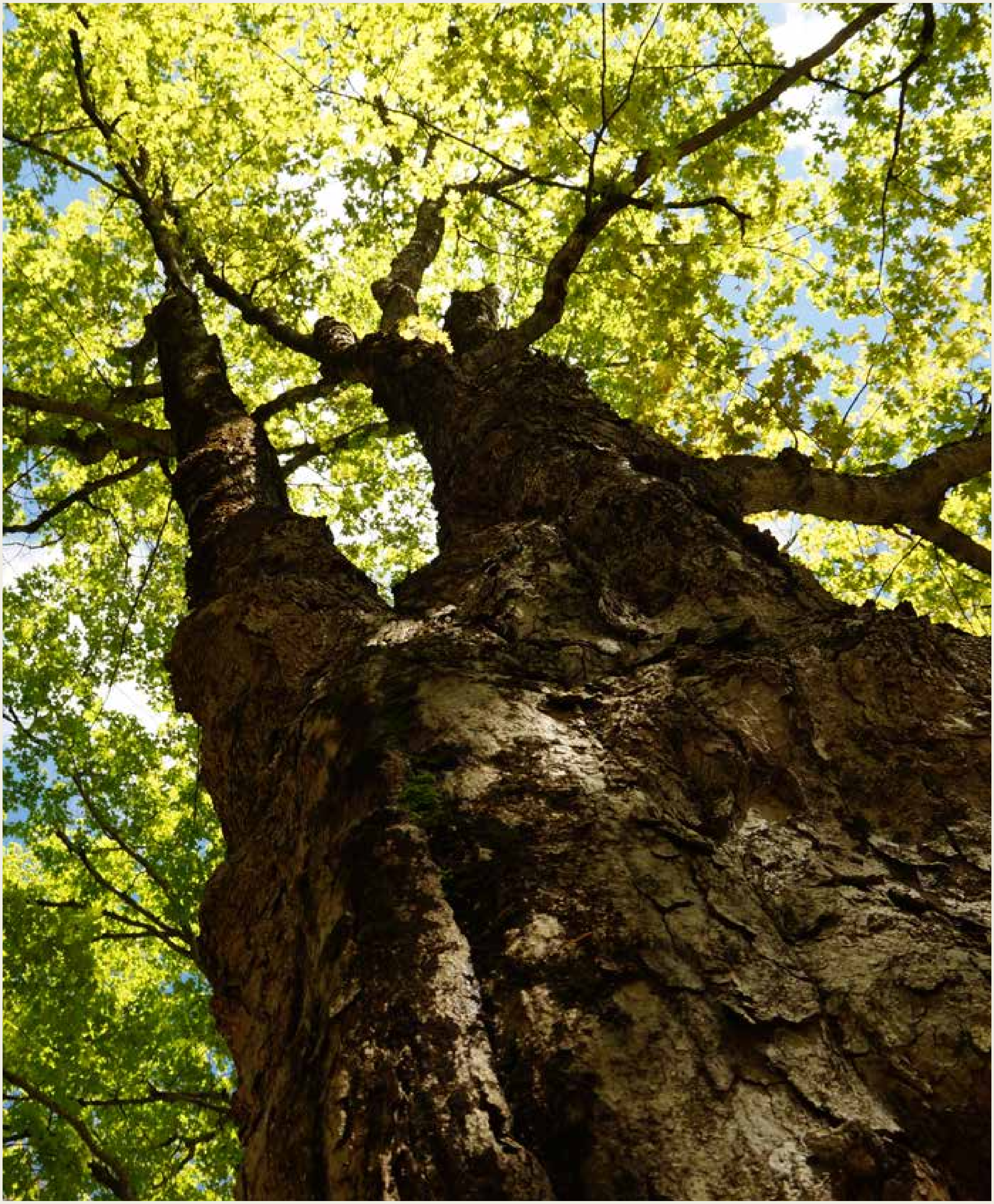

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