FOREST CARBON

An essential natural solution for climate change

UMass Amherst

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(MAIN PHOTO) Photo by Vermont Land Trust/David Middleton
(LEFT CIRCLE) Photo by Adella Catanzaro
(RIGHT CIRCLE) Photo by Adella Catanzaro

Introduction

YOUR FOREST HAS ALWAYS PROVIDED TREMENDOUS PERSONAL AND PUBLIC BENEFITS, INCLUDING CLEAN WATER, WILDLIFE HABITAT, RECREATIONAL OPPORTUNITIES, AND FOREST PRODUCTS. RECENTLY, AN ADDITIONAL FOREST BENEFIT HAS BEEN RECOGNIZED: FORESTS AS AN ESSENTIAL NATURAL SOLUTION FOR CLIMATE CHANGE.

Climate change can seem like an overwhelming challenge, and it can be difficult to find meaningful ways to make a difference. The good news is that as a forest landowner, or as someone who helps to steward forests, you can have a significant impact on climate change through the land-use decisions you make—specifically your decisions about the future use and management of your forest. These land-use decisions play a regionally and globally important role in reducing the effects of climate change.

Forests take in carbon dioxide from the atmosphere to make energy through photosynthesis. Trees then use this energy to maintain themselves and grow. Through this process, trees capture carbon in the form of wood and other organic matter, such as leaves. In fact, one half of a tree's weight consists of stored carbon. Since more than 80 percent of New England is forested, our landscapes play a globally important role in both sequestering and storing carbon, ultimately helping to reduce the impact of climate change. Most of New England's forests are owned by families and individuals. Therefore, the land-use decisions family forest owners make will have the greatest impact on the amount of carbon our forests absorb from the atmosphere and store as a means to reduce the effects of climate change. There is also a significant amount of New England forests that are owned by public agencies, conservation organizations, and corporations, whose actions can also reduce the effects of climate change.

Many landowners have begun to ask how their forest management strategy affects the carbon within their forest and thus the forest's ability to mitigate climate change. Every strategy has its trade-offs; therefore, to meet all of society's needs, we will ultimately need a mix of passive and active strategies across the region. What role will your forest play?

The intent of this publication is to help prepare you to make informed decisions about your land by giving you a better understanding of the role carbon plays within your forest, the impacts of various land-use options on forest carbon, and the trade-offs of these decisions.

A **CARBON POOL** IS A PART OF THE FOREST THAT STORES CARBON AND CAN ACCUMULATE OR LOSE CARBON OVER TIME

(e.g., live aboveground biomass, such as trees, soil, and organic matter).

2 There are two basic aspects to a carbon pool: how much it contains, and how much it is changing. These aspects are referred to as **carbon storage** and **carbon sequestration**.

The terms *storage* and *sequestration* are often used interchangeably; however,

EACH ONE HAS A SPECIFIC MEANING AND REACHES ITS MAXIMUM LEVEL AT DIFFERENT TIMES DURING FOREST DEVELOPMENT.

Nevertheless, both are necessary for reducing the effects of climate change.

CARBON STORAGE:

The amount of carbon that is retained in a carbon pool within the forest.

Storage levels increase with forest age and typically peak in the northeastern United States when forests are old (>200 years old).

CARBON SEQUESTRATION:

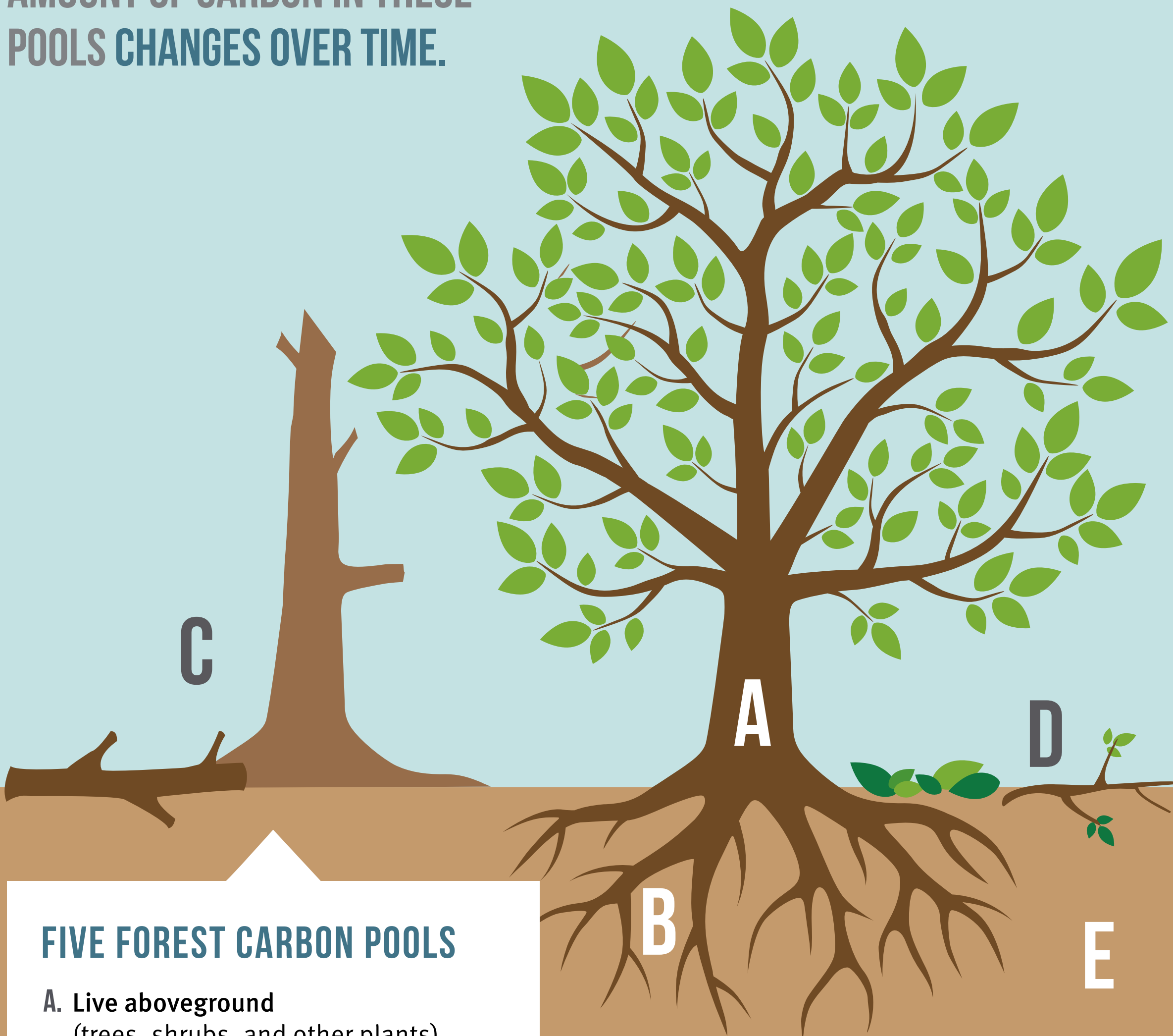
The process of removing carbon from the atmosphere for use in photosynthesis, resulting in the maintenance and growth of plants and trees.

The rate (or amount and speed) at which a forest sequesters carbon changes over time. In the northeastern United States, carbon sequestration typically peaks when forests are young to intermediate in age (around 30–70 years old), but they continue to sequester carbon through their entire life span.

Photo by Anthony D'Amato

WHERE IS CARBON STORED IN A FOREST?

A FOREST STORES CARBON IN DIFFERENT POOLS, AND THE AMOUNT OF CARBON IN THESE POOLS CHANGES OVER TIME.



FIVE FOREST CARBON POOLS

A. Live aboveground
(trees, shrubs, and other plants)

B. Live belowground
(roots)

C. Deadwood
(standing dead trees [snags] and downed logs)

D. Litter
(leaves, needles, and small branches)

E. Soil organic matter
(organic material in the soil, such as dead and decayed biomass [e.g., plant material and insects])

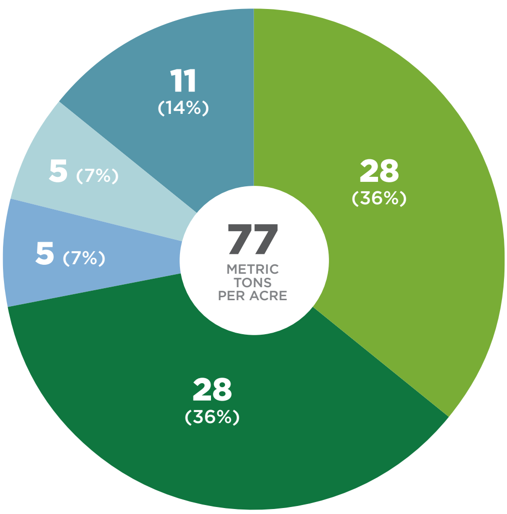
Factors that influence the amount and proportion of carbon in each of these pools:

- the age of the forest
- the species of trees making up the forest
- natural and human disturbances
- soil characteristics (e.g., texture and drainage)
- past agricultural land-use history

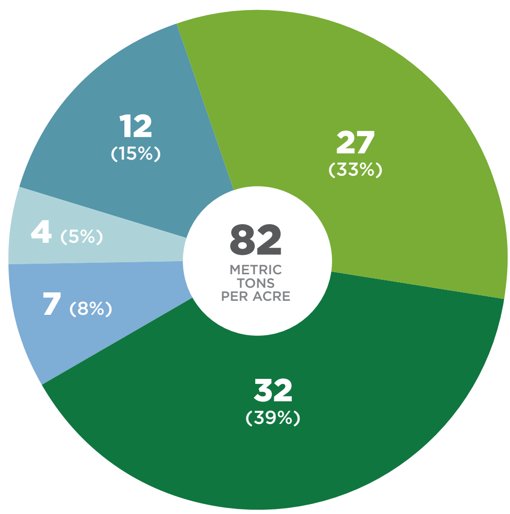
In addition to carbon storage changing over time within and among the pools, carbon storage varies among forest types. This variation is strongly influenced by the climate in which these forests grow. Generally, the warmer the climate, the longer the growing season and the greater amount of carbon stored aboveground in trees. Warmer climates also result in less carbon stored in the soil due to faster decomposition rates. The figures below show the average amount of carbon stored in each of the different pools for common 80- to 100-year-old New England forest types (U.S. Forest Service [2018]).

Soil Organic | Live Aboveground | Live Belowground | Deadwood | Litter

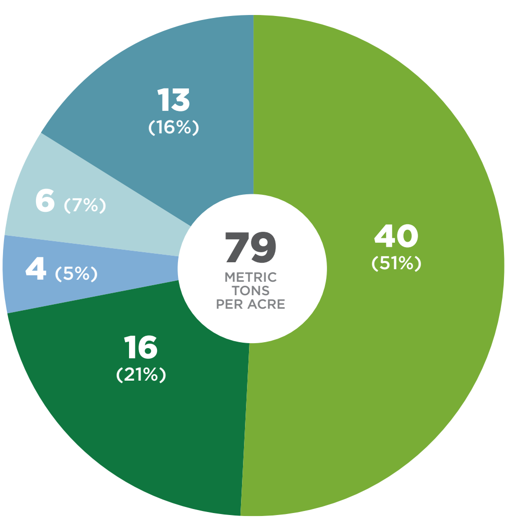
NORTHERN HARDWOOD



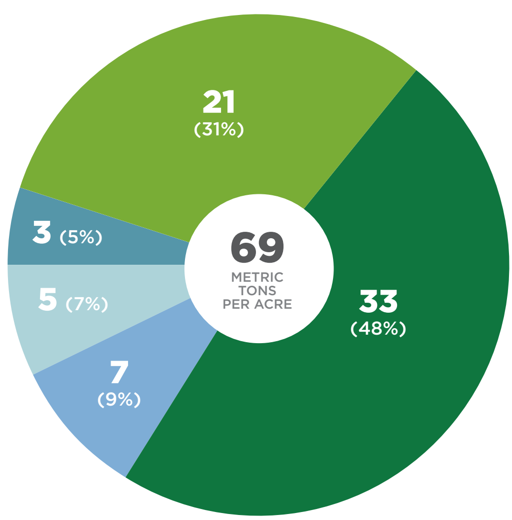
OAK-PINE



SPRUCE-FIR



OAK-HICKORY



Individual Tree vs. Forest-Level Growth and Sequestration Rates

When trying to understand forest carbon and the amounts that might be sequestered and stored by a given forest, a common point of confusion is assuming the growth of a forest follows the same pattern as the growth of an individual tree. There are important differences between an individual tree and forest-wide growth rates, which need to be considered when evaluating forest carbon benefits.

Individual trees growing within the main canopy of a forest increase in biomass at an accelerating rate as they age. Their growth continues until they reach old age (>200 years old), at which time their growth rate slows, leading to the natural decline and death of the trees. This is a pattern long recognized by forest scientists and recently popularized, as the important role that carbon storage and sequestration play in mitigating climate change has become a more prominent forest management objective.

However, growing space and resources are finite in a forest, so not all trees within a particular forest can grow at an optimal rate over time. While vigorous individuals grow in size and dominance, gaining disproportionate access to site resources, less vigorous trees have slow growth rates due to a lack of space and resources. So even though some trees (i.e., those in upper canopy positions) continue to grow at high rates until old age, many do not. The net result is a reduction in the growth and sequestration rates of the forest as a whole. The ability of these dominant individuals to continue growing is an important attribute to consider when objectives include restoring large-tree habitat conditions or developing large diameter sawlogs, but it should not be confused with forest-level growth and sequestration rates, which generally decline with age, regardless of the tree species or soil conditions (Ryan, Binkley, and Fownes 1997; Smith and Long 2001; Binkley et al. 2002). Despite lower forest-level sequestration rates as the years go by, the forest continues to increase its level of carbon storage.

Photo by Adella Catanzaro

Young, Old, and Multi-Aged Forests

A forest goes through stages of succession and development on its way from a seedling forest to a late successional forest. (See the Forest Succession & Development Clock on page 8.) As forests grow older, the species within them shift from those that need full sunlight to grow (shade intolerant) to those that grow best in partial sunlight (shade mid-tolerant) to those that are most competitive in full shade (shade tolerant). Each stage of forest succession and development provides unique benefits based on the forest's structure (age, number, size, and arrangement of living and dead trees) and composition (mix of tree species). For example, young forests (consisting of seedlings and saplings <5″ in diameter) provide one type of wildlife habitat, and old forests (consisting of large sawtimber trees >18″ diameter) provide habitat for a different suite of species. Similarly, a forest's maximum rate of carbon sequestration (the process of removing carbon dioxide from the atmosphere) happens at one stage of forest development (ranging from sapling-size trees of approximately 4″ diameter through medium sawtimber trees of 16″ diameter), and the maximum amount of carbon storage (the amount of carbon retained in a forest) happens at another stage (when trees are large sawtimber >18″ in diameter). The age of the forest strongly influences both the rate at which forests sequester carbon and the amount of carbon that they store. For more information about forest development, see the "Supporting Literature" section.

Young Forests

Maximizing carbon sequestration—the amount and rate at which carbon dioxide is removed from the atmosphere

After a disturbance, forests in New England naturally regenerate themselves through seeds and sprouts. Seedlings and sprouts grow into saplings, and as saplings grow, there is tremendous competition for resources as they occupy available growing space. The saplings grow vigorously until their crowns grow into one another and occupy all available growing space. Trees that can grow faster than neighboring trees become dominant and claim more and more space in which to grow and survive. Those trees that lose space are outcompeted and eventually die. The space and resources vacated by these dead trees are increasingly used by the remaining trees. In this way, the resources of the site continue to be concentrated into fewer and fewer trees that grow larger and larger. **This is the stage of forest development at which the rate of carbon sequestration is highest, as the amount of leaf area and the rate of photosynthesis peak during this period of high tree-to-tree competition.** These higher rates generally occur when the forest is approximately 30–70 years old or the trees are approximately 4"–16" in diameter, though the specific age and size will depend on such factors as site quality and land-use history. Soon after the forest canopy closes, the overall growth of the forest slows down and, with it, the sequestration rate. However, trees continue to sequester significant amounts of carbon in order to grow and maintain themselves.

One important thing to recognize is that the forest might actually be a source of carbon immediately following a disturbance, as rates of tree growth, although rapid, are unable to counteract losses of carbon due to the decomposition of organic matter in the soil. This loss of carbon from decomposition is enhanced when large openings are created in the forest, which increases soil temperature and moisture availability and hence microbial activity. It generally takes 10–15 years before there is enough forest growth to shift a disturbed area from a carbon source to a carbon sink.

(LEFT) Photo by Paul Catanzaro, (RIGHT) Photo by Anthony D'Amato

Old Forests

Maximizing carbon storage—the amount of carbon that is retained in the forest

As forests age, the total amount of carbon stored in the forest continues to increase as carbon accumulates in the different pools. Trees grow larger in height and diameter, increasing the live aboveground pool. As trees get larger over time, their roots grow and spread, increasing the soil organic pool. At the same time, they drop more leaves and branches on the ground, adding to the litter pool. As the forest ages, trees die due to insects, disease, wind and ice storms, and competition. As they die, the deadwood pool increases in the form of snags and downed logs. The litter and dead trees all contribute to the soil pool over time. Together, these processes increase an older forest's ability to store carbon in the various pools. Therefore, **this is the stage of forest development with the highest amount of carbon storage**.

Old-growth forests can provide us a guide as to how much carbon mature forests store. Estimates of the carbon stored in these forests range from 100 to 120 metric tons of carbon per acre (Hoover, Leak, and Keel 2012). Due to our past land-use history, our current forests are relatively young, many around 100 years old, and generally store 60–80 metric tons of carbon per acre. Carbon in our current aged forests accumulates at a rate of about 0.41 metric tons per acre each year in a typical maple–beech–yellow birch forest (Smith et al. 2006). Given this rate of carbon accumulation, our current maple–beech–yellow birch forests would need to continue growing at this rate, without a major forest disturbance, *for about another 100 years* before they would have the levels of carbon storage that we find in old-growth forests. Future gains in forest carbon will primarily come from the diameter growth of trees, additions to the deadwood pool from dying trees, and the accumulation of soil organic carbon from root growth and decomposition.

Multi-Aged Forests

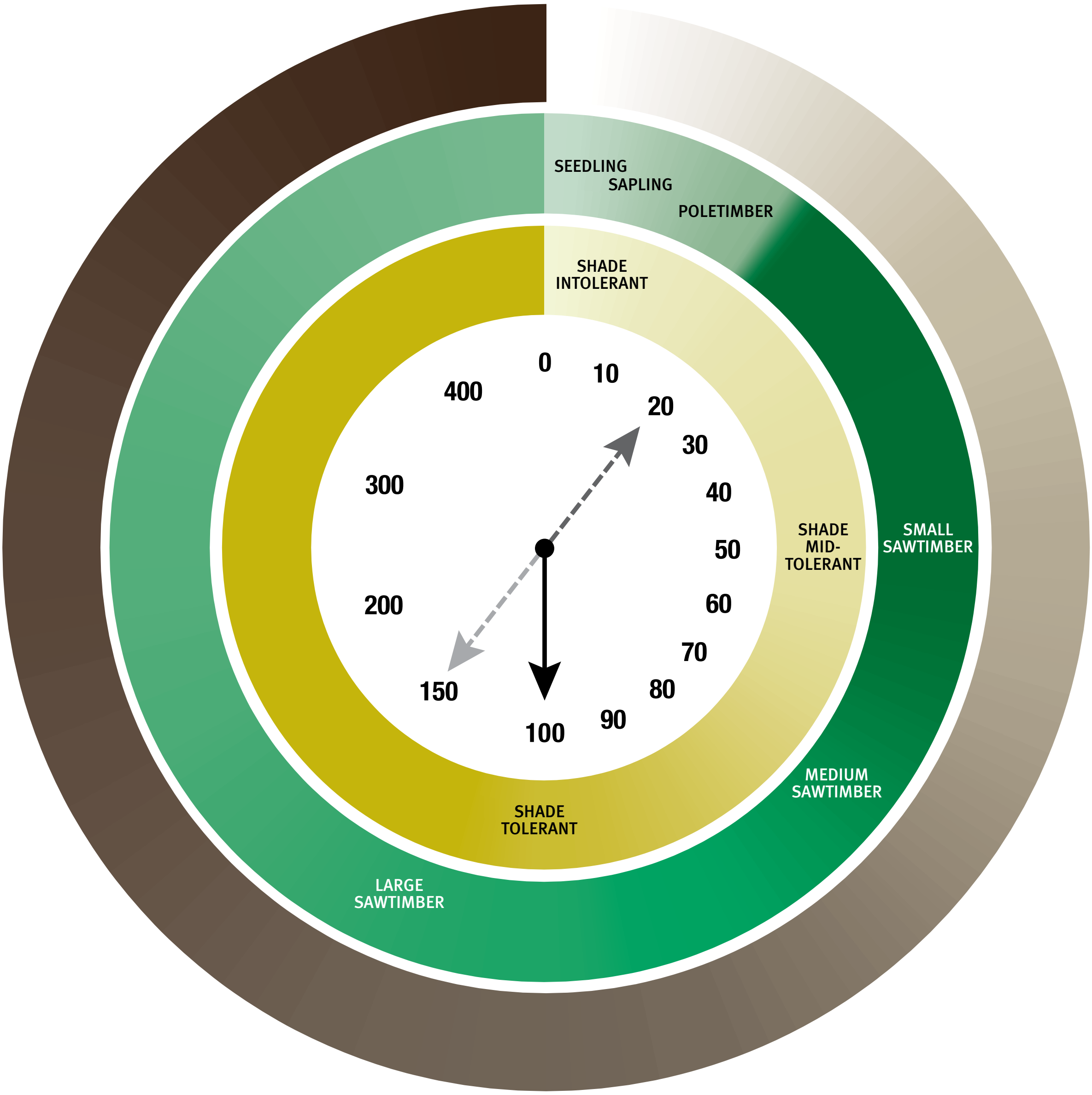
Balancing carbon sequestration and storage

It's easiest to describe all the trees in a forest as being the same age—that is, all young or all old. In fact, many of our forests are the same age, also called "even aged," due to our land-use history of agricultural clearing and forest harvesting, which initiated many forests at the same time. However, the older our forests get, the more they will shift from even-aged forests to multi-aged forests. In New England, it is common for trees to die individually or in small groups due to frequent low-severity disturbances, such as wind, ice, and insects, or to partial harvests, which do not remove all the trees at once. These types of partial disturbances leave some older trees while creating the opportunity for seedlings to establish themselves and saplings to grow in the gaps created by the death of canopy trees. Some forest management strategies—such as single-tree and group-selection systems—mimic the region's frequent low-severity disturbances and thus create multi-aged forests.

Forests composed of trees of various ages have the combination of characteristics that the trees of each age possess. For example, a forest with equal areas of young trees and old trees will have high rates of sequestration from the younger trees while maintaining the storage capacity and sequestration rates of the surviving older trees. When making decisions about your forest management strategy, one consideration is whether you want to maximize carbon storage, sequestration, or a combination of the two.

For more information on forest succession and development and peak carbon sequestration and carbon storage, see the Forest Succession & Development Clock on page 8.

FOREST SUCCESSION & DEVELOPMENT CLOCK



LEGEND

0–400 Age of the forest in years

Changes in carbon storage over time. The darker the brown, the more carbon storage.

Changes in carbon sequestration over time. The darker the green, the more forest level carbon sequestration.

Changes in tree species shade tolerance over time. The darker the yellow, the more likely shade-tolerant trees (e.g., hemlock, sugar maple, and beech) are to be competitive.

Saplings >1"–4.9" diameter
Poletimber 5"–10.9" diameter

Medium Sawtimber
14"–17.9" diameter

Large Sawtimber
>18" diameter

Understanding the Forest Succession & Development Clock

As described in the "Young, Old, and Multi-Aged Forests" section, forests change over time. With these changes come changes to the benefits they provide. The Forest Succession & Development Clock illustrates changes in forest species and structure over the years and highlights the times in forest development when carbon sequestration peaks and the times when carbon storage is maximized.

The clock hand in the diagram indicates the approximate age of many of our current forests (i.e., 100 years old) and the corresponding stage of forest succession and development.

The species and structure of a forest can be **moved back** to an earlier time of forest development (e.g., 20 years old) through natural disturbances (insects, disease, hurricanes, ice storms) and forest management that involves changing the light levels of a forest to favor shade-intolerant species and simplifying the forest structure.

The species and structure of a forest can also be **moved forward** to a later stage (e.g., 150 years old) through time, natural disturbances, and forest management that involves releasing shade-tolerant species and increasing structural complexity through the addition of deadwood and the growth of large-diameter trees.

(TOP) Photo by Vermont Land Trust/David Middleton
(MIDDLE AND BOTTOM) Photos by Anthony D'Amato

Land-Use Decisions

With a greater understanding of forest carbon, it's now possible to better consider the implications of land-use decisions on forest carbon sequestration and storage. Two of the most influential decisions that landowners make regarding forest carbon are (1) whether their forest will be converted to non-forest use by them or a future owner, and (2) whether to engage in active forest management—and, if so, how to do it in a way that meets their goals.

Land-Use Decision 1: Future of the Land

The first and most significant decision landowners will make is what will happen to their forest in the future. Will it be converted to another use, such as residential, commercial, agriculture, or energy development (solar fields, pipelines), by them or a future owner, or will they decide to keep their forest as forest and make the necessary plans to ensure it?

Forest Conversion

Between 1990 and 2010, 77 acres of New England forests were converted to some type of non-forest use each day (see table 1). That's more than 28,000 acres each year. Conversion of forests to non-forest use affects all of a forest's carbon pools. Converting a forest to non-forest land use eliminates most of the carbon storage and all of the forest's capacity to store and sequester carbon in the future. Forest conversion eliminates the live aboveground, deadwood, and litter pools of the forest by removing them from the site. Soil disturbance from stumping, grading, and plowing decreases soil carbon. In addition to these losses, conversion of forests to other land uses is often permanent, or at least lasts decades, meaning that the carbon that was lost from these forests is generally not recovered. In addition, forest conversion means not only a loss of carbon sequestration and storage but also a loss of all forest benefits (habitat, clean water, local wood products). Though some loss of forest may be necessary to achieve personal and societal goals, it is important to remember that the most significant losses in forest carbon are the result of conversion of forests to non-forest uses.

TABLE 1: AVERAGE ACRES OF FOREST LOSS PER DAY AND PER YEAR IN NEW ENGLAND, 1990–2010

Region	Acres of Forest Loss Each Day	Acres of Forest Loss Each Year
Southern New England		
Connecticut	11	4,049
Massachusetts	20	7,414
Rhode Island	2	838
Northern New England		
Maine	23	8,398
New Hampshire	15	5,485
Vermont	6	2,123
New England		
Region-wide average	77	28,307

New England Landscape Futures Explorer (newenglandlandscapes.org)
Data source: P. Olofsson et al. (2016).

Keeping Forests as Forests

Keeping forests as forests is the single most important action a family forest owner can take to maintain forest carbon sequestration and storage, reducing the impact of climate change. It is therefore the single most important action a forester or natural resource professional can facilitate. There are several conservation-based estate planning tools that can be used to help family forest owners keep their land in its forested condition, including permanent conservation options such as conservation easements/restrictions, which keep the land in private ownership while ensuring that the forest will remain forest in perpetuity. There are professionals working locally that can help you evaluate your options for passing your land on as forest. For more information about conservation-based estate planning options and to find people working locally to help, see the “Additional Resources” section of this publication.

Afforestation

If the biggest loss of carbon sequestration and storage is conversion of forests to other land uses, then the biggest gain is the reversion of other non-forest land uses back to forests. If forest carbon is your primary goal, then one option is to allow non-forest land uses, such as abandoned or unproductive fields, to revert back to forest. However, the balance between maximizing forest carbon storage and sequestration and accommodating the need for local agriculture is an important trade-off to consider.

Land-Use Decision 2: Forest Management

A second major decision is the forest management strategy you choose for your forest. The management of our forests can take a passive or an active approach. Both approaches have implications for carbon, and both have trade-offs.

Passive Forest Management

Many landowners choose to adopt a passive approach to their land by not engaging in timber harvesting and letting nature take its course. Though a passive approach to forest management means no timber harvesting, it can still be active in terms of other activities that can help increase forest resiliency, such as invasive plant control. This passive approach to forest management will likely maximize forest carbon storage through the accumulation of carbon in each pool as the forest grows older but will not maximize the carbon sequestration rate, which, as previously described, occurs in younger forests.

Having forests within our landscapes that are allowed to accumulate and store high amounts of carbon is a critical part of reducing the impact of climate change. The water and nutrient resources of the forest determine how many trees can grow and the height these trees can obtain. Sites with ample water and nutrients can grow larger trees than sites with low amounts of water and nutrients. Therefore, forests on these richer, more fertile sites will be able to grow and store more carbon than those on less fertile sites. In

(LEFT) Photo by Vermont Land Trust/Caleb Kenna; **(MIDDLE)** Photo by Anthony D’Amato; **(RIGHT)** Photo by Paul Catanzaro addition to site quality, large areas of forest with low fragmentation may be more resilient to disturbances and therefore better able to store carbon.

Considering the Carbon Trade-Offs of the Passive Approach

Forests provide many essential benefits, including carbon, but not always in equal proportion. Choosing a strategy for your forest may mean that some benefits are enhanced while others are reduced. These are decisions that every landowner must make, hopefully after a full understanding of the trade-offs. Climate change is a critically important issue. Taking a passive approach to forest management will likely provide the greatest amount of carbon storage. However, there are other important trade-offs of the passive approach to consider.

FOREST RESILIENCY

Forest conversion and timber harvesting are not the only ways in which forests lose carbon. One of the anticipated impacts of climate change is more frequent and more severe natural disturbances, such as wind and ice storms. In addition, invasive insects and plants and deer overpopulation pose an increasing threat to our forests. Typically, these forest disturbances disproportionately affect one part of a forest (wind events affect the trees with the biggest crowns in the overstory, insects affect certain species of trees). Opportunities exist to use active forest management to make our forests more resilient to these disturbances by increasing species and structural diversity. Forests with diverse species and structure increase forest resiliency by reducing the risk that a disturbance will kill all the trees in a forest because the trees are all the same species or a similar size. In addition, forests with these diverse conditions contain multiple mechanisms for recovery following such events, which will allow for carbon levels to return to pre-disturbance levels more quickly. Resilient forests can help avoid a potentially large loss of carbon in the future due to a single disturbance (hurricane, invasive insect) and ensure a steady flow of other forest benefits. **Though active forest management would temporarily reduce the amount of carbon stored in the forest, it may help prevent an even larger reduction in carbon storage by avoiding losses due to a large-scale disturbance** (D'Amato et al. 2011; Bradford et al. 2013). Forests in vulnerable landscape positions to natural disturbances (such as exposed sites), even-aged forests, forests dominated by a limited number of species, and forests with a high proportion of species with known forest-

Carbon Credits: A Future Carbon Option?

Your forest provides many critical functions for society, such as removing carbon dioxide from the atmosphere through carbon sequestration and storing it within the forest, reducing the impact of climate change. There are ongoing efforts to establish programs to pay forest landowners for providing this service. In order to sell carbon credits (one metric ton of carbon dioxide equivalent), a landowner typically needs to meet several requirements, including verifying that the forest is sustainably managed through a certification system, providing a detailed inventory of the amount of carbon in the forest and future projections of growth, and signing a long-term contract to ensure that the forest remains a forest and won't be harvested in a manner that reduces the amount of carbon stored in it. Meeting these requirements typically takes large amounts of acreage to make it profitable. The necessary acreage can be in one large property or in a number of smaller ownerships.

For more information about selling carbon, visit masswoods.org/carbon.

health issues (ash, hemlock) are most susceptible. For more information about forest resiliency, see "Additional Resources" at the end of this publication.

WILDLIFE

Maintaining populations of native wildlife is a common goal of many landowners, both public and private. Approximately 80 percent of our region's vertebrate wildlife species rely on forests of different ages (seedling, sapling, sawtimber) for different parts of their life cycle (DeGraaf and Rudis 1986). Therefore, in order to maintain native populations, there needs to be enough forest habitat of different ages to support these populations.

Based on our land-use history, most of our forests are approximately 100 years old. This means that our landscapes have limited amounts of both young (<15 years old) and old (>200 years old) forests, both of which offer unique habitat opportunities. For example, species that rely on the currently limited amount of young forest (e.g., the chestnut-sided warbler and the New England cottontail) are in significant decline. Creating young forest habitats for these declining species through active forest management will mean sacrificing carbon storage at the property level, but it will have a disproportionate positive impact on regional biodiversity, given the current rarity of this critical habitat type. Similarly, active management strategies for increasing old forest characteristics, such as large trees, will reduce overall carbon storage of a forest in the near term but provide the opportunity to accelerate the development of old-growth characteristics, which are also very rare. Ultimately, to sustain our native wildlife populations, we need a range of forest ages and types across the landscape.

(TOP) Photo by Brian Hawthorne; (LEFT CIRCLE) ©Shutterstock/Jeff Holcombe; (RIGHT CIRCLE) ©Shutterstock/Kevin Wells Photography

The John W. Olver Design Building at the University of Massachusetts Amherst has a unique cross-laminated timber structural system, which reduces its carbon footprint.

WOOD PRODUCTS

Maximizing forest carbon storage and sequestration in your forest is only part of the global carbon picture. To understand the full role of forests in the global carbon cycle, it is critical to consider both the amount of carbon stored in forest products and the amount of carbon that is saved when wood is used in place of more carbon-intensive materials, such as steel and concrete (i.e., substitution).

All carbon removed from the forest during a timber harvest is not immediately returned to the atmosphere. Approximately one-third of the forest products harvested in the northeastern United States are made into products, such as furniture, flooring, and dimensional lumber (two-by-fours) with long life spans (Oswalt et al. 2018). Forest management provides the opportunity to improve the quality of forest products by concentrating growth on higher-quality trees, which will increase the number of trees that produce the wood products that will store carbon for long periods of time (sawtimber, veneer).

If we choose to not use wood, what are the carbon costs of substitute materials? How much energy does it take to acquire these materials? How much energy does it take to convert them into a usable product? Wood plays an important role as a renewable, environmentally friendly building material, with climate and carbon advantages.

If we decide to continue using wood because it is environmentally friendly but do not harvest it in

Carbon is stored in wood products.

New England, it must then come from somewhere else. If it comes from outside New England, it takes energy and carbon emissions to bring those wood products to our region. In addition, the places from which we typically import wood may have the potential to store more carbon than New England (Pacific Northwest) or may have less environmental oversight protecting forest resources (other countries).

Understanding the whole forest carbon story necessitates looking beyond the property level to both the regional and global scale and includes considering the role forest products play. For more information, see the "Forest Products and Carbon" section of "Additional Resources."

TO UNDERSTAND THE FULL ROLE OF FORESTS IN THE GLOBAL CARBON CYCLE, IT IS CRITICAL TO CONSIDER BOTH THE AMOUNT OF CARBON STORED IN FOREST PRODUCTS AND THE AMOUNT OF CARBON THAT IS SAVED WHEN WOOD IS USED IN PLACE OF MORE CARBON-INTENSIVE MATERIALS, SUCH AS STEEL AND CONCRETE (I.E., SUBSTITUTION).

(PAGE 14) Photo by Alex Schreyer; **(PAGE 15)** Photo by Adella Catanzaro

Active Forest Management

Many landowners choose to implement some form of active forest management, including timber harvesting, in order to achieve their ownership goals. Active forest management can also help generate income, which may help pay taxes and other costs necessary to keep the land forested. Following are descriptions of the implications of active forest management on the two biggest carbon pools in a forest: live aboveground and soil. There are also implications for the deadwood pool, which holds the potential for significant increased storage of carbon in the future. For more information about the effects of active forest management on forest carbon, see "Supporting Literature."

- **Live aboveground carbon**: All harvesting reduces carbon storage of a forest below the maximum potential for the site. However, timber harvesting also often results in the establishment of a new cohort of young trees that can increase the carbon sequestration rate of the forest. The amount and type of trees removed, as well as the timing, will determine the specific impact on carbon. (See "Carbon-Informed Forest Management.")
- **Soil carbon:** Harvesting has little appreciable impact on soil carbon as long as soil disturbance is minimized and all the slash (treetops and non-merchantable lengths) is not removed (Hamburg et al. 2019). Best management practices should be used to protect soil during forestry operations (Nave et al. 2010).
- **Deadwood:** Since dead standing trees and downed logs have little to no merchantable value, they are typically not removed from the forest during a timber harvest. Depending on the level of utilization, slash, treetops, and non-merchantable lengths of logs may be left in the forest. Timber harvests can be implemented to maximize the amount of deadwood left on-site.

Considering the Carbon Trade-Offs of the Active Approach

The most important carbon consideration of active forest management is the loss of forest carbon storage resulting from the removal of trees. Though some of the trees removed during a timber harvest will end up in long-term forest products, any removal of trees is a temporary reduction in carbon storage on that property and at that time. This reduction can be minimized by applying strategies that reduce carbon loss. (See "Carbon-Informed Forest Management.")

The effects of active forest management on carbon storage are often considered only at the property level. However, it is also important to consider the effects at the regional scale. Table 2 compares forest growth and removals for each state in New England and across New England. For every unit (measured in cubic feet) of wood that is removed from the region's forests as part of timber harvesting, a greater amount of wood (and therefore carbon) is accumulated in each state. This means that while forest management reduces carbon storage at the property level, from both a statewide and a regional perspective New England continues to grow more wood (and carbon) than it harvests. The amount of wood removed and grown, and therefore the amount of carbon sequestered and stored, changes over time as landowners make decisions about the management of their forests.

Continuous-cover irregular shelterwood maintains diverse species and a mature forest structure.

Photo by Anthony D'Amato

TABLE 2: RATIO OF GROWTH TO REMOVAL OF WOOD THROUGH TIMBER HARVESTING IN NEW ENGLAND STATES

Region	Amount of Wood Removed (cubic feet)	Amount of Wood Growth (cubic feet)
Southern New England		
Connecticut	1	6.1
Massachusetts	1	5.3
Rhode Island	1	5.9
Northern New England		
Maine	1	1.4
New Hampshire	1	1.8
Vermont	1	2.1
New England		
Region-wide average	1	1.8

Data source: USDA Forest Service, Forest Inventory and Analysis Unit (2017)

Carbon-Informed Forest Management

If you choose to move forward with some type of active forest management on your land, there are strategies that can be implemented to reduce the loss of carbon storage from the forest while increasing carbon sequestration and resiliency. Since the soil and live aboveground carbon are the largest pools within the forest and the deadwood pool has significant potential to increase, focusing on strategies for these pools will have the greatest impact.

SOIL POOL

Apply Forestry Best Management Practices (BMPs): Forestry BMPs protect soil and water health through the implementation of practices to avoid soil damage and control the overland flow of water. See "Additional Resources" for more information about your state's forestry BMPs. Work with a forester to

- develop a strong contract that specifies soil and water performance standards for the timber harvest to protect soil and water (e.g., rutting depths and timing of harvest);
- lay out logging roads to minimize their number, and ensure that they are located on stable ground;
- avoid soil disturbance by timing the harvest to frozen or stable conditions;
- monitor the harvest to make sure that the ground is stable enough to operate and that the contract provisions are being followed;
- conduct a final inspection before the timber harvesters leave the site to make sure that the site has been stabilized and the contract has been satisfied.

LIVE ABOVEGROUND POOL

As described in the introduction, the benefits a forest provides is dependent on its structure (size of the trees, number of trees, and arrangement of trees) and its composition (species of trees). Carbon-informed forest management strategies must consider both of these characteristics to achieve the desired benefits. In addition, consideration should also be given to the importance of both carbon sequestration and storage in order to maximize the forest's role in mitigating climate change. Active management offers the opportunity to establish a desirable balance of both small, young, fast-growing trees and large, old, slow-growing trees to achieve landowner goals.

Implementing carbon-informed forest management strategies can reduce the loss of carbon storage from the forest while increasing carbon sequestration and resiliency.

Photo by Anthony D'Amato

Stand Structure

Size of Trees

Grow and maintain large-diameter trees, as they make up a disproportionate amount of the live aboveground carbon stored in a forest.

- Maximize a tree's ability to store carbon by letting trees grow larger. For planned timber harvests, grow vigorous trees an extra 15–20 years past your harvest timeline, or 1"–2" larger than your target diameter. Sometimes harvests are unplanned, triggered by events that do not allow the timber harvest to be delayed. In these cases, consider leaving additional retention trees on-site (see "retention tree" bullet below).
- When it is time to regenerate, use methods that maintain large trees across the forest. Example regeneration methods include irregular shelterwoods, selection methods, two-aged variants of clearcutting and seed-tree methods, variable-retention harvesting systems, and variable-density thinning.
- Designate large trees to permanently retain in your forest in the live aboveground pool, which will eventually be added to the deadwood pool. These "retention trees" can be individually scattered across the forest or in small groups of at least a quarter acre in size. In addition to the carbon-storage benefits, these large-diameter trees are excellent for providing wildlife with cavities and food, may be an important seed source for future trees, and have high aesthetic value. Groups of retention trees can be placed around areas of high ecological value, such as vernal pools or other sensitive sites.

Tree Regeneration

Establish a new age class of trees.

- Ensure that tree regeneration goals are met by addressing interfering vegetation (invasive plants) and excessive herbivory (e.g., deer and moose browse). Timely regeneration of species well-suited to the site and future conditions will ensure that there are trees in place to sequester and store carbon into the future.

Distribution of Tree Ages

Identify the appropriate combination of young and old trees to meet your goals, and develop forest resiliency through diversity.

- As previously described, carbon sequestration rates peak when forests are young and then decline with age. Carbon storage is maximized in old forests. Maintaining forests with multiple age classes of trees will provide a balance of large, older trees for storage and younger, faster-growing trees for sequestration. In addition, multi-aged forests increase a forest's resiliency to natural disturbances (see "Forest Resiliency").
- Trees of different ages often vary in height, which increases the vertical structure within the forest. Forests with multiple layers will store more carbon. Implementing strategies that allow for the development of a multi-aged, stratified forest will provide the opportunity to increase the levels of "carbon packing."

Species Composition

Identify the appropriate mix of tree species to meet your goals, and foster forest resiliency through diversity.

- Establishing and promoting native, locally adapted tree species that have no known forest-health issues and that are predicted to be competitive in future climatic conditions—especially drought tolerant—will help achieve a vigorous forest.
- Promoting a diversity of species will increase the forest's resilience to natural disturbances by ensuring that diseases or insects that kill one species will not kill an entire forest.
- Promoting trees such as red oak and white pine, which have the capacity to become dominant and grow very large, can increase forest carbon storage.
- Tree species have different wood densities. Promoting tree species with high-density wood that can grow to be dominant trees can increase carbon storage in a forest. For example, hardwood trees are denser than softwood trees.

There are even differences among hardwood species. For example, red oak and sugar maple are denser than red maple.

- Promoting shade-tolerant trees (e.g., sugar maple), which can grow in the shade below the main canopy, can help increase the number of live trees growing in the forest, maximizing the opportunity for carbon packing by creating forests of multiple layers.

Deadwood Pool

Promote increases in the deadwood pool.

- Designating retention trees will ensure a future source of deadwood, as the trees are left on-site until they die.
- Work with a forester to establish utilization standards that maximize the amount of slash left on-site, and include these in your contract.
- Felling or girdling poor-quality trees will add to the deadwood pool while also providing habitat benefits and freeing up space and resources to increase the growth rates on adjacent trees.

Legacy or retention trees can be left on-site to maintain carbon storage, continue sequestering carbon, and provide complex structure for resiliency and habitat.

Taking a Joint Passive and Active Approach

It doesn't have to be all or nothing! When considering the trade-offs of your decisions, it is important to realize that you do not need to treat your whole property in the same manner. You can decide to engage in active forest management on some parts of your forest and not on others. In fact, by leaving retention trees within a harvest, you are taking both an active and a passive approach in the same area. Similarly, those making decisions on public or private conservation land do not need to treat each of their individual properties the same way.

Your forest is part of a complex pattern of other owners across the landscape. Each property has certain characteristics that make it unique, and each is surrounded by other unique properties. Therefore, each forest should be considered individually and within the context of its surrounding landscape with the help of a professional forester. Some properties may be more suited to active forest management, while other land may be better suited to a passive approach. You do not have to feel the pressure of meeting all the demands of our region's forests. **Ultimately, we need landscapes with both active and passive approaches to provide the many benefits forests provide, including carbon sequestration and storage.**

Conclusions

The land-use decisions of New England's landowners, particularly family forest owners, will have a profound impact on our forests' ability to sequester and store carbon and therefore on the role they play in mitigating the effects of climate change. The greatest impact family forest owners can have on carbon is to ensure that their land remains a forest by engaging in conservation-based estate planning. Contact a local land trust or state conservation agency to learn more about your options.

In addition to keeping forests as forests, landowners' decisions about the management of their forest and carbon should be made with an understanding of the trade-offs between maximizing carbon sequestration and storage and meeting their other goals (forest resiliency, wildlife, local wood products). There is not one right strategy for all landowners. Some may choose to make carbon a primary goal and maximize the role their forest plays in carbon storage by taking a passive approach to its management. Others may see carbon as a complementary goal and incorporate some elements of carbon-informed management recommendations into their forest management strategy. Landowners should work with a professional forester to evaluate their unique combination of landowner goals, forest characteristics, and landscape context to develop a strategy that will meet their needs.

(PAGE 20) Photo by Paul Catanzaro; (TOP LEFT) Photo by Anthony D'Amato
(MIDDLE) Photo by John O'Keefe; (RIGHT) Photo by Wendy Ferris

ADDITIONAL RESOURCES

Conservation-Based Estate Planning

CONNECTICUT
ctwoodlands.org/land-conservation/property-management-and-forestry

MAINE
forest.umaine.edu/legacy

MASSACHUSETTS
masswoods.org/legacy

NEW HAMPSHIRE
extension.unh.edu/resource/estate-planning-nh-woodlot-owners

RHODE ISLAND
rhodeislandwoods.uri.edu/future-of-your-land/estate-planning

VERMONT
ourvermontwoods.org/legacy

Find a Forester

CONNECTICUT
ct.gov/deep/cwp/view.asp?a=2697&q=322772&DeepNav_GID=1631

MAINE
maine.gov/dacf/mfs/archive/woodswise/consulting.html

MASSACHUSETTS
masswoods.org/professionals

NEW HAMPSHIRE
extension.unh.edu/resource/directory-licensed-foresters

RHODE ISLAND
rhodeislandwoods.uri.edu/local-businesses/foresters

VERMONT
ourvermontwoods.org/resources/find-consulting-forester

Photo by Adella Catanzaro

Climate Change and Carbon

CLIMATE CHANGE RESPONSE FRAMEWORK
forestadaptation.org

CLIMATE CHANGE TOPICS
fs.usda.gov/ccrc/topics

FOREST CARBON MENU OF ADAPTATION AND MITIGATION STRATEGIES AND APPROACHES
forestadaptation.org/node/6450

FOREST CARBON SCIENCE, POLICY, AND MANAGEMENT
fs.usda.gov/ccrc/index.php?q=education/forest-carbon-science-policy-and-management

INCREASING FOREST RESILIENCY FOR AN UNCERTAIN FUTURE
masswoods.org/resiliency

NATURAL CLIMATE SOLUTIONS
naturalclimatesolutions.org

USDA CLIMATE CHANGE RESOURCE CENTER
VIDEO COLLECTIONS: FORESTS AND CARBON
fs.usda.gov/ccrc/index.php?q=videos/collections/forests-and-carbon

Forestry BMPs

CONNECTICUT
ct.gov/deep/cwp/view.asp?a=2697&q=379248&deepNav_GID=1631

MAINE
maine.gov/dacf/mfs/publications/handbooks_guides/bmp_manual.html

MASSACHUSETTS
masswoods.org/caring-your-land/water

NEW HAMPSHIRE
extension.unh.edu/goodforestry

RHODE ISLAND
rifco.org/publications.htm

VERMONT
ourvermontwoods.org/topic/water-quality

Forest Products and Carbon

CONSORTIUM FOR RESEARCH ON RENEWABLE INDUSTRIAL MATERIALS (CORRIM)
corrim.org/fact-sheets

"THE ILLUSION OF PRESERVATION: A GLOBAL ENVIRONMENTAL ARGUMENT FOR THE LOCAL PRODUCTION OF NATURAL RESOURCES"
harvardforest.fas.harvard.edu/publications/pdfs/illusion.pdf

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- Soil Organic: go.usa.gov/xyqnS
- Live Aboveground: go.usa.gov/xyqn6
- Litter: go.usa.gov/xyqnJ
- Live Belowground: go.usa.gov/xyqne
- Deadwood: go.usa.gov/xyqnz

Photo by Adella Catanzaro

Ultimately, we need landscapes with both active and passive approaches to maintain the many benefits forests provide, including carbon sequestration and storage.

NIACS Northern Institute of Applied Climate Science

NECASC Northeast Climate Adaptation Science Center

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(MAIN) Photo by Anthony D'Amato; (LEFT CIRCLE) Photo by Adella Catanzaro; (MIDDLE CIRCLE) Photo by USDA Forest Service/Todd Ontl; (RIGHT CIRCLE) Photo by Adella Catanzaro