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U.S. Forest Carbon Data: In Brief

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Introduction

The *flux*—or flow—of carbon dioxide (CO_2) and other greenhouse gases into the atmosphere is the dominant contributor to the observed warming trend in global temperatures.[1] Trees, however, store (*sequester*) CO_2 from the atmosphere, accruing significant stores of carbon over time. Trees also release some CO_2 back into the atmosphere (e.g., emissions). This process is known as the forest *carbon cycle*.

The forest carbon cycle starts with the sequestration and accumulation of atmospheric CO_2 due to tree growth. The accumulated carbon is stored in five different *pools* in the forest ecosystem: aboveground biomass (e.g., leaves, trunks, and limbs), belowground biomass (e.g., roots), deadwood, litter (e.g., fallen leaves and stems), and soils. As trees or parts of trees die, the carbon cycles through those different pools, specifically from the living biomass pools to the deadwood, litter, and soil pools. The length of time carbon stays in each pool varies considerably, ranging from months (litter) to millennia (soil). The cycle continues as carbon flows out of the forest ecosystem and returns to the atmosphere through several processes, including respiration, combustion (e.g., fire), and decomposition. Carbon also leaves the forest ecosystem through timber harvests, by which it enters the *product pool*. This carbon is stored in harvested wood products (HWPs) while they are in use but eventually will return to the atmosphere upon the wood products' disposal and eventual decomposition, which could take several decades or more. In total, there are seven pools of forest carbon: five in the forest ecosystem and two in the product pool (HWPs in use and HWPs in disposal sites).

Carbon is always moving through the pools of forested ecosystems. The size of the various pools and the rate at which carbon moves through them vary considerably over time. The amount of carbon sequestered in a forest relative to the amount of carbon released into the atmosphere is constantly changing with tree growth, death, and decomposition. If the total amount of carbon released into the atmosphere by a given forest over a given period is greater than the amount of carbon sequestered in that forest, the forest is a *net source* of carbon emissions to the atmosphere. If the forest sequesters more carbon than it releases into the atmosphere, the forest is a *net sink* of carbon.

These forest carbon dynamics are driven in large part by different anthropogenic and ecological disturbances. *Anthropogenic disturbances* are planned activities, such as timber harvests, whereas *ecological disturbances* are unplanned, such as weather events (e.g., hurricanes, ice storms, droughts), insect and disease infestations, and wildfires. Generally, disturbances result in tree mortality, causing the transfer of carbon from the living pools to the deadwood, litter, soil, and product pools, and/or eventually to the atmosphere. If a disturbed site regenerates as forest, the carbon releases caused by the disturbance generally are offset over time. If, however, the site changes to a different land use (e.g., agriculture), the carbon releases may not be offset.

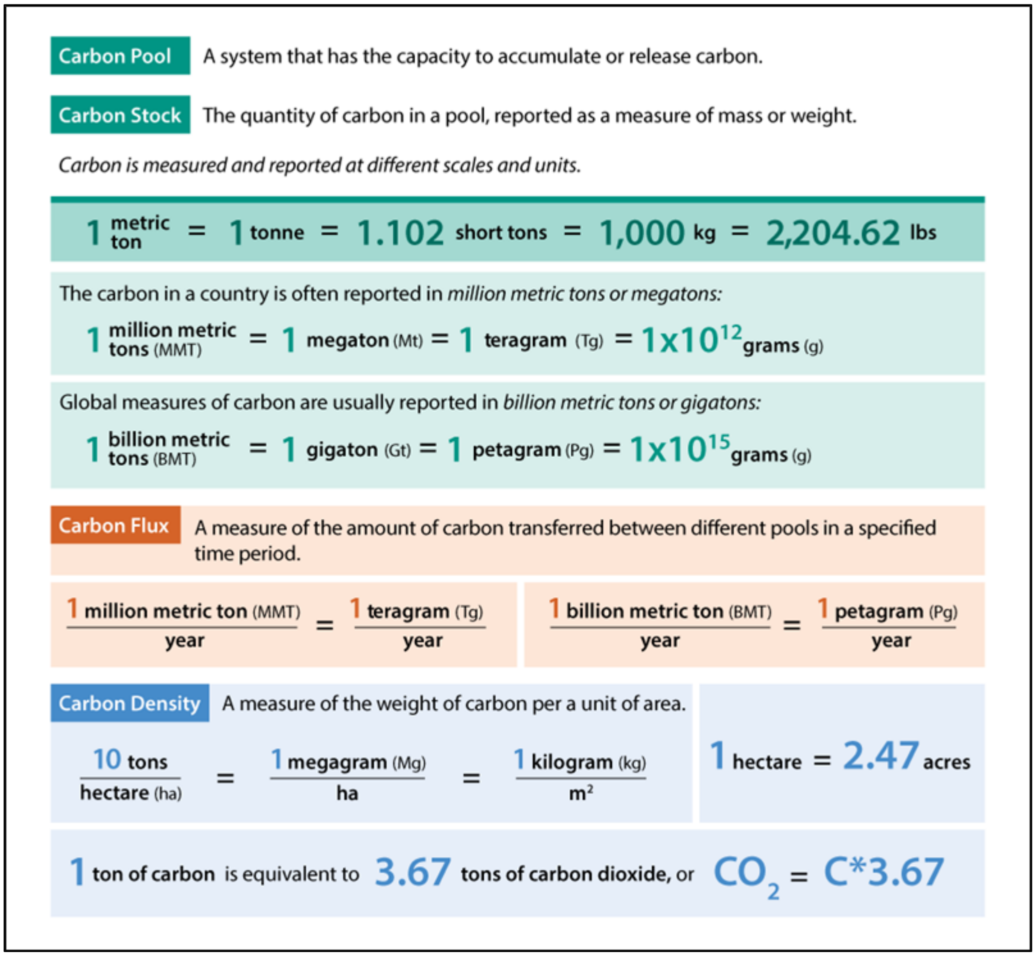
Congressional debates over climate policy have often included ideas for optimizing carbon sequestration in forests as a potential mitigation strategy for global warming. To facilitate those debates, this report provides data on the amount of carbon that is stored in and flows through U.S. forests. Since the early 1990s, the U.S. Environmental Protection Agency (EPA) has prepared an annual *Inventory of U.S. Greenhouse Gas Emissions* (*Inventory)*, which has included an

[1] Other greenhouse gases include methane (CH_4), nitrous oxide (N_2O), and several fluorinated gases. D. J. Wuebbles et al., "Executive Summary," in *Climate Science Special Report: Fourth National Climate Assessment (NCA), Volume II,* U.S. Global Change Research Program, 2018.

accounting of carbon in U.S. forests in the Land Use, Land-Use Change, and Forestry (LULUCF) sector.[2] Estimates of forestland area and forest inventory data are used to estimate *carbon stocks*, or the amount of carbon stored in a pool. Carbon flux is then measured by comparing changes in forest carbon stocks over time. This report includes data for the most recent year available as well as data for every five years back to 1990, as available.[3]

Figure 1 introduces some of the terms and units for measuring and reporting carbon that are used throughout this report. An accompanying report, CRS Report R46312, *Forest Carbon Primer*, addresses basic questions concerning carbon sequestration in forests and provides an overview of forest carbon accounting methodologies.

Figure 1. Carbon Terms and Units



Source: CRS, adapted from Maria Janowiak et al., *Considering Forest and Grassland Carbon in Land Management*, U.S. Department of Agriculture, Forest Service, GTR-WO-95, June 2017, p. 4.

Notes: Because much of the data for this report are based on international standards, this report uses the metric system for consistency purposes. Forest carbon stocks are reported as measures of carbon, whereas

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[2] Environmental Protection Agency (EPA), *Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2020*, EPA430-R-22-003, April, 2022. Hereinafter referred to as *EPA Inventory (2022).*

[3] The *EPA Inventory (2022)* reported changes to figures across the entire time series (1990-2021), related to updated and refined methodologies and correcting for errors in previous iterations (see *Chapter 9—Recalculations and Improvements* for more information). Consequently, figures reported here may not be consistent with figures reported in earlier versions of this report or other CRS products.

greenhouse gas emissions and removals (e.g., sequestration) are reported as measures of carbon dioxide or carbon dioxide equivalents (to facilitate comparisons with other greenhouse gases). As a chemical element, the mass of carbon (C) is based on its molecular weight. Carbon dioxide (CO_2) is a compound consisting of one part carbon and two parts of the element oxygen (O). The conversion factor between C and CO_2 is the ratio of their molecular weights. The molecular weight of carbon is 12 atomic mass units (amu), and the molecular weight of CO_2 is 44 amu, which equals a ratio of 3.67. The same method is used to convert measurements of other greenhouse gases to carbon dioxide equivalents (CO_2 eq.).

U.S. Forest Carbon Stocks

According to the *Inventory*, U.S. forests stored 61.0 billion metric tons (BMT) of carbon in 2021 (see **Figure 2** and **Table 1**).[4] The majority of forest carbon was stored in the forest ecosystem pools (96%); the remainder was stored in the product pool (i.e., harvested wood products, HWP). The largest pool of carbon was forest soils, which contained approximately 54% of total forest carbon in 2021. The next-largest pool was aboveground biomass, which contained approximately 26% of the total. Each of the other pools stored 6% or less of the total carbon.

Since 1990, U.S. forest carbon stocks have increased 10%. Nearly all forest pools have gained more carbon as of 2021. The exceptions are the litter and soil pools, which each continue to store around the same amount of carbon for each year of reported data. Although forest carbon stocks have increased, the rate of increase has slowed across recent years.

Since 1990, the size of U.S. forests has remained mostly constant. About one-third of the United States is forested.[5] These forested areas vary considerably by location, climate, vegetation type, and disturbance histories, among other factors. Because of this variation, U.S. forests contain varying amounts of carbon stored in varying proportions across the different forest pools. Accordingly, the amount of carbon within a certain area, or *carbon density*, also varies.[6]

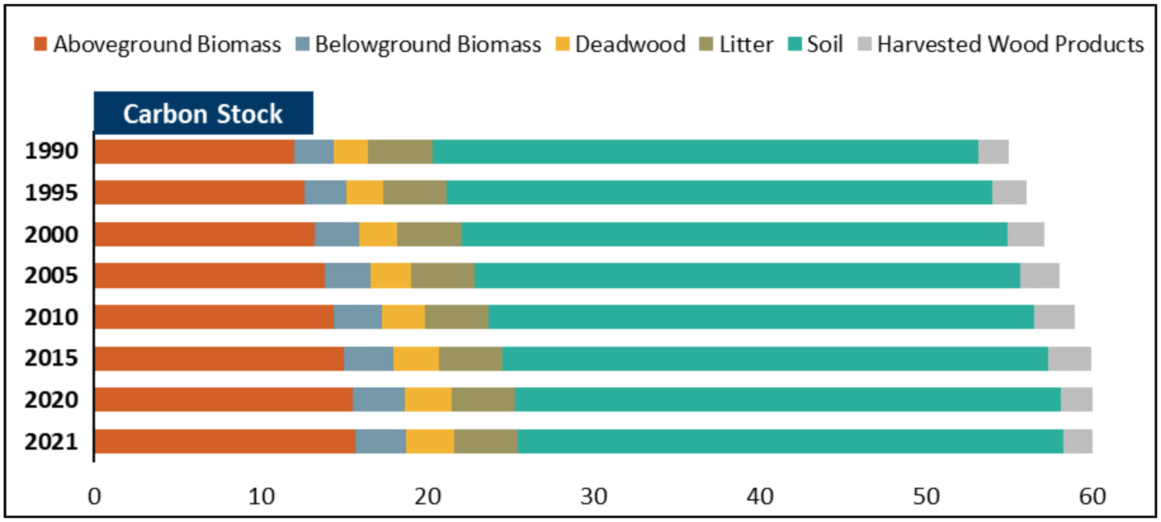
[4] Chapter 6, "Land Use, Land-Use Change, and Forestry (LULUCF)," in *EPA Inventory, 2022,* April, 2022. Hereinafter referred to as *EPA Inventory (2022): Ch. 6—LULUCF*.

[5] The total land area of the United States is approximately 936 million hectares (2.3 billion acres, not including the U.S. territories). Estimates for U.S. forestland area vary primarily based on how *forestland* is defined. See for example, S. Oswalt et al., *Forest Resources of the United States (FROTUS), 2017*, USDA Forest Service, GTO-WO-97, March 2019, estimating 310 million hectares (766 million acres) of forestland. In contrast, the *EPA Inventory* defines forest area more narrowly and estimates 289 million hectares (714 million acres) of managed and unmanaged forestland in 2020 (*EPA Inventory (2022): Ch. 6—LULUCF,* p. 10). For more information, see CRS Report R46976, *U.S. Forest Ownership and Management: Background and Issues for Congress*, by Katie Hoover and Anne A. Riddle.

[6] The forests in the Pacific Northwest and Great Lakes regions contain the highest carbon density in the conterminous United States, though the distribution of carbon across the different pools varies between those regions (see Barry Wilson et al., "Imputing Forest Carbon Stock Estimates from Inventory Plots to a Nationally Continuous Coverage," *Carbon Balance and Management*, vol. 8, no. 1 [2013]). The forests in Alaska also are estimated to contain significant stocks of carbon (see U.S. Geological Survey, *Baseline and Projected Future Carbon Storage and Greenhouse-Gas Fluxes in Ecosystems of Alaska*, professional paper 1826, 2016, and *EPA Inventory (2022): Ch. 6—LULUCF*, p. 28).

Figure 2. U.S. Forest Carbon Stocks by Pool

(billion metric tons [BMT] of carbon [C])



Source: Data from EPA, Table 6-10 in Chapter 6, "Land Use, Land-Use Change, and Forestry," *U.S. National Greenhouse Gas Inventory*, April 2022.

Notes: Harvested wood products (HWPs) includes both HWPs in use and HWPs in disposal sites.

Table 1. U.S. Forest Carbon Stocks by Pool

(million metric tons [MMT] of carbon [C])

Pool	1990	1995	2000	2005	2010	2015	2020	2021 MMT C	2021 % of Total
Forest Ecosystem	53,148	54,039	54,909	55,721	56,538	57,369	58,156	58,316	96%
Soil (Mineral and Organic)	*32,813*	*32,811*	*32,810*	*32,810*	*32,811*	*32,816*	*32,814*	*32,816*	*54%*
Aboveground Biomass	*12,062*	*12,687*	*13,294*	*13,874*	*14,445*	*15,020*	*15,579*	*15,688*	*26%*
Litter	*3,838*	*3,845*	*3,852*	*3,834*	*3,829*	*3,828*	*3,809*	*3,810*	*6%*
Belowground Biomass	*2,375*	*2,502*	*2,625*	*2,743*	*2,858*	*2,973*	*3,085*	*3,106*	*5%*
Deadwood	*2,060*	*2,194*	*2,328*	*2,460*	*2,595*	*2,732*	*2,868*	*2,896*	*5%*
Harvested Wood Products (HWP)	1,895	2,061	2,218	2,353	2,462	2,567	2,695	2,718	4%
HWP in Use	*1,249*	*1,326*	*1,395*	*1,447*	*1,471*	*1,490*	*1,530*	*1,536*	*3%*
HWP in Disposal	*646*	*735*	*823*	*906*	*991*	*1,076*	*1,165*	*1,182*	*2%*
Total C Stock	**55,043**	**56,100**	**57,128**	**58,074**	**59,000**	**59,936**	**60,851**	**61,034**	*100%*

Sources: Data from EPA, Table 6-10 in Chapter 6, "Land Use, Land-Use Change, and Forestry," *U.S. National Greenhouse Gas Inventory*, April 2022.

Notes: Data reflect carbon stocks for managed forestland remaining forestland in Alaska and the conterminous 48 states and do not include Hawaii or the U.S. territories. The EPA inventory (2022) reported changes to figures across the entire time series (1990-2021), related to updated and refined methodologies and correcting for errors in previous iterations (see pp. 35-37 for more information). Consequently, figures reported here may not be consistent with figures reported in earlier versions of this report or other CRS products. The years were selected to show carbon stocks over time at regular intervals; 2021 is the most recent year for which data are available. Columns may not add due to rounding.

Carbon Emissions and Sinks from U.S. Forests

Carbon flux is the net annual change in carbon stocks. The flux estimate for any given year (e.g., 2019) is the change between stock estimates for that year (2019) and the following year (2020). Negative flux values indicate more carbon was removed from the atmosphere and sequestered than was released in that year (e.g., net carbon sink); net negative flux is typically called *net sequestration* (or sometimes just *sequestration*). Positive flux values indicate more carbon was released than was sequestered in that year (e.g., *net carbon source*).

According to the *Inventory*, U.S. forests were a net carbon sink in 2020, having sequestered 767 MMT CO_2 equivalents (or 209 MMT of carbon) that year (see **Figure 3** for net sequestration by MMT CO_2 equivalents, **Table 2** for flux data by MMT CO_2 equivalents, and **Table 3** for flux data by MMT of carbon).[7] This total represents an offset of approximately 13% of the gross greenhouse gas emissions from the United States in 2020.[8]

The net sink reflects carbon accumulation on existing forestland and carbon accumulation associated with land converted to forestland within the past 20 years. Most of the sink is associated with existing forests (85%). Within the carbon pools, most of the flux is associated with aboveground biomass (59%). The carbon flux into the living biomass pools (above- and belowground) reflects net carbon accumulation from the atmosphere. The carbon flux into the other pools represents the movement of carbon from the living biomass pools into the nonliving pools (e.g., deadwood, litter), primarily through the decomposition process.

Although soils store significant amounts of carbon, the carbon accumulates slowly over long periods of time, so the annual flux is minimal. In some years, soils are a net source of carbon to the atmosphere. In some years, litter may be a net source to the atmosphere, particularly in years of increased wildfire activity. Overall, the annual net flux of carbon into U.S. forests is small relative to the amount of carbon forests store. For example, U.S. forests gained an additional 209 MMT of carbon between 2019 and 2020, but that represents only a 0.3% increase to the total forest carbon stock (61.0 BMT of carbon). In addition, the total stock of carbon stored in forests is equivalent to the sum of several decades of U.S. greenhouse gas emissions.[9]

From 1990 to 2020, U.S. forests were a net carbon sink. However, the net amount of carbon sequestered by U.S. forests varies annually. As stated earlier, interannual variation depends largely on the size, duration, and severity of unplanned disturbances, which disrupt forest ecosystems. For example, wildfire activity in Alaska drives a significant portion of the interannual variability, due in part to fluctuations in the size of the area in the state affected by wildfire each year and because more of the carbon in Alaska is stored in pools (e.g., litter) that are likely to be combusted in a fire as compared to other states.[10] Other factors influencing the net flux of carbon in U.S. forests over the time series include management activities (e.g., timber harvests) and land use trends (e.g., afforestation or deforestation).[11]

[7] *EPA Inventory (2022): Ch. 6—LULUCF*.

[8] In 2020, gross U.S. greenhouse gas emissions were 5.98 billion metric tons of CO_2 equivalents, not including any emissions related to the LULUCF sector (Table 2-1, *EPA Inventory (2022): Ch. 2: Trends in Greenhouse Gas Emissions*, p. 5).

[9] David N. Wear and John W. Coulston, "From Sink to Source: Regional Variation in U.S. Forest Carbon Futures," *Scientific Reports*, vol. 5, no. 16518 (2015). Hereinafter referred to as Wear and Coulston, 2015.

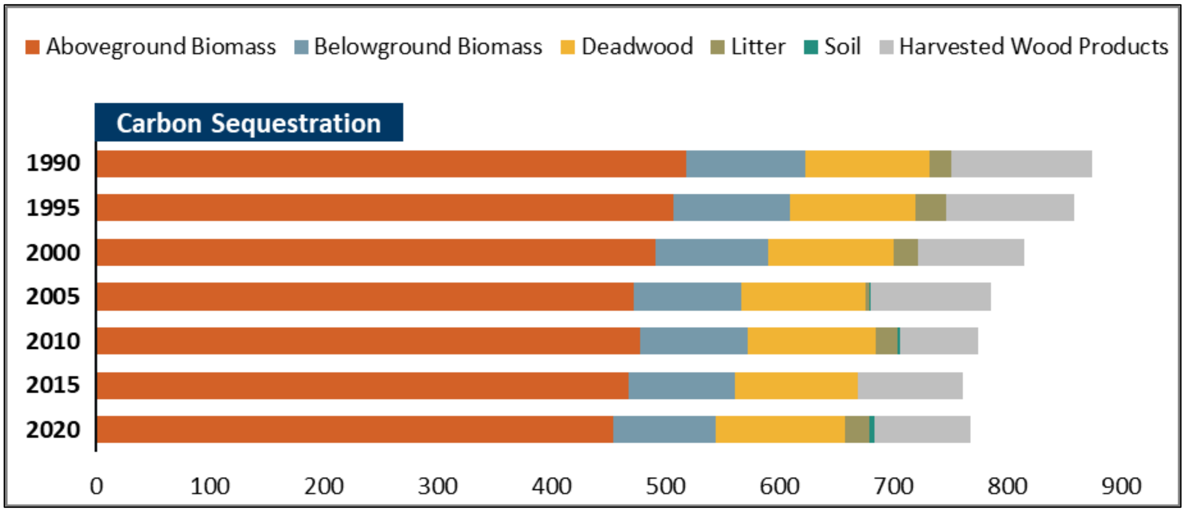
[10] *EPA Inventory (2022): Ch. 6—LULUCF*, p. 28.

[11] Afforestation is the conversion of non-forestland to forest; deforestation is the conversion of forestland to non-

Although the *Inventory* reflects the net carbon flux associated with forest disturbances through annual changes in the carbon stock, recent iterations of the *Inventory* also have included the estimated emissions specifically associated with wildfires. The *Inventory* reports that wildfires, including prescribed fires, resulted in emissions of 237 MMT CO_2 equivalents in 2020.[12] Annual emissions from wildfire vary significantly, because wildfire activity varies annually. For example, the *Inventory* reports that wildfire-related emissions in the previous year (2019) were significantly lower: 83 MMT CO_2 equivalents.

Figure 3. U.S. Forest Carbon Sequestration by Pool

(million metric tons [MMT] of carbon dioxide equivalents [CO_2 eq.] per year)



Source: Data from EPA, Tables 6-8 and 6-24 in Chapter 6, "Land Use, Land-Use Change, and Forestry," *U.S. National Greenhouse Gas Inventory*, April, 2022.

Notes: Harvested wood products (HWPs) includes both HWPs in use and HWPs in disposal sites. The figure reflects the net amount of carbon sequestered by forests, after accounting for the amount of carbon released by forests in that year (e.g., the net amount of the carbon sink). Because this figure reflects net carbon sequestration—and not carbon flux as in the following tables—the values on the x-axis are positive numbers. Litter was a net source of carbon in 2015 (32 MMT CO_2 eq/yr) and soil was a net source of carbon in four years: 1990 (2 MMT CO_2 eq/yr), 1995 (1 MMT CO_2 eq/yr), 2000 (<1 MMT CO_2 eq/yr), and 2015 (2 MMT CO_2 eq/yr); these figures are not reflected in the bars above. Data reflect sequestration estimates for forest remaining forestland and land converted to forestland (forest ecosystem pools only) for managed forestland in Alaska and the conterminous 48 states and do not include Hawaii or the U.S. territories. The years were selected to show carbon sequestration rates over time at regular intervals; 1990 is the first year data are available, and 2020 is the most recent year data are available.

forestland. For more information on the impacts of land use change on forest carbon, see CRS Report R46312, *Forest Carbon Primer*, by Katie Hoover and Anne A. Riddle.

12 Table 6-11 and Table 6-15 in *EPA Inventory (2022): Ch. 6—LULUCF*.

Table 2. U.S. Forest Carbon Flux by Pool, Carbon Dioxide Equivalents

(million metric tons [MMT] per year, CO_2 equivalents)

Carbon Pool	1990	1995	2000	2005	2010	2015	2020	
							CO_2 Eq.	% of Total
Forest Ecosystem	-749	-745	-721	-680	-706	-636	-684	89%
Aboveground Biomass	*-518*	*-507*	*-491*	*-472*	*-477*	*-468*	*-455*	*59%*
Deadwood	*-105*	*-102*	*-99*	*-95*	*-95*	*-93*	*-90*	*12%*
Belowground Biomass	*-109*	*-110*	*-110*	*-109*	*-112*	*-109*	*-113*	*15%*
Litter	*-19*	*-27*	*-21*	*-4*	*-19*	*32*	*-22*	*3%*
Soil	*2*	*1*	*0*	*-1*	*-2*	*2*	*-4*	*1%*
Harvested Wood Products (HWP)	-124	-112	-93	-106	-69	-92	-84	11%
HWP in Disposal	*-55*	*-52*	*-32*	*-43*	*-7*	*-27*	*-20*	*3%*
HWP in Use	*-69*	*-61*	*-62*	*-63*	*-62*	*-64*	*-64*	*8%*
Total Carbon Flux	-872	-857	-815	-786	-775	-728	-767	—

Sources: Data from EPA, Tables 6-10 and 6-26 in Chapter 6, "Land Use, Land-Use Change, and Forestry," in *U.S. National Greenhouse Gas Inventory*, April, 2022.

Notes: Negative flux values indicate more carbon was removed than was released in that year (e.g., carbon sink)—or net sequestration; positive flux values indicate more carbon was released than was removed in that year (e.g., carbon source). Data reflect flux estimates for forest remaining forestland and land converted to forestland (forest ecosystem pools only) for managed forestland in Alaska and the conterminous 48 states and do not include Hawaii or the U.S. territories. The EPA inventory (2022) reported changes to figures across the entire time series (1990-2020), related to updated and refined methodologies and correcting for errors in previous iterations (see pp. 35-37 for more information). Consequently, figures reported here may not be consistent with figures reported in earlier versions of this report or other CRS products. The years were selected to show carbon stocks over time at regular intervals; 1990 is the first year data are available, and 2020 is the most recent year flux data are available. Columns may not add due to rounding.

Table 3. U.S. Forest Carbon Flux by Pool

(million metric tons [MMT] of carbon [C] per year)

Carbon Pool	1990	1995	2000	2005	2010	2015	2019	
							MMT C	% of Total
Forest Ecosystem	-204	-203	-197	-186	-193	-174	-186	89%
Aboveground Biomass	*-141*	*-138*	*-134*	*-129*	*-130*	*-128*	*-124*	*59%*
Deadwood	*-29*	*-28*	*-27*	*-26*	*-26*	*-25*	*-25*	*12%*
Belowground Biomass	*-30*	*-30*	*-30*	*-30*	*-31*	*-30*	*-31*	*15%*
Litter	*-5*	*-7*	*-6*	*-1*	*-5*	*9*	*-6*	*3%*
Soil	*1*	*0*	*0*	*0*	*-1*	*0*	*-1*	*1%*
Harvested Wood Products (HWP)	-34	-31	-26	-29	-19	-25	-23	11%
HWP in Disposal	*-15*	*-14*	*-9*	*-12*	*-2*	*-7*	*-6*	*3%*
HWP in Use	*-19*	*-17*	*-17*	*-17*	*-17*	*-18*	*-17*	*8%*
Total Carbon Flux	-238	-234	-222	-214	-211	-199	-209	—

Sources: Data from EPA, Tables 6-9 and 6-25 in Chapter 6, "Land Use, Land-Use Change, and Forestry," in *U.S. National Greenhouse Gas Inventory*, April, 2022.

Notes: Negative flux values indicate more carbon was removed than was released in that year (e.g., carbon sink); positive flux values indicate more carbon was released than was removed in that year (e.g., carbon source). Data reflect flux estimates for forest remaining forestland and land converted to forestland (forest ecosystem pools only) for managed forestland in Alaska and the conterminous 48 states and do not include Hawaii or the U.S. territories. The EPA inventory (2022) reported changes to figures across the entire time series (1990-2020), related to updated and refined methodologies and correcting for errors in previous iterations (see pp. 35-37 for more information). Consequently, figures reported here may not be consistent with figures reported in earlier versions of this report or other CRS products. The years were selected to show carbon stocks over time at regular intervals; 1990 is the first year data are available, and 2020 is the most recent year flux data are available. Columns may not add due to rounding.

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