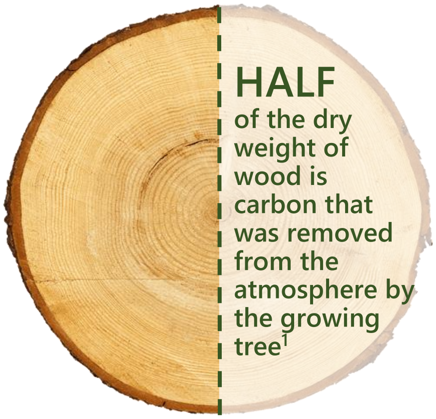
What is Forest Carbon?

The carbon cycle

The carbon cycle is the key to life on Earth. Through natural processes, carbon is exchanged among living organisms, soil, rocks, water, and the atmosphere. However, humans have disrupted the carbon cycle by burning fossil fuels and disturbing ecosystems, resulting in a significant increase in emissions of carbon dioxide (CO_2) and other greenhouse gases (GHG) into the atmosphere where they alter the Earth's energy balance and cause climate change. Because CO_2 is removed from the atmosphere through photosynthesizing plants, forests and other plant-based ecosystems are vital in maintaining the carbon cycle.

How do forests use carbon?



Through photosynthesis, trees and other plants take in CO_2 from the air to make carbon-based sugars (*carbo*hydrates) using water and sunlight, releasing oxygen to the atmosphere in the process. Trees use these sugars to maintain day-to-day processes (and respire CO_2 in doing so). But trees also use carbohydrates to grow their trunk, branches, roots, leaves, and other parts. The proportion that a tree uses for growth compared to respiration depends on the tree's species and age, along with the time of year and environmental conditions. When a tree produces seeds or makes defense chemicals to ward off insects, there is less energy (carbohydrates) to devote to growth.

Unlike non-woody plants, trees can store an incredible amount of carbon in wood. Wood gets its strength and flexibility from the carbon-based compounds cellulose, hemicellulose, and lignin. About 50% of a tree's dry weight is made up of carbon.

If a tree dies and is decomposed by microbes or burned in a fire – whether in the forest or a woodstove – CO_2 is released back to the atmosphere but at different rates. This carbon can then be taken in by another tree and the cycle repeats.

What is the difference between carbon storage and carbon sequestration?

Carbon storage is the total amount of carbon contained in a forest or a part of the forest (trees, soil).

Carbon sequestration is the process of removing carbon from the atmosphere and storing it in another form that cannot immediately be released, like wood. It is the rate of uptake of carbon from the atmosphere. In forests, living plants sequester the most carbon, but soils can sequester smaller amounts through natural geologic processes. The carbon *stored* in the forest accrues over time because of the annual carbon *sequestration* of living plants through photosynthesis and the comparatively slow decomposition of dead plant matter. Carbon sequestration is expressed as a negative number over a unit of time, for example the amount of carbon sequestered in a year. Carbon sequestration is expressed as a negative value because it indicates the removal of CO_2 from the atmosphere, such that there is less CO_2 to contribute to climate change.

[1] Image concept: The Forest Carbon Working Group

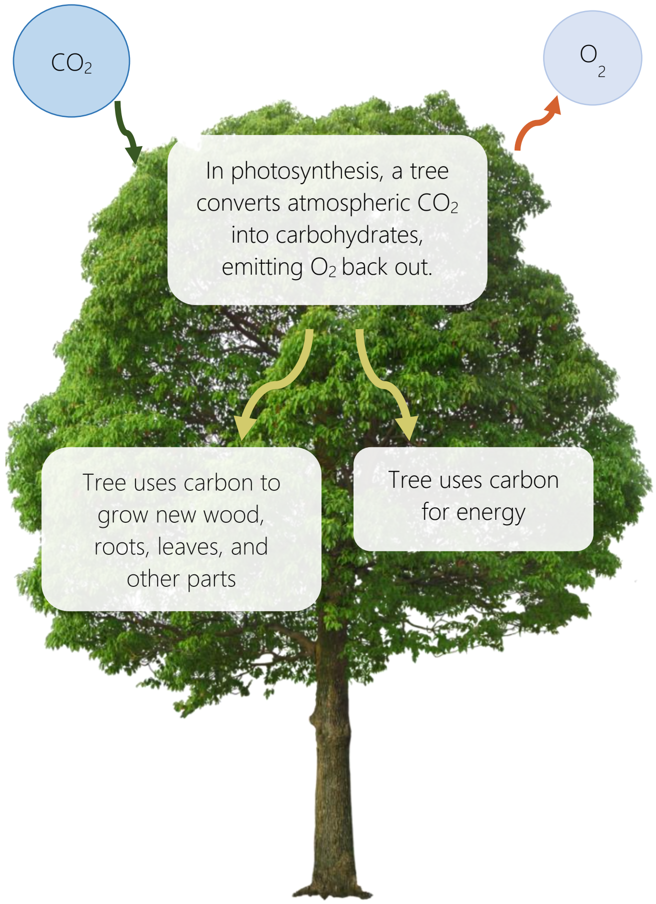
What is Forest Carbon?

Carbon emissions are the opposite of carbon sequestration. It is the rate of CO_2 released to the atmosphere. Forest carbon can be re-emitted to the atmosphere through decomposition, respiration, or combustion. The rate of carbon emissions is expressed as a positive number per unit of time because when CO_2 is emitted to the atmosphere, the amount of CO_2 in the atmosphere increases.

In a forest ecosystem, the combination of carbon sequestration and carbon emissions is the **net carbon flux** or the change in carbon storage over time. In other words, net flux accounts both for the uptake of CO_2 by live plants and soils, for emissions of CO_2 due to respiration, decomposition, and disturbances, and for the transfer of carbon to other parts of the forest.

When carbon flux is a negative number (less than zero), the forest sequestered more CO_2 than it emitted. This is called a **carbon sink** and the total carbon storage of the forest will increase by the amount sequestered. This is the current status of Vermont's forests.

When carbon flux is a positive number (greater than zero), the forest emitted more CO_2 than it took in. This is called a **carbon source** and the total carbon storage of the forest will decrease by the amount emitted. This can occur if a large amount of carbon was released from the forest due to land clearing or fire, or if the trees were not able to sequester as much carbon because they were injured or killed by insects or disease. If the forest can regrow, it can quickly return to being a carbon sink.



We want to make sure that Vermont's forests store a large amount of carbon and that the annual rate of carbon sequestration is high, however, these two processes peak at different stages of forest development. Older forests store more carbon than younger forests, but they sequester it at a slower rate. **Age diversity within a forest and across the landscape is the best way to maximize both storage and sequestration, plus diversity is a good strategy for climate resilience, too.**

What is the difference between carbon and carbon dioxide?

When a tree releases stored carbon through respiration, decomposition, or combustion, the carbon rejoins oxygen to make carbon dioxide (CO_2), which is released back to the atmosphere. Converting the carbon in a tree to the equivalent amount of CO_2 makes it easier to compare greenhouse gas mitigation strategies[2]. Therefore,

[2] For more information on carbon offset markets and credits see *Forest Carbon Markets for VT Landowners* (Kosiba, 2021).

forest carbon is usually expressed as **carbon dioxide equivalent (CO_2e)**. To convert carbon to CO_2e, multiply the amount of carbon by 3.67. This is because a molecule of CO_2 is 3.67 times heavier than a single carbon atom.

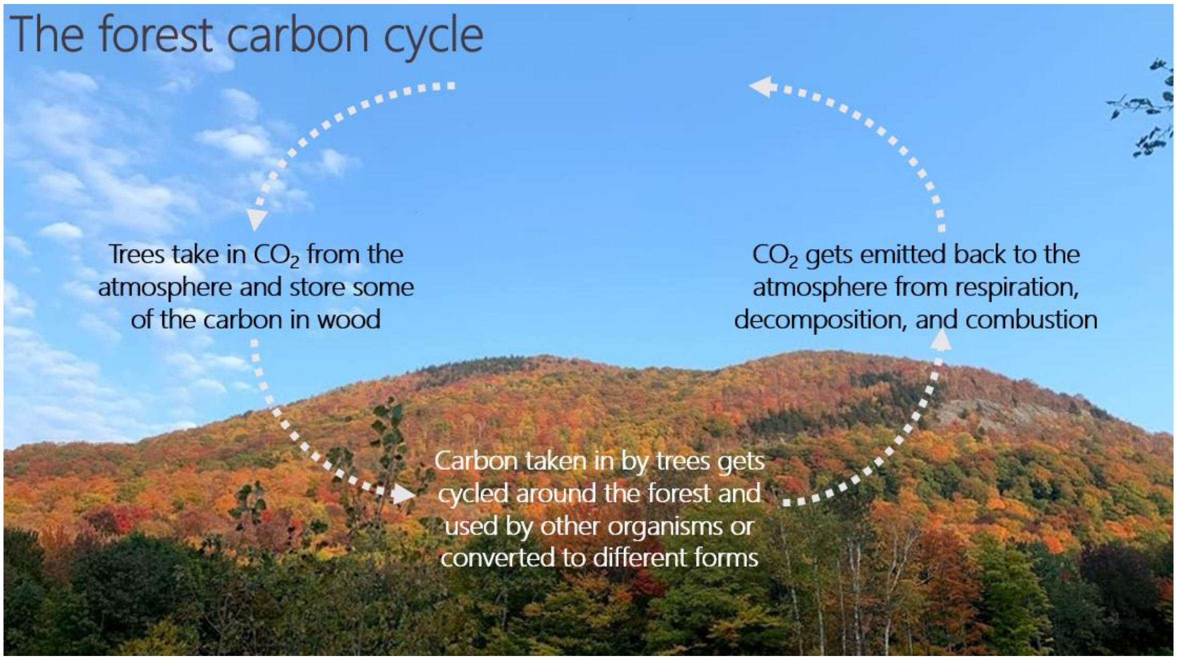
The common unit for CO_2 is a **metric ton** (Mt; also called a 'tonne'; about 2,205 lbs). One metric ton of CO_2 can be visualized as a cube measuring 27 feet on all sides[3] (about 729 cubic yards). This is equivalent to the amount of CO_2 the average Vermonter emits through day-to-day activities over three weeks[4]. For large quantities, CO_2 may be expressed as a million metric tons (MMt).

Because trees take in CO_2 but use the carbon to make wood, **wood stores more than its weight in equivalent CO_2**:

1 Mt of dry wood is equal to 0.5 Mt of carbon because dry wood is about 50% carbon. Because the CO_2 molecule is heavier than a carbon atom, this is equivalent to 1.8 Mt CO_2 that was taken out of the atmosphere by the growing tree.

What are forest carbon pools?

Carbon is constantly in flux in a forest. As new atmospheric CO_2 is sequestered by trees and other plants, carbon is also transferred to other pools as live plants die or shed leaves or branches.

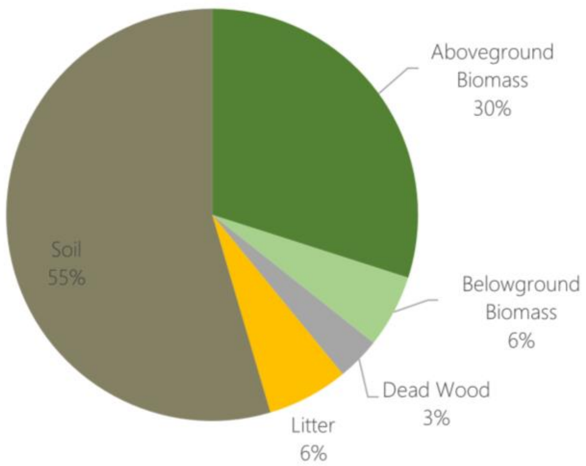


Carbon that is used in a tree's cells for branches, leaves, roots, and other living parts is the **live biomass carbon pool.** The carbon is stored in the live biomass pool until it is transferred to another pool or removed (burned, harvested, or consumed by an insect or fungi). Live roots also exude carbon directly into the soil to increase microbial processes and nutrient availability. When branches break, leaves are shed, or a tree dies, the carbon is transferred to the **dead wood carbon pool** or **leaf litter carbon pool**. As these pools are decomposed by fungi,

[3] United Nations. 2009. Press Conference on 'CO2 Cubes – Visualize a Tonne of Change. https://www.un.org/press/en/2009/091201_Cubes.doc.htm

[4] Vermont Agency of Natural Resources, Air Quality and Climate Division. 2020. Vermont Greenhouse Gas Emissions Inventory and Forecast: 1990 – 2016. https://dec.vermont.gov/sites/dec/files/aqc/climate-change/documents/_Vermont_Greenhouse_Gas_Emissions_Inventory_and_Forecast_1990-2016.pdf

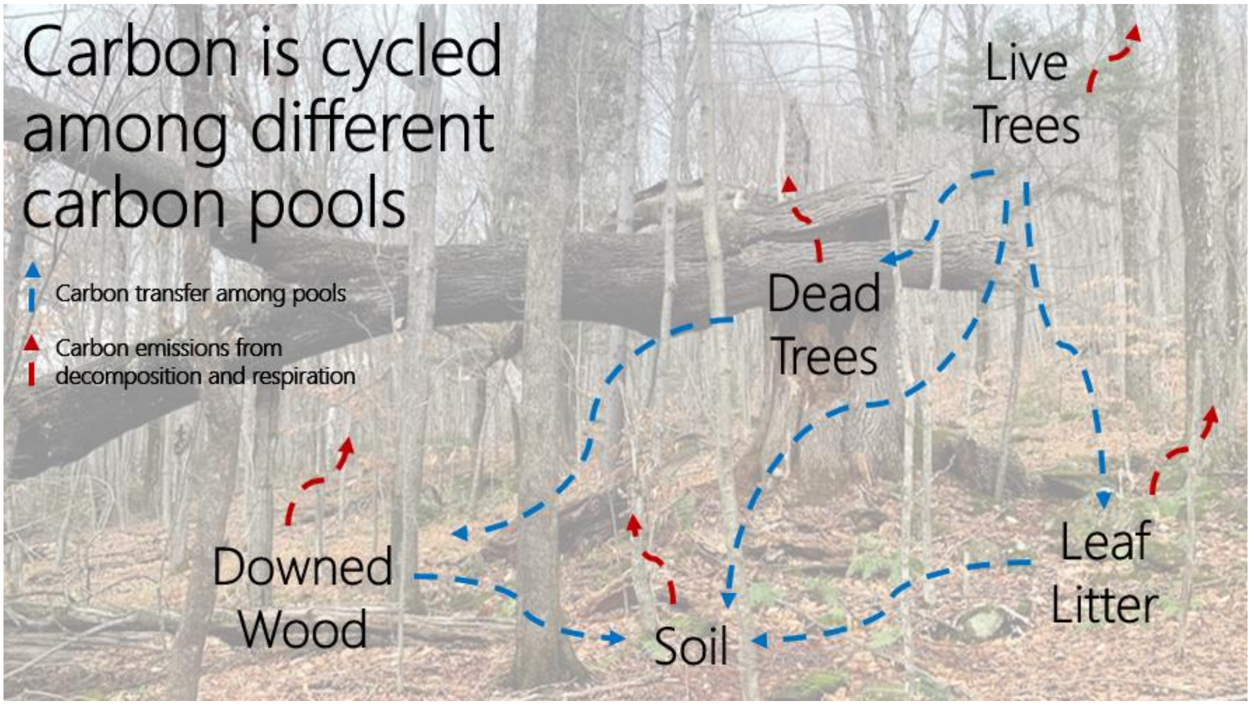
insects, and other organisms, they release CO_2 back to the atmosphere, but some carbon is transferred to the **soil carbon pool** where it can reside for a long, if variable, time – up to centuries or millennia. Carbon in the soil can eventually make its way into rivers and lakes.



More than half of the carbon found in Vermont's forest resides in the soil. Live trees and shrubs store about one third of the forest carbon[1]

The live biomass carbon pool can be divided into aboveground (trunk, branches, leaves, bark) and belowground (roots) portions. The live biomass pool is the most dynamic of the five carbon pools, meaning that it fluctuates the most from year to year due to weather conditions and the length of the growing season. However, trees do not make up the largest carbon pool in the forest; the soil pool contains about 1.5 times more carbon than the live biomass pool[5].

For managed forests, there are also non-forest carbon pools: the **harvested wood products in use** and the **harvested wood products in landfill**. Carbon stored in durable wood products like furniture, cabinets, floors, and buildings may be secured for decades or even centuries – as long as the product is in use. Other wood products, like paper or cardboard, also store carbon, but for shorter periods. The landfill carbon pool accounts for the end of life of wood products that release CO_2 as they decompose.



[5] Domke GM, Walters, BF, Nowak, DJ, Smith, J, Ogle, SM, Coulston, JW and Wirth, TC. 2020. Greenhouse gas emissions and removals from forest land, woodlands, and urban trees in the United States, 1990-2018. Resource Update FS-227. Madison, WI: US Department of Agriculture, Forest Service, Northern Research Station. 227:1-5. https://doi.org/10.2737/FS-RU-227.

What is Forest Carbon?

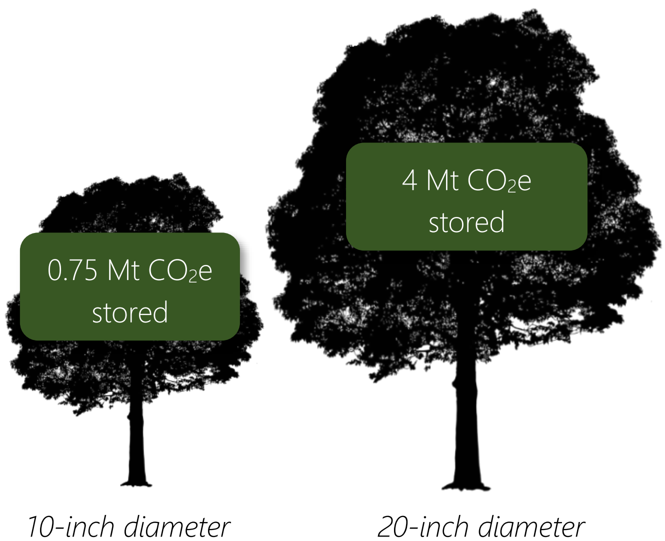
How do you measure carbon in a forest?

It is very difficult to measure the amount of carbon in a tree or a forest. Instead, we estimate the amount of carbon using inventory data and established equations based on real samples. Scientists weighed parts of trees to derive species-specific equations that are based on a set ratio between a tree's diameter, height, and weight. We can easily estimate the carbon content from the weight because a tree is about 50% carbon. For rotten trees, dead trees, or dead wood on the ground, we also factor in the amount of decay because as a tree decomposes, it loses carbon – emitted back to the atmosphere through decomposition or added to the soil carbon pool. Soils are the hardest carbon pool to estimate because soil is highly variable even over a small area. Plus, soils can range from a few inches to many feet in depth. Soil carbon is usually estimated from samples that are burned in a laboratory where the emitted carbon can be captured and measured.

How much CO_2 does an individual tree sequester and store?

A single sugar maple tree with a trunk 10 inches in diameter stores about 0.75 Mt CO_2e. If this tree grows a quarter of an inch in diameter (to 10¼ inches in diameter), it sequesters and stores an additional 0.04 Mt CO_2e[6]. This is roughly equivalent to amount of CO_2e emitted by driving a car about 100 miles[7].

In comparison, a 20-inch diameter sugar maple stores 4 Mt CO_2e, or about five times more carbon than the smaller sugar maple. As trees are three-dimensional in shape, the doubling of a tree's diameter results in a much larger increase in the tree's total size. The larger tree has more wood volume in the trunk, bark, branches, and roots. If the 20-inch tree also grows a quarter of an inch, it sequesters and stores an additional 0.1 Mt CO_2e -- more than twice the amount of the smaller tree.



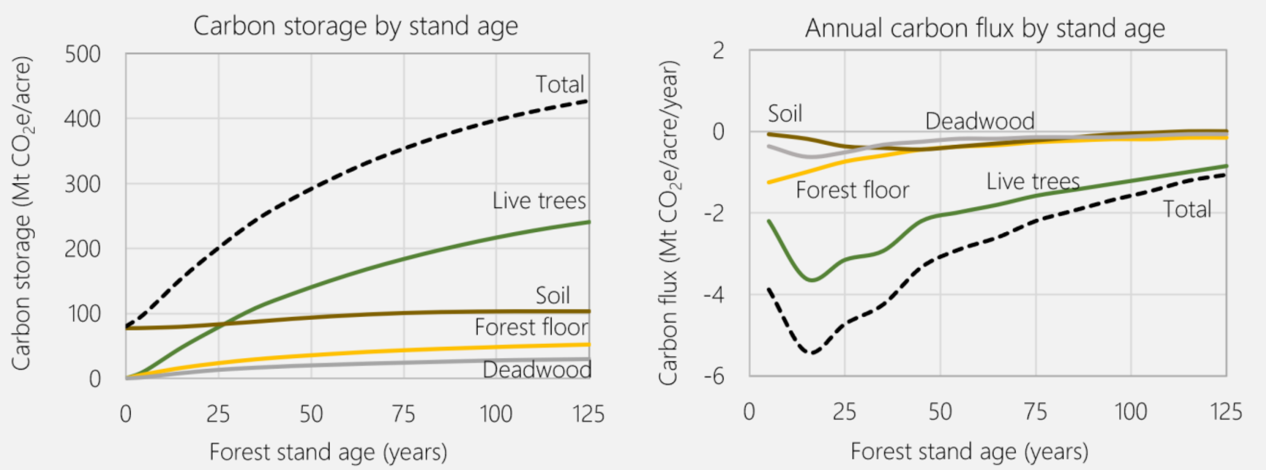
Because a tree must continually add wood to an ever-increasing volume, as a tree grows larger in size it usually does not put on the same amount of diameter growth as it did when it was smaller. Usually, the amount of diameter growth decreases as the tree gets larger. If the 20-inch sugar maple only grows a tenth of an inch in diameter, it would sequester and store the same amount of CO_2e as the smaller tree did by growing a quarter of an inch.

How much CO_2 does a forest sequester and store?

In a forest, things are more complex: a few small trees can occupy the same amount of space as one large tree and young trees usually have the most vigorous growth because there is fierce competition for sunlight and other

[6] Using Jenkins et al. 2003 allometric equations for sugar maple above- and below- ground biomass.
[7] Assuming 20 lbs CO_2e emitted per gallon and 25 MPG.

resources. In the graphs below, carbon storage per acre of forest increases with age (left), but carbon sequestration peaks when forests are younger (right)[8]. When we consider the amount of carbon per acre of forest, the density, diversity, arrangement, and health of the trees are important.



Carbon storage (left) increases as a forest ages and if there are no significant disturbances or stressors. Carbon flux (right, negative values indicate carbon sequestration) shows a different pattern by stand age. For this maple-beech-birch forest, carbon sequestration peaks when the stand is 15-20 years[1].

Forest carbon dynamics are complex. The amount of carbon that forests store and sequester is dependent on many factors, including:

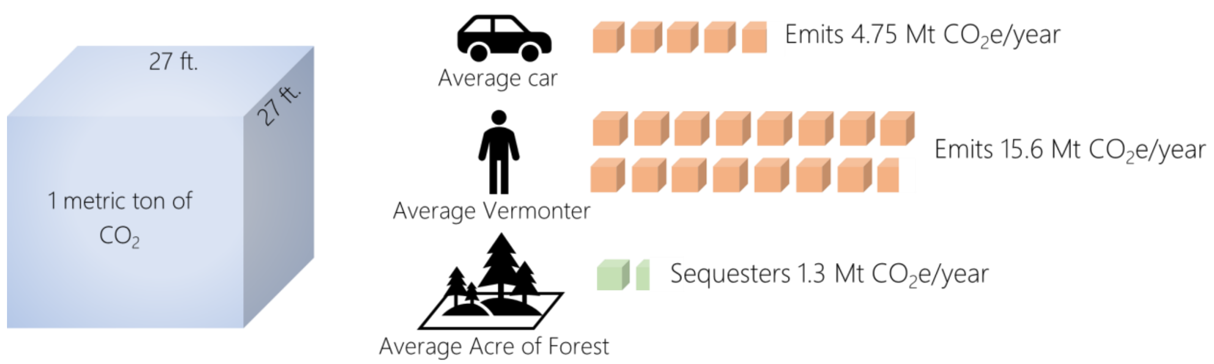
- Tree species composition
- Tree density
- Tree condition and age
- Availability of water and nutrients
- Weather events
- Climate
- Growing season length
- Soil type and depth
- Proportion of dead standing and downed trees
- Presence of earthworms
- Animal browse pressure
- History of disturbance (wind, ice, logging, insects, and disease)

[8] Carbon storage and flux data by stand age for a Maple-Beech-Birch forest from Smith et al. (2006)

What is Forest Carbon?

It is difficult to accurately estimate the amount of carbon stored in and sequestered by a forest, particularly the amount of soil carbon because it varies considerably from one location to the next. Based on estimates from long-term inventory plots, on average an acre of Vermont's forest stores about 300-400 Mt CO_2e and sequesters an additional metric ton each year[9]. The diagram below shows how the average annual sequestration rate of Vermont's forests compares to emissions from an average car and average Vermonter.

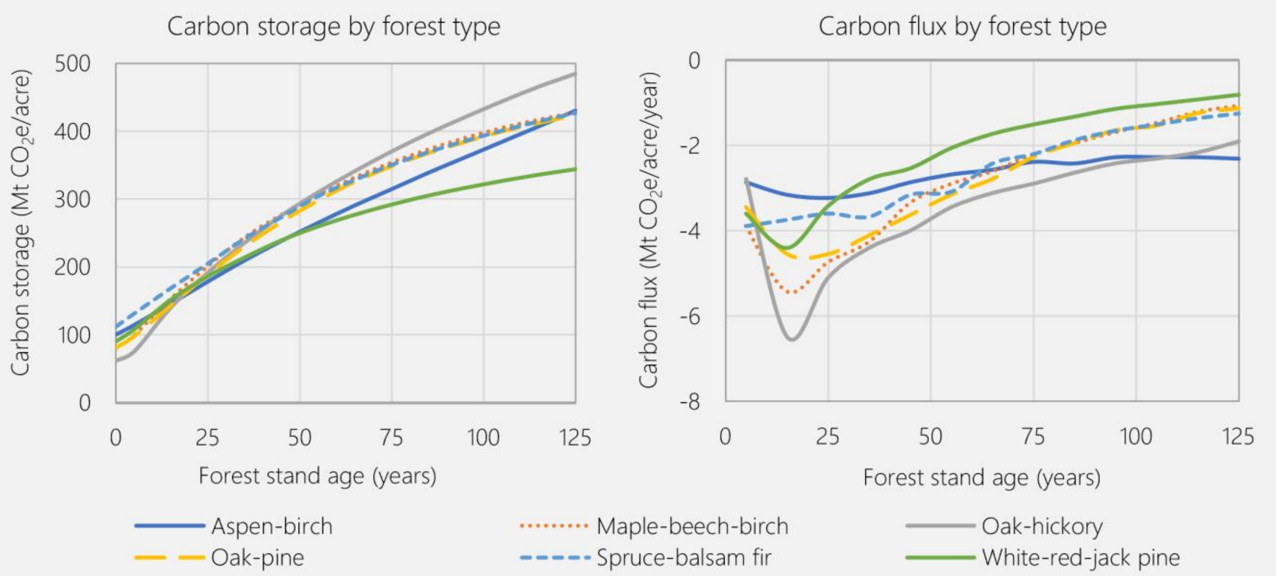
You would need about 12 acres of forest to remove the same amount of CO_2e that an average Vermonter emits in a year from day-to-day activities.



Which forest types store the most carbon?

Generally, an individual hardwood tree stores more carbon than a softwood (conifer) tree of the same size because hardwood trees usually have denser wood. But when we look at the different carbon pools, there can be differences among forest types. Spruce-fir forests can store high amounts of carbon in the litter and soil pools because spruce and fir needles take a long time to decompose on the forest floor, leading to a buildup of carbon in the litter and soil pools. In the graphs on the next page, carbon storage (left) increases for all forest types as the stand ages. Some forest types, like oak-hickory forests, store more carbon than other forest types, like white-red-jack pine forests. Carbon flux (right) shows that across all forest types, younger forests sequester carbon at a faster rate, but rates differ considerably among forest types and ages[10].

[9] Refer to the *Vermont Forest Carbon Inventory* (Kosiba, 2021) for more specific values and analysis.
[10] Carbon storage and flux data by stand age and forest type from Smith et al. (2006)



Forest of different types have similar patterns of carbon storage (left), although differences become more pronounced as forests age. Carbon flux (right, negative values indicate carbon sequestration) shows more pronounced differences among forest types when stands are young[10].

It is important to recognize that the amount of carbon a forest stores and the rate at which it stores carbon depends not only on the tree species and age of the stand, but the weather conditions, soil, site conditions, and past disturbance. Generally, forests that have many different species and sizes of trees, along with a deep litter layer, undisturbed soils, and lots of dead wood, store more carbon. Forests in colder climates also contain more carbon in soil and dead wood because of slower decomposition rates compared to warmer locations.

How does forest management affect carbon?

Harvesting trees for lumber, veneer, firewood, chips, or pulp removes carbon from the forest, but as long as the forest is allowed to remain a forest, other trees will quickly occupy the newly created space and sequester carbon from the atmosphere as they grow, sometimes at an accelerated rate. Creating gaps in the forest emulates natural processes and allows young trees to have sufficient sunlight and space to grow. If harvested wood is used for long-lived products, like lumber for buildings, furniture, or flooring, the carbon remains in the product for its life. There are many houses in Vermont that contain carbon that was sequestered by trees hundreds of years ago. Additional carbon benefits can come from using wood products as a substitute for concrete, steel, or fossil fuels, thus avoiding emissions from the transport and manufacture of these high-intensity products. Forest management can also help move carbon from living biomass to the dead wood, litter, and soil pools. Dead wood is particularly important in water and nutrient cycling, providing food and habitat for insects, mushrooms, and wildlife, and protecting young trees.

Additional Resources

Catanzaro P and D'Amato A. 2019. Forest Carbon: an essential natural solution for climate change. https://masswoods.org/sites/masswoods.org/files/Forest-Carbon-web_1.pdf

Catanzaro P, Ontl T, and Hagenbuch S. Forest Carbon Management and Climate Adaptation. December 11, 2019. https://youtu.be/cMZ1IDNJp5A