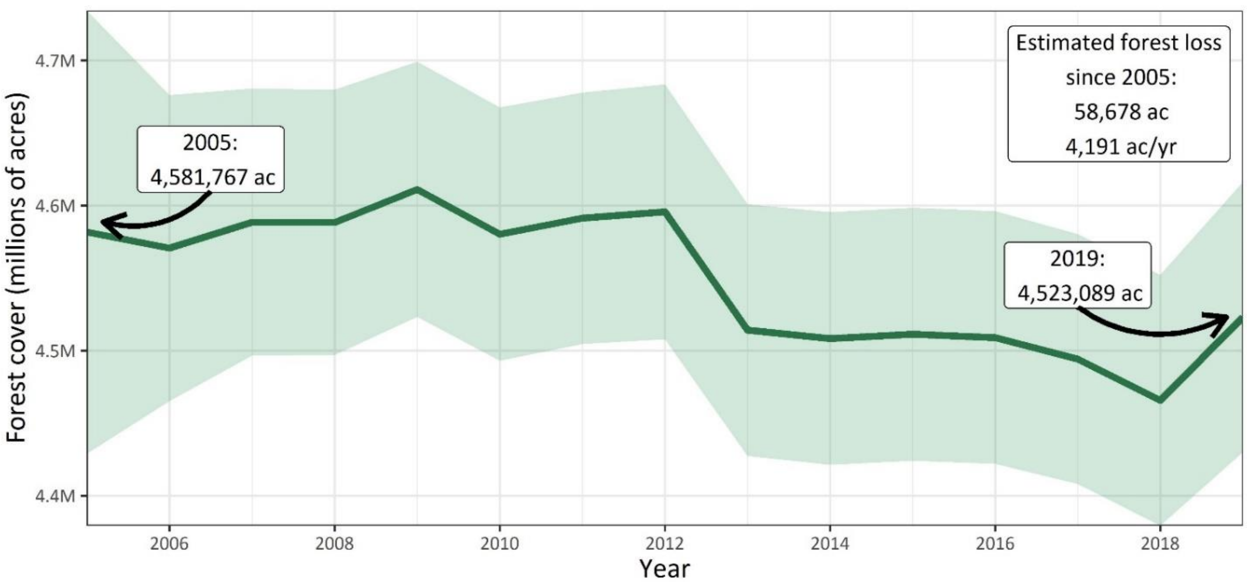
Forest Carbon Inventory

Quantifying the amount of carbon contained in Vermont's forests, along with the fluxes between carbon pools over time and the impacts of human intervention (land-use conversion, harvested wood products), is necessary for maintaining the natural greenhouse gas mitigation potential of forests. Continued monitoring is essential: the impacts of climate change, coupled with other stressors, could alter forest carbon dynamics through changes in tree health and forest cycling rates. Estimates of forest cover, carbon, and land-use change were derived from the USFS Forest Inventory and Analysis program[1,2] and follow guidelines by the Intergovernmental Panel on Climate Change (IPCC 2006)[3]. More information about forest carbon, a description of pools, and definitions of terms can be found in *What is Forest Carbon?*[4]

The amount of forestland is the most important factor in determining Vermont's forest carbon.

Based on data from multiple sources, Vermont has been losing forestland to other land uses since the early 1990s. Data from the USFS FIA Program[1] estimate the loss to be 4,191 acres per year (2005-2019) and NOAA's C-CAP[5] estimate the loss to be 2,051 acres per year (1996-2016). Despite uncertainty in the amount lost, as Vermont loses any amount of forestland, statewide carbon storage and sequestration decline.



Estimated Vermont forest cover (shown in millions of acres) between 2005 and 2019 according to the USDA Forest Inventory and Analysis program (solid green line). Data were derived from forest inventory plots sampled on a rotating basis and extrapolated to the state; a complete inventory of all plots occurs every 5-7 years. Green shading shows the upper and lower uncertainty around the estimated forest area (95% confidence that the actual amount of forestland is within the green area). Even with this high amount of uncertainty, these data strongly suggest that forest cover has declined statewide.

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[1] USDA Forest Service. 2020. Forest Inventory and Analysis (FIA) National Program. https://www.fia.fs.fed.us/tools-data/

[2] 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.

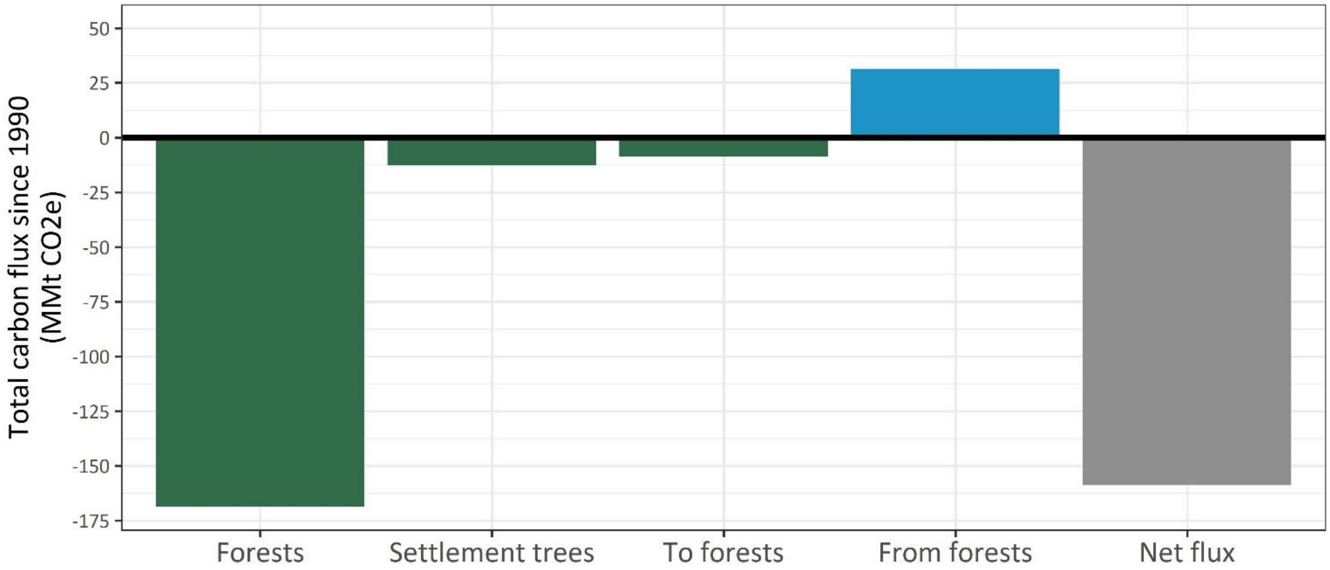
[3] IPCC. 2006. Guidelines for National Greenhouse Gas Inventories.

[4] Kosiba AM. 2021. What is Forest Carbon? Vermont Department of Forests, Parks and Recreation.

[5] NOAA. 2019. Coastal Change Analysis Program (C-CAP). https://coast.noaa.gov/ccapatlas/

Loss of Vermont's forestland has resulted in carbon emissions, but overall forests remain a carbon sink.

Since 1990, Vermont's forests that have remained forests sequestered more CO_2 than they emitted through respiration, decomposition, and disturbance -- about -168.7[6] MMt CO_2e[7,8]. In this same period, trees in towns and public areas took in an additional -12.7 MMt CO_2e. The gain of forestland was a net sink (-8.7 MMt CO_2e since 1990), but the loss of forestland to other land uses was a net source of CO_2 to the atmosphere (+31.3 MMt CO_2e since 1990). When combined across all land uses, the net carbon flux of forests remains negative, totaling over -159 MMt CO_2e taken in since 1990, or about -5.5 MMt CO_2e per year. Reducing the amount of forest land converted to other uses will help preserve this carbon sink. Note that this analysis does not include carbon sequestration by other land types, like wetlands or agriculture.

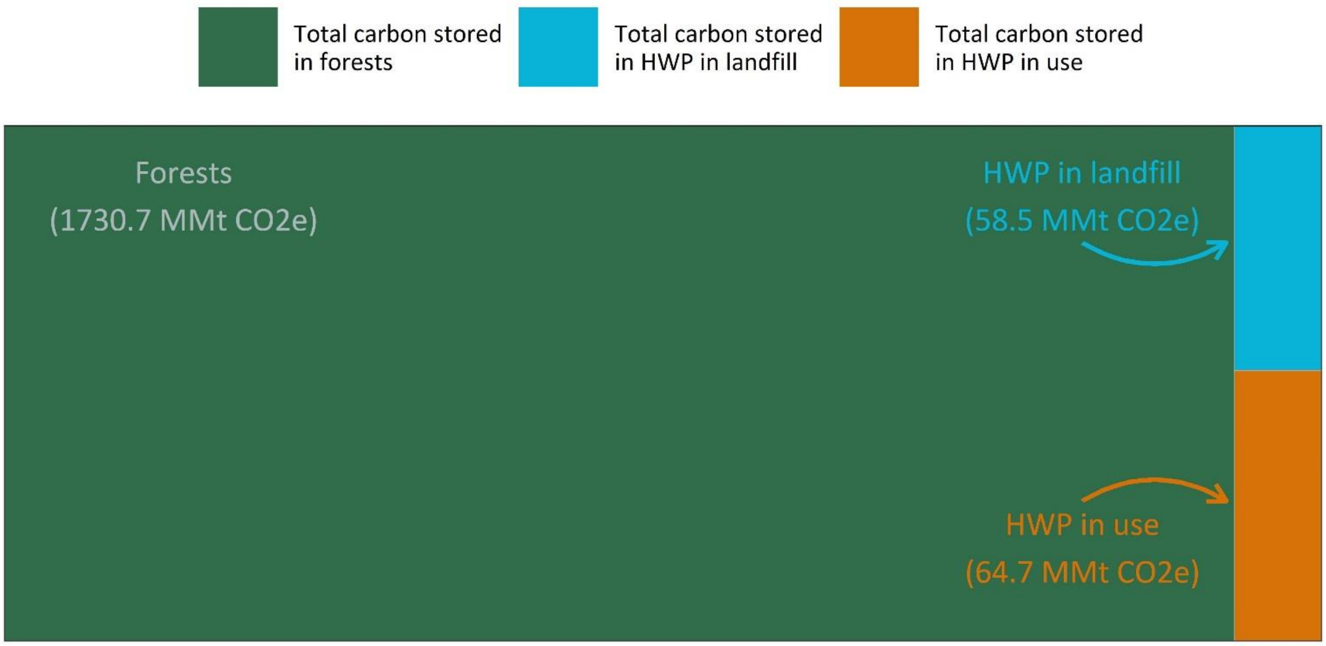


Estimated total carbon flux between 1990 and 2018 by land-use type. Carbon is expressed as a million metric tons of carbon dioxide equivalent (MMt CO_2e); negative values indicate negative emissions (net carbon uptake; green bars) and positive values indicate positive emissions (net carbon release; blue bar). Land use types are (1) forests that remained forests ('forests'), (2) settlement trees, (3) land converted to forests ('to forests'), and (4) land converted from forests ('from forests'). 'Settlement trees' are trees in developed land, including transportation infrastructure and human settlements of any size (IPCC 2006). The net flux of these four land-use types is shown in grey. Estimates were extracted from Domke et al. 2020 who used data collected by the USDA Forest Inventory and Analysis program and greenhouse gas inventory guidelines developed by the Intergovernmental Panel on Climate Change (IPCC 2006).

[6] Negative carbon sequestration values indicate carbon uptake, while positive values indicate emissions. For a more detailed description of forest carbon see *What is Forest Carbon?* (FPR, 2020).
[7] MMt CO_2e = Million metric tons of carbon dioxide equivalent.
[8] 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.

Vermont's forests stored over 1.7 billion metric tons of CO_2e in 2018. Harvested wood products (HWP), both in use and in landfill, contributed an additional 1.2 million Mt CO_2e in carbon storage.

Vermont's forest store the equivalent of 200 years of current state annual CO_2 emissions[9]. Carbon harvested from the forest in the form of sawlogs, pulpwood, chips, and roundwood is not immediately released into the atmosphere. About a third of wood harvested in Vermont is for durable products, like floors and furniture, which store carbon for the life of the product. When harvested wood products (HWP) reach the end of their life, they continue to store carbon as they slowly decay in landfills. The amount of carbon stored in HWP both in use and in landfill has been accumulating over time, acting as a net sink of atmospheric CO_2[10]. Locally harvested wood products support the Vermont economy and can displace other sources of emissions if they are used as a substitute for higher emissions products, like concrete, steel, or fossil fuels. Unlike land-use conversion, sustainable forest management allows remaining trees to continue to capture and store carbon.



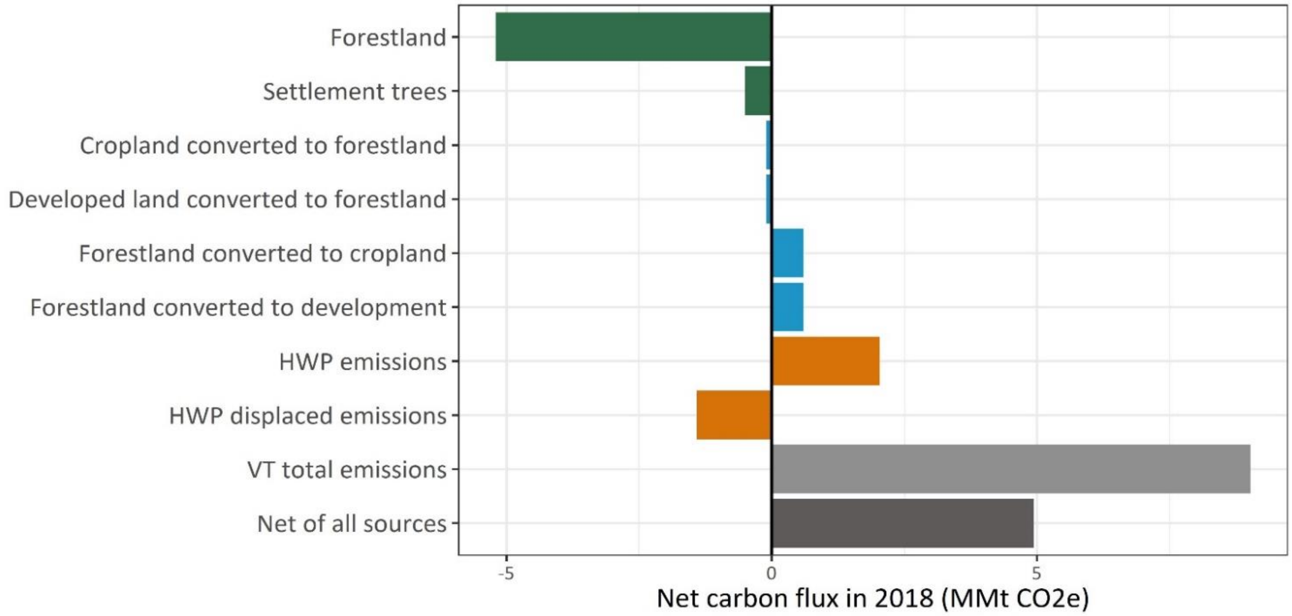
Estimated total carbon storage in Vermont's forests (sum of all five carbon pools; green) and carbon stored in harvested wood products (HWP) both in use and in landfill. All data are for 2018. Carbon is expressed as million metric tons of carbon dioxide equivalent (MMt CO_2e). Harvest data only capture aboveground carbon removed and not fluxes between carbon pools that may accompany management. Forest carbon storage was extracted from Domke et al. 2020 who used data collected by the USDA Forest Inventory and Analysis program and greenhouse gas inventory guidelines developed by the Intergovernmental Panel on Climate Change (2006). HWP estimates were extracted from Dugan et al. 2020 who modeled HWP emissions based on harvest reports provided by the Vermont Department of Forests, Parks and Recreation using the Carbon Budget Model.

[9] Current state level emissions are about 8-10 MMt CO_2e per year. Refer to Vermont Agency of Natural Resources. 2020. Vermont Greenhouse Gas Emissions Inventory and Forecast: Brief, 1990-2016. https://dec.vermont.gov/sites/dec/files/aqc/climate-change/documents/_Vermont_Greenhouse_Gas_Emissions_Inventory_and_Forecast_1990-2016.pdf

[10] Dugan AJ, Steele A, Hollinger DY, Bick S, and Lichstein JW. 2020. An assessment of forest sector carbon trends and mitigation potential for forests of Vermont. A report for the Vermont Department of Forests, Parks and Recreation

Across all carbon sinks and sources, Vermont's forest sector took in about 45% of state annual emissions in 2018[11].

Vermont's forest sector has both sinks and sources of CO_2. In 2018, forests sequestered -5.2 MMt CO_2e, with trees in towns and public areas contributing an additional -0.5 MMt CO_2e. There were both lands converted to forests (net sinks) and land converted from forests (net sources). Combined land-use changes resulted in net emissions of +1 MMt CO_2e. Importantly, land converted from forest not only emits stored carbon, but it also reduces the strength of Vermont's future forest carbon sequestration. Harvested wood products emitted +2.1 MMt CO_2e from the burning of bioenergy and decay of retired products but displaced -1.5 MMt CO_2e in emissions from the harvest and use of durable wood products and substitution of higher emissions products like steel, concrete, and fossil fuels. Comparing the total forest sector flux to the statewide total greenhouse gas emissions, estimated to be about +9 MMT CO_2e for 2018[12], the remainder is +4.9 MMt CO_2e. In other words, the forest sequestered about half of the state's annual emissions. Reducing Vermont's GHG emissions coupled with maintaining intact, healthy, and productive forests will help us preserve forests as a natural climate solution.



Estimated forest sector carbon flux in 2018 expressed as a million metric tons of carbon dioxide equivalent (MMt CO_2e): negative values indicate negative emissions (net carbon uptake) and positive values indicate positive emissions (net carbon release). Net carbon flux by forests and settlement trees is shown in green. 'Settlement trees' are trees in developed land, including transportation infrastructure and human settlements of any size (IPCC 2006). Land converted to and from forest is shown in blue. Harvested wood product (HWP) emissions from bioenergy combustion and decay in landfills and displaced emissions from the use of durable wood products and substitution benefits are shown in orange. Statewide total greenhouse gas emissions estimated for 2018 are shown in light grey with the net flux across all sources in dark grey. Estimates of fluxes from forests, settlement trees, and land-use conversion were extracted from Domke et al. 2020 who used data collected by the USDA Forest Inventory and Analysis program and greenhouse gas inventory guidelines developed by the Intergovernmental Panel on Climate Change (IPCC 2006). Harvested wood product estimates were extracted from Dugan et al. 2020 who used Vermont timber harvest data to model emissions from harvested wood products. Vermont statewide emissions were extracted from the Vermont Greenhouse Gas Emissions Inventory and Forecast (Vermont Agency of Natural Resources, 2020).

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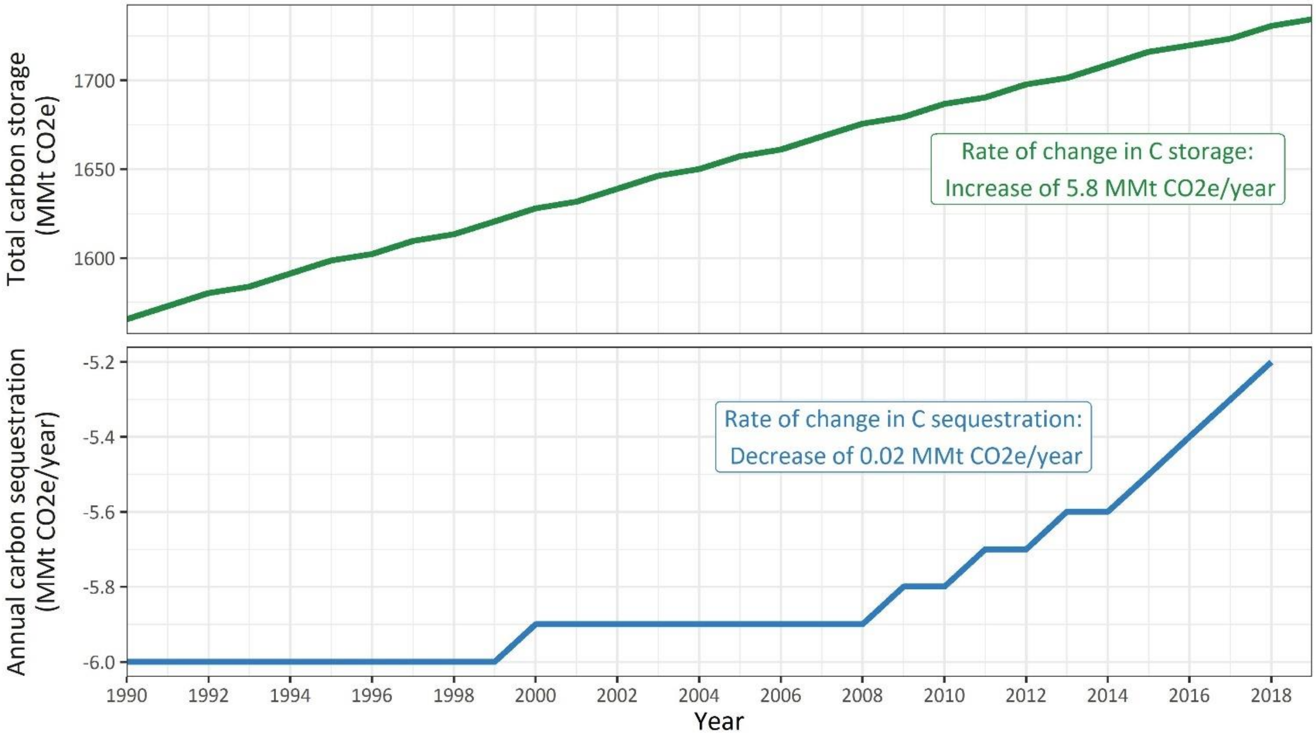
[11] Note that the forest sector sinks and sources are estimates and not included in the state GHG inventory.

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

For forests that have remained forests, the amount of carbon storage has increased over time, but the annual rate of carbon sequestration has decreased.

In 2019, Vermont's forests stored an estimated 1,734 MMt CO_2e[13]. Since 1990, storage has increased by 168.7 MMt CO_2e, but the rate of carbon uptake by forests has slowed over time. In the early 1990s, forests sequestered -6.0 MMt CO_2e per year, but in 2019, the rate declined to -5.2 MMt CO_2e, meaning that Vermont's forests are storing carbon at a slower rate than they did two decades ago. This decline is likely because of our similarly aged and aging trees. While older forests store much more carbon than younger trees, they sequester carbon at a slower rate. Another factor may be due to climate change: higher air temperatures can speed up the rate of nutrient cycling in a forest.

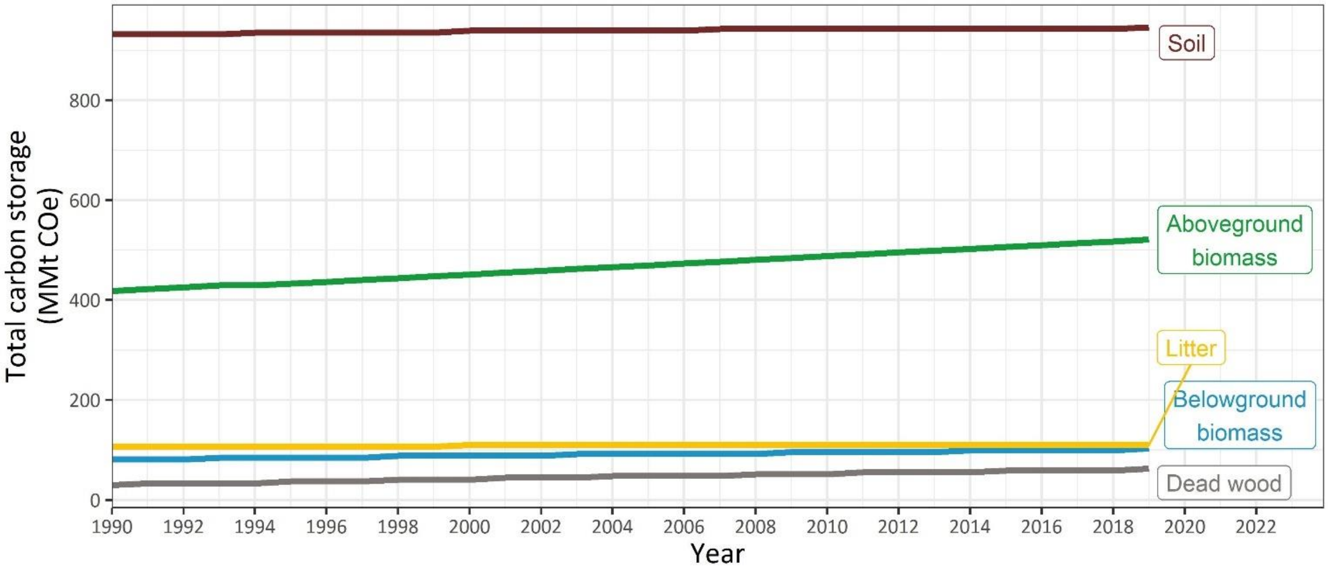


Estimated total carbon storage and net annual carbon sequestration for forests that have remained forests in Vermont between 1990 and 2019. Carbon is expressed as a million metric tons of carbon dioxide equivalent (MMt CO_2e). For sequestration, negative values indicate negative emissions (net carbon uptake). Estimates were extracted from Domke et al. 2020 who used data collected by the USDA Forest Inventory and Analysis program and greenhouse gas inventory guidelines developed by the Intergovernmental Panel on Climate Change (2006). These data suggest that while the total carbon storage of Vermont's forests has increased, the amount of carbon sequestered each year has decreased.

[13] To convert from carbon dioxide equivalent (CO_2e) to carbon, divide by 3.67.

For forests that have remained forests, carbon stored in the five carbon pools has increased or remained stable; the largest increase has occurred in the live biomass pool.

Across Vermont's forestland, carbon storage in each of the five forest carbon pools[14] has increased since 1990. Soils store more than half of the carbon in the forest: 946 MMt CO_2e compared to 796 MMt CO_2e for the four other pools combined. The live biomass carbon pool is the most dynamic of the carbon pools and has increased at the fastest rate. As a tree grows larger, it stores more carbon. While carbon is constantly relocating from the live biomass pool to the other carbon pools, this process is slow; natural disturbances, tree mortality, and forest management are required to see quicker increases in the other carbon pools.

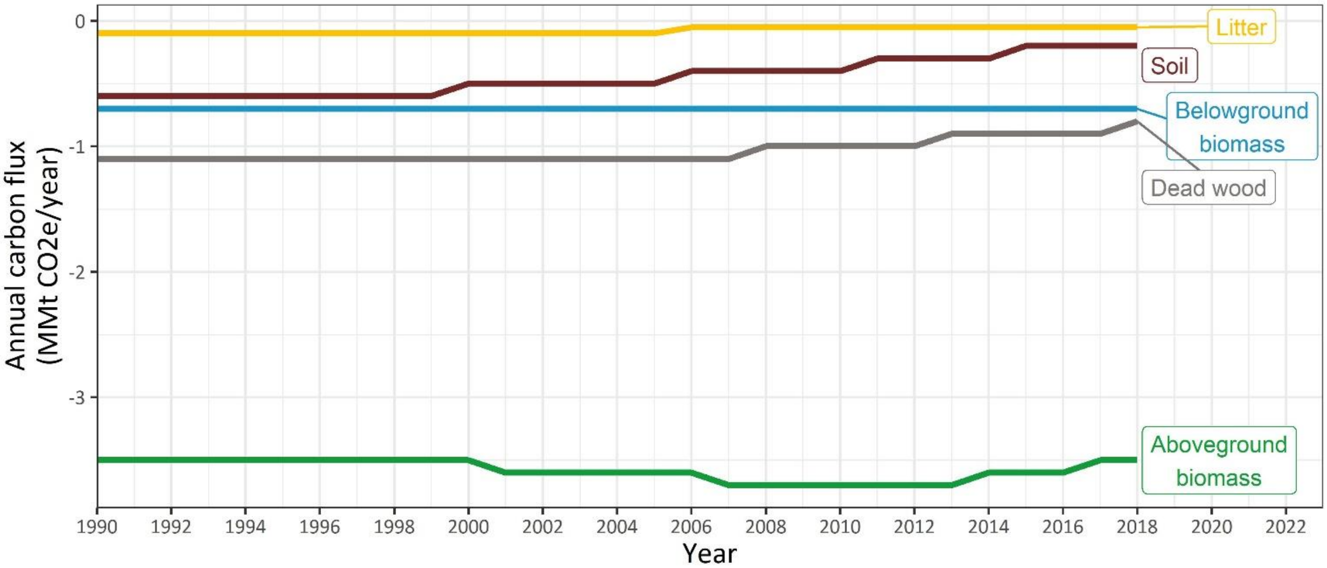


Estimated total carbon storage for forests that have remained forests in Vermont, shown by carbon pool and year. Carbon is expressed as a million metric tons of carbon dioxide equivalent (MMt CO_2e). The five carbon pools are (1)soil (1 m depth), (2) aboveground biomass (live trees and shrubs), (3) litter (leaves, needles, twigs), (4) belowground biomass (roots of live biomass > 2 mm diameter), and (5) dead wood (standing dead trees, downed logs and branches). Estimates were extracted from Domke et al. 2020 who used data collected by the USDA Forest Inventory and Analysis program and greenhouse gas inventory guidelines developed by the Intergovernmental Panel on Climate Change (2006). Data suggest that Vermont's forest carbon stocks have increased over time, primarily due to increased carbon stored in live biomass.

[14] For more information on forest carbon pools refer to *What is Forest Carbon?* (Kosiba, 2021).

For forests that have remained forests, the flux rate of the five carbon pools has remained a net carbon sink, but the dead wood, litter, and soil carbon pools show reduced carbon uptake over time.

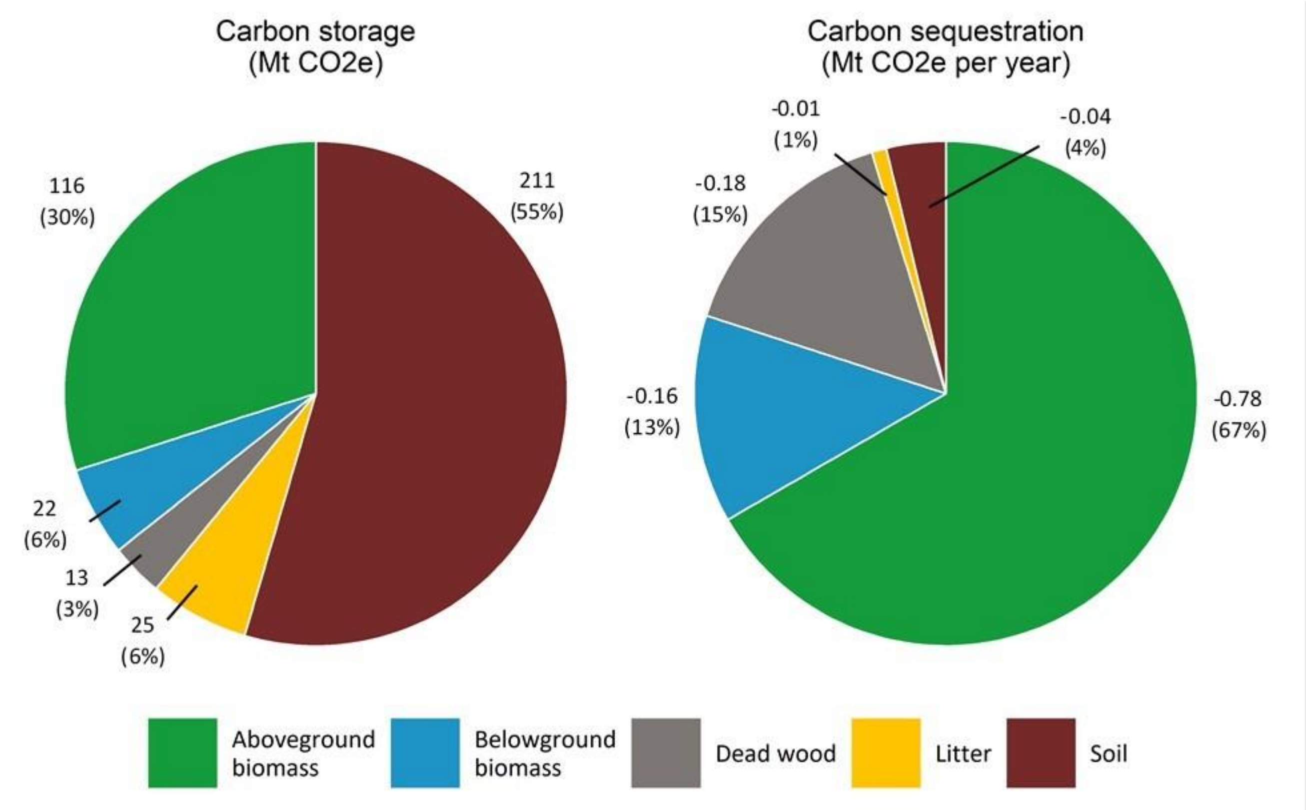
Since 1990, all five of the forest carbon pools have remained a carbon sink, meaning that they sequestered more CO_2 than they emitted through respiration, decomposition, and disturbance. The live aboveground biomass pool sequestered twice the amount of CO_2 as the other four pools combined (-3.50 MMt CO_2e compared to -1.75 MMt CO_2e). The dead wood, litter, and soil pools show a worrisome slowing rate of carbon uptake over time. These changes may be due to warmer air temperatures that have occurred because of climate change. Warmer air temperatures can increase the rate of decomposition in a forest. This decline in the uptake of soils, litter, and dead wood pools also suggests that increased storage in live biomass is not being transferred into the dead wood, litter, and soil pools. These pools could be enlarged using management techniques designed to increase downed material, which would also increase the sequestration rate in live biomass.



Estimated annual carbon sequestration (flux) for forests that have remained forests in Vermont, shown by carbon pool and year. Carbon is expressed as a million metric tons of carbon dioxide equivalent per year (MMt CO_2e/year); negative values indicate negative emissions (net carbon uptake) and positive values indicate positive emissions (net carbon release). The five carbon pools are (1) soil (1 m depth), (2) aboveground biomass (live trees and shrubs), (3) litter (leaves, needles, twigs), (4) belowground biomass (roots of live biomass > 2 mm diameter), and (5) dead wood (standing dead trees, downed logs and branches). Estimates were extracted from Domke et al. 2020 who used data collected by the USDA Forest Inventory and Analysis program and greenhouse gas inventory guidelines developed by the Intergovernmental Panel on Climate Change (2006). These data suggest that the strength of Vermont's forest carbon sink has decreased over time due to the soil, litter, and dead wood pools.

On average, an acre of Vermont's forests stored 389 Mt CO_2e and sequestered an additional -1.3 Mt CO_2e in 2018, but the relative contribution to total storage and sequestration varied by carbon pool.

In an average acre of Vermont's forests, soils store more than half of the total carbon. The live biomass pool (a combination of the above- and belowground live biomass pools) makes up about 36% of the total carbon storage. In terms of the rate of carbon uptake (sequestration), the live biomass pool sequesters 80% of the carbon. Carbon sequestered by live plants is transferred to the other pools over time as trees shed parts or die. While soils are the largest pool of stored carbon in a forest, they accrue carbon much more slowly than other pools, meaning that a loss of soil carbon can take a long time to recuperate. Note that these values are the estimated average carbon per acre in Vermont; an actual acre of forest may store and sequester less or more carbon and the ratios among the pools may differ.



Estimated average forest carbon storage per acre (left) and the annual rate of carbon sequestration per acre (net flux, negative values indicate net uptake; right). Carbon data are for 2018 and expressed as metric tons of carbon dioxide equivalent (Mt CO_2e). The five carbon pools are (1) soil (1 m depth), (2) aboveground biomass (live trees and shrubs), (3) litter (leaves, needles, twigs), (4) belowground biomass (roots of live biomass > 2 mm diameter), and (5) dead wood (standing dead trees, downed logs and branches). Estimates of carbon sequestration by forests were extracted from Domke et al. 2020 who used data collected by the USDA Forest Inventory and Analysis program.