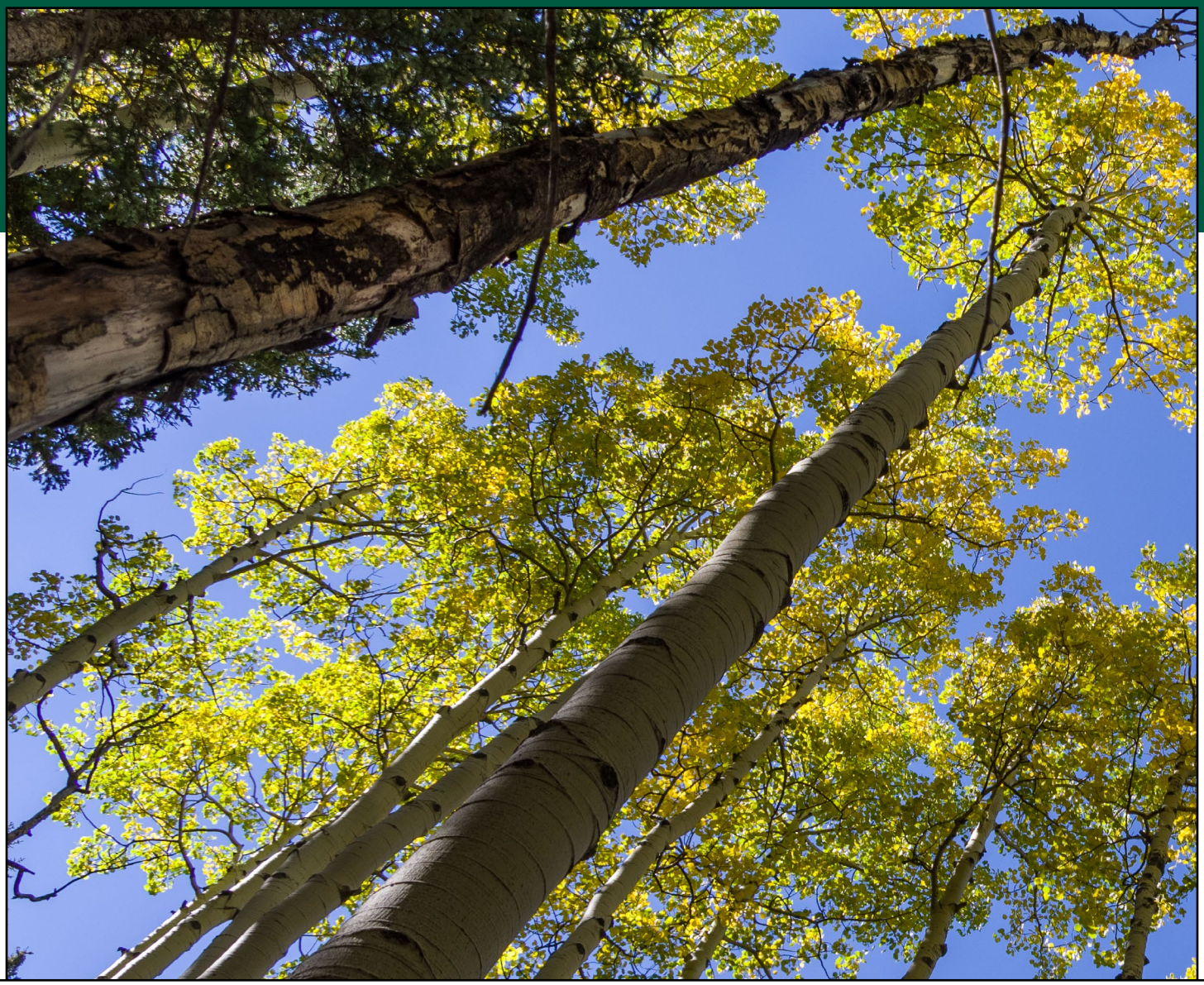
USDA Forest Service
U.S. DEPARTMENT OF AGRICULTURE

Resource Bulletin WO-102 | December 2024



Greenhouse Gas Emissions and Removals

From Forest Land, Woodlands, Urban Trees, and Harvested Wood Products in the United States, *1990–2022*

Front cover and back cover photo:
Aspen trees along the Abineau Trail in Coconino National Forest. USDA Forest Service photo by Deborah Lee Soltesz.

Introduction

As a party to the 1992 United Nations Framework Convention on Climate Change (UNFCCC), the United States has reported an inventory of greenhouse gas (GHG) emissions and removals by sector every year, using the methodological guidance from the Intergovernmental Panel on Climate Change (IPCC), since the mid-1990s (U.S. EPA 2024). The United States is also party to the 2015 Paris Agreement. In 2024, the annual inventory supports both agreements for the first time. It follows guidelines under these agreements and presents information in a common and consistent format to assess the relative contribution of different GHG emissions and removals in the United States to climate change.

In 2022, U.S. net GHG emissions increased by more than 1.3 percent relative to 2021 net emissions, which had decreased substantially from previous years due, in large part, to the global COVID-19 (coronavirus) pandemic. Forest land, harvested wood products, woodlands, and urban trees within the land sector collectively continue to represent the largest net carbon sink in the United States, removing the equivalent of more than 14 percent of total (i.e., gross) GHG emissions in 2022 (U.S. EPA 2024). U.S. Department of Agriculture (USDA), Forest Service researchers and partners compile estimates of GHG emissions and removals, based primarily on Nationwide Forest Inventory (NFI) data collected and maintained by the Forest Inventory and Analysis (FIA) Program within the Forest Service. This resource bulletin provides an overview of the status and trends of GHG emissions and removals from forest land, harvested wood products, woodlands, and urban trees in the United States from 1990 to 2022. The estimates summarized here are based on the compilation reported in the "Land Use, Land-Use Change, and Forestry" chapter of the U.S. EPA (2024) inventory submission to the UNFCCC.

Among the guiding principles agreed to under the UNFCCC and the Paris Agreement are improved reporting over time—including continuous advances in inventory methods and models—and improved transparency, accuracy, consistency, completeness, and comparability of reported information. To that end, five methodological, model, and data improvements were implemented in the latest inventory (U.S. EPA 2024), resulting in substantial changes in estimates over the time series for the key categories included in this resource bulletin:

1. New methods for estimating standing live and dead aboveground biomass carbon were implemented in the NFI (Westfall et al. 2024) resulting in changes not only in live aboveground and belowground biomass carbon but also estimates of dead wood and litter carbon stocks and stock changes. This is because aboveground live biomass is a variable in the models used to estimate downed dead wood and litter carbon stocks and stock changes.

2. Managed forest land in Hawaii and the U.S. Territories of American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands (hereafter referred to as the U.S. Territories) were included for the first time in UNFCCC reporting.

3. Compilation methods used for the conterminous United States were applied, for the first time, in coastal southeast and south-central Alaska. When combined with the changes in aboveground and belowground biomass carbon estimates due to new methods described in (1) above, this resulted in substantial increases in total forest ecosystem carbon stocks in coastal Alaska.

4. Updates to climate variables in the models used to estimate litter and soil carbon resulted in decreases in estimates of carbon stocks in the litter and mineral soil pools and increases in estimates of carbon stocks in the organic soil pool. These updates were in support of formally implementing the models to estimate litter and soil carbon stocks in the FIA Program and associated public-facing database.

5. New data from the latest inventories in the NFI since the last UNFCCC submission were incorporated into the compilation of forest ecosystem estimates. Collectively, these

improvements implemented in the latest inventory resulted in a 9.1-percent increase in estimates of forest ecosystem carbon stocks when compared to estimates from the same year (2022) in the previous inventory and a 26-percent increase in estimates of carbon stock changes relative to estimates for the same year in the previous inventory.

Most of the national-scale estimates included in UNFCCC and the Paris Agreement reporting are also developed and published at the individual State level for the entire 1990–2022 time series and are available in a companion research dataset (Walters et al. 2024). This report also includes regional carbon stock and stock change estimates for forest land by broad ownership category (i.e., private or public land) and the National Forest System. New in this resource bulletin are disaggregated estimates for Tribal lands within private lands, estimates on forest land for each national forest (fig. 1), and carbon density estimates of carbon stocks and stock changes by forest type group in the United States (tables 6 and 7).

Forest Carbon Cycle

In forests, carbon is cycled among ecosystem pools and the atmosphere as a result of biogeochemical processes (e.g., photosynthesis, respiration, decomposition, and disturbances such as fires or pest outbreaks) and anthropogenic activities (e.g., land use and land use change). Carbon is removed from the atmosphere by living trees through photosynthesis and is allocated to and stored

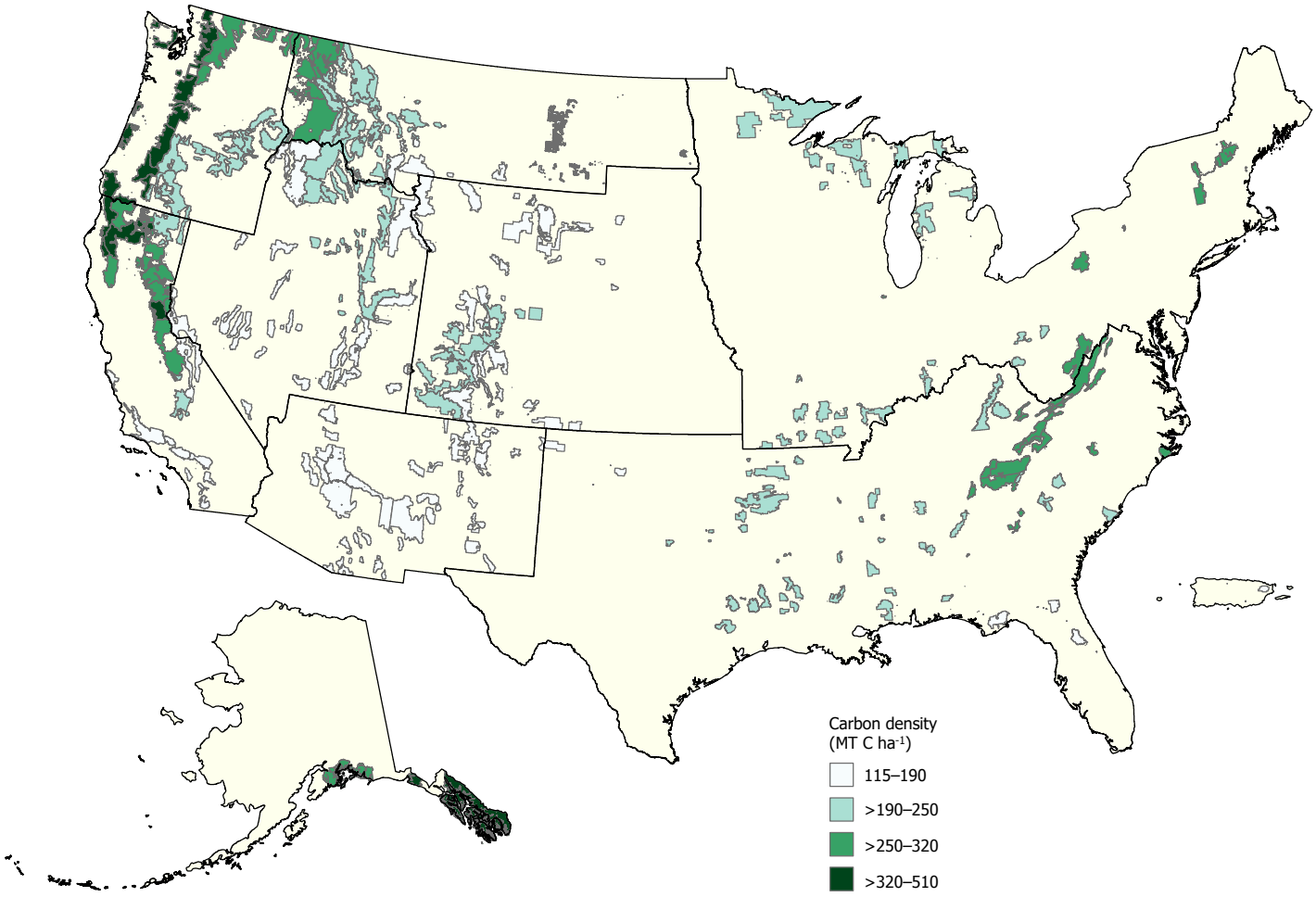


Figure 1—Total forest ecosystem carbon density (MT C ha^{-1}) for each national forest.

in aboveground and belowground biomass. Respiration returns carbon to the atmosphere. Carbon can also be transferred from live tree biomass to the dead wood pool through mortality. Stems, foliage, and other debris are deposited on the forest floor, transferring carbon to either the dead wood, litter, or soil pools, depending on attributes (e.g., size) of the debris and how the pools are defined (see sidebar). Carbon is cycled between dead wood, litter, and soil pools by organisms that facilitate decomposition and transfer of carbon between pools and the atmosphere through heterotrophic respiration.

The net change in forest carbon is not equivalent to the net flux between forests and the atmosphere because timber harvests do not result in an immediate release of all harvested biomass carbon to the atmosphere. Instead, following harvesting, a portion of the carbon stored in wood may be transferred to a wood "product pool." Once in a product pool, the carbon is emitted over time as carbon dioxide (CO_2) from decomposition and as CO_2, methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO), and other nitrogen oxides (NO_x) when the wood product combusts, or the carbon in the product may be transferred and stored in solid waste disposal sites. The rate of emission varies considerably among different product pools and solid waste disposal sites (U.S. EPA 2024).

In addition, carbon can cycle among forest land and other land use categories (e.g., grasslands, croplands, settlements, wetlands, or other lands). Carbon can enter or exit a forest ecosystem through processes such as lateral transport (e.g., through erosion and land-water transport). Carbon can also be transferred from forest land to other land use categories through land conversion, or the reverse can occur through reforestation, afforestation, or both. Finally, emissions estimates associated with some of the anthropogenic land uses within forest ecosystems in the United States (e.g., fuel use associated with forest harvesting) and the use of those products (e.g., energy use and/or waste disposal from paper manufacturing) resulting from those uses are included in other sectoral chapters in the U.S. EPA (2024) inventory.

Carbon Pools

When estimating carbon stocks or stock change (flux), carbon in forest ecosystems can be divided into the following five storage pools (IPCC 2006):

- **Aboveground biomass—all living biomass above the soil including stems, stumps, branches, bark, seeds, and foliage. This pool includes live understory biomass as well.**
- **Belowground biomass—all living biomass of coarse living roots with diameters greater than 2 millimeters.**
- **Dead wood—all nonliving woody biomass either standing, lying on the ground (but not including litter), or in the soil.**
- **Litter—all duff, humus, and fine woody debris above the mineral soil, including woody fragments with diameters of up to 7.5 centimeters.**
- **Soil organic carbon—all organic material in soil to a depth of 1 meter but excluding the coarse roots of the belowground pools. Organic (e.g., peat and muck) soils have a minimum of 12 to 20 percent organic matter by mass and develop under poorly drained conditions of wetlands. All other soils are classified as mineral soil types and typically have relatively low amounts of organic matter.**

Two harvested wood pools are also included when estimating carbon flux:

- **Harvested wood products in use**
- **Harvested wood products in solid waste disposal sites**

Total Emissions and Removals

Forest land, harvested wood products, woodlands in the grassland category, and urban trees in settlements individually and collectively represent a net GHG sink over the 1990–2022 time series. Interannual variability is driven, in large part, by natural and anthropogenic forest disturbances (e.g., wildfire, harvesting), land conversions (e.g., forest land converted to cropland and settlements, reforestation/afforestation), and changes in harvested wood product stocks in use and transfers to solid waste disposal sites (table 1) (U.S. EPA 2024). In 2022, forest land, harvested wood products, woodlands in the grassland category, and urban trees in settlements collectively represented an estimated net increase in carbon stocks of 889.3 million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.). The forest land remaining forest land category is the largest net sink in the land sector, with an estimated uptake of -694.3 MMT CO_2 Eq. from forest ecosystem pools in 2022. For categories included in this report, the largest source of annual emissions and/or transfers of carbon was from the conversion of forest land to other land use categories, with estimated emissions of 136.6 MMT CO_2 Eq. (table 1) (U.S. EPA 2024).

Forest Land Remaining Forest Land and Harvested Wood Products

Within the forest land remaining forest land category, aboveground live biomass is the largest contributor to the net uptake over the reporting period, followed by transfers from live biomass to dead wood and belowground live biomass (table 2). Harvested wood products in use and in solid waste disposal sites are also an important contributor to the net sink in the land sector. In 2022, net uptake/transfer for both harvested wood product pools decreased slightly from previous years.

Table 1—Emissions and removals (net flux) from land use, land use change, and forestry (MMT CO_2 Eq.) by year

Emissions and removals category[a]	1990	1995	2000	2005	2010	2020	2021	2022
Forest land remaining forest land[b]	(851.0)	(846.4)	(825.2)	(770.0)	(786.6)	(765.2)	(749.5)	(694.3)
Non-CO_2 emissions from fire	5.8	1.0	9.7	15.5	3.1	15.3	19.9	14.8
N_2O emissions from forest soils	0.1	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Non-CO_2 emissions from drained organic soils	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Forest land converted to nonforest land[b]	129.8	130.9	131.8	133.0	134.2	136.7	136.7	136.6
Nonforest land converted to forest land[b]	(100.1)	(100.0)	(99.9)	(100.1)	(100.1)	(100.2)	(100.3)	(100.3)
Harvested wood products	(123.8)	(112.2)	(93.4)	(106.0)	(69.1)	(96.8)	(94.7)	(92.8)
Woodlands remaining woodlands[c]	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.2)
Urban trees in settlements[d]	(96.6)	(103.2)	(110.1)	(117.0)	(124.4)	(136.7)	(137.7)	(138.5)
Total carbon stock change[e]	**(1,041.8)**	**(1,031.1)**	**(997.0)**	**(960.2)**	**(946.0)**	**(962.4)**	**(945.7)**	**(889.3)**
Total net emissions and removals[f]	**(1,035.9)**	**(1,029.8)**	**(986.8)**	**(944.2)**	**(942.4)**	**(946.6)**	**(925.3)**	**(874.1)**

Totals may not sum due to independent rounding. Parentheses indicate net carbon uptake (i.e., a net removal of carbon from the atmosphere or transfer from another carbon pool).

[a] For details on how estimates were compiled, see U.S. EPA (2024).

[b] Estimated emissions and removals include the net changes to carbon stocks stored in all ecosystem pools. Note that in the forest land converted to nonforest land category, emissions and removals from forest land converted to other lands are not currently included in the U.S. EPA (2024) report; forest land converted to wetlands estimates were not compiled by the Forest Service in the U.S EPA (2024) report but are included here based on methods used to compile estimates for other land conversion categories. Estimates of soil carbon change are not included for forest land converted to other lands and forest land converted to wetlands.

[c] Estimates for woodlands, which are included in the grassland land use category, were compiled using the same methods and models as those in the forest land category.

[d] Estimates of emissions and removals from urban trees in settlements were compiled using percentage tree cover in carbon sequestration density per unit of tree cover.

[e] Total carbon stock change includes any carbon stock gains and losses from all land use and land use conversion categories.

[f] Total net emissions and removals is the net sum of all non-CO_2 (CH_4 and N_2O) emissions to the atmosphere plus net carbon stock changes in units of MMT CO_2 Eq.

Table 2—Emissions and removals (net flux) from forest land remaining forest land and harvested wood pools (MMT CO_2 Eq.) by year

Carbon pool[a]	1990	1995	2000	2005	2010	2020	2021	2022
Forest	**(851.0)**	**(846.4)**	**(825.2)**	**(770.0)**	**(786.6)**	**(765.2)**	**(749.5)**	**(694.3)**
Aboveground biomass	(600.9)	(589.7)	(576.6)	(550.8)	(545.8)	(522.8)	(513.0)	(491.7)
Belowground biomass	(116.8)	(114.3)	(112.0)	(107.5)	(106.2)	(102.2)	(100.9)	(96.9)
Dead wood	(132.0)	(133.8)	(134.0)	(131.2)	(135.0)	(136.2)	(135.3)	(131.4)
Litter	(2.4)	(9.5)	(3.7)	20.5	0.7	(3.4)	(0.1)	26.4
Soil (mineral)	2.0	1.6	1.7	(0.8)	(0.3)	(1.3)	(0.9)	(1.2)
Soil (organic)	(1.6)	(1.4)	(1.3)	(1.0)	(0.7)	(0.1)	(0.1)	(0.1)
Drained organic soil	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Harvested wood	**(123.8)**	**(112.2)**	**(93.4)**	**(106.0)**	**(69.1)**	**(96.8)**	**(94.7)**	**(92.8)**
Products in use	(54.8)	(51.7)	(31.9)	(42.6)	(7.4)	(32.3)	(30.4)	(28.8)
Solid waste disposal sites	(69.0)	(60.5)	(61.5)	(63.4)	(61.7)	(64.5)	(64.3)	(63.9)
Total net flux	**(974.8)**	**(958.7)**	**(918.6)**	**(876.0)**	**(855.7)**	**(862.0)**	**(844.2)**	**(787.0)**

Totals may not sum due to independent rounding. Parentheses indicate net carbon uptake (i.e., a net removal of carbon from the atmosphere or transfer from another carbon pool).

[a] For details on these estimates and how they were compiled, see U.S. EPA (2024).

Carbon stock estimates for forest ecosystem and harvested wood carbon storage pools are presented in table 3. Together, the estimated aboveground biomass and soil carbon pools account for more than 83 percent of total forest ecosystem carbon stocks. By maintaining current harvesting practices and regeneration activities on these forested lands, along with continued input of harvested products into the harvested wood products pool, carbon stocks in forests are likely to continue to increase in the near term, though possibly at a lower rate. Because most of the timber harvested from U.S. forest land is used in wood products and many discarded wood products are disposed of in solid waste disposal sites rather than by incineration, significant quantities of carbon in harvested wood are transferred to these long-term storage pools rather than being released rapidly to the atmosphere (Skog 2008).

Table 3—Carbon stocks in forest land remaining forest land and harvested wood pools (MMT C) by year

Carbon pool[a]	1990	1995	2000	2005	2010	2020	2021	2022	2023
Forest	**55,142**	**56,306**	**57,450**	**58,536**	**59,610**	**61,717**	**61,926**	**62,130**	**62,320**
Aboveground biomass	12,739	13,553	14,350	15,122	15,872	17,340	17,483	17,622	17,757
Belowground biomass	2,255	2,413	2,568	2,718	2,864	3,151	3,179	3,207	3,233
Dead wood	1,977	2,158	2,341	2,521	2,704	3,074	3,111	3,148	3,184
Litter	3,789	3,799	3,810	3,794	3,787	3,767	3,768	3,768	3,761
Soil (mineral)	28,407	28,404	28,402	28,401	28,402	28,400	28,401	28,401	28,401
Soil (organic)	5,976	5,978	5,979	5,981	5,982	5,983	5,983	5,983	5,983
Harvested wood	**1,895**	**2,061**	**2,218**	**2,353**	**2,462**	**2,694**	**2,721**	**2,747**	**2,772**
Products in use	1,249	1,326	1,395	1,447	1,471	1,530	1,538	1,547	1,555
Solid waste disposal sites	646	735	823	906	991	1,165	1,182	1,200	1,217
Total stocks	57,037	58,367	59,668	60,890	62,072	64,411	64,647	64,877	65,092

Totals may not sum due to independent rounding. Forest ecosystem carbon stocks on managed forest land in Interior Alaska, Hawaii, and the U.S. Territories were compiled using the gain-loss method described in the U.S. EPA (2024) report in Annex 3.13. Harvested wood product stocks include exports, even if the logs are processed in other countries, and exclude imports. Harvested wood estimates are based on results from annual surveys and models. Population estimates compiled using Forest Inventory and Analysis data are assumed to represent stocks as of January 1 of the inventory year. Flux is the net annual change in stock. Thus, flux estimates for 2022 require carbon stocks for 2022 and 2023.

[a] For details on these estimates and how they were compiled, see U.S. EPA (2024).

Ownership

In 2022, private forest land accounted for nearly 78 percent (-565 MMT CO_2 Eq.) of the estimated net sink strength in the conterminous 48 States and coastal Alaska. The private forests of the Southern United States, in particular, continued to account for the majority (-343 MMT CO_2 Eq.) of carbon uptake. New in this resource bulletin and associated research dataset (Walters et al. 2024), Tribal forest land area estimates and associated carbon stocks and stock changes within the private forest land base by broad region in the United States have been disaggregated in table 4. The majority (61 percent) of the Tribal forest land area is in the Rocky Mountain region (3.1 million hectares [ha]), which also represents more than 50 percent (456 MMT C) of the forest ecosystem carbon in this ownership category. Tribal forest lands are a net carbon sink in each region of the United States. The Pacific Coast region has the largest annual net uptake (-2.4 MMT CO_2 Eq.) for Tribal forest land followed by the North region (-2.0 MMT CO_2 Eq.; table 4).

Public forest land makes up a relatively small but important part of the U.S. forest carbon sink. Much of the public forest land is in the Western United States, where wildfire (see "Fire Emissions and Area Burned" section) and other disturbances have led to substantial emissions and transfers of carbon from live trees to the dead organic matter pools (i.e., dead wood and litter), altering the capacity of forests to sequester and store carbon. This is particularly true on forest land within the National Forest System, which accounts for approximately 39 percent (-63.1 MMT CO_2 Eq.) of the public land sink in 2022, although nearly all the annual net carbon sink (-48.8 MMT CO_2 Eq.) is due to transfers from the live biomass carbon pool to dead wood carbon pool in the Western United States (table 5). The regional National Forest System estimates have been further disaggregated by individual national forest for the first time as part of this resource bulletin (fig. 1) and can be found in the research dataset (Walters et al. 2024).

Table 4—Carbon stock changes (net flux) from Tribal forest land remaining forest land by region and year (MMT CO_2 Eq.)

Region	1990	1995	2000	2005	2010	2020	2021	2022
North	(1.4)	(1.4)	(1.5)	(1.6)	(1.7)	(2.0)	(2.0)	(2.0)
Pacific Coast	(1.6)	(1.7)	(2.0)	(2.3)	(2.5)	(2.4)	(2.4)	(2.4)
Rocky Mountain	(0.9)	(0.9)	(1.2)	(1.2)	(1.2)	(0.3)	(0.7)	(0.7)
South	(0.4)	(0.5)	(0.5)	(0.5)	(0.8)	(0.7)	(0.8)	(0.9)
Net carbon stock changes	**(4.3)**	**(4.4)**	**(5.2)**	**(5.6)**	**(6.1)**	**(5.4)**	**(5.9)**	**(5.9)**

Parentheses indicate net carbon uptake (i.e., a net removal of carbon from the atmosphere or transfers from another carbon pool).

Table 5—Carbon stock changes (net flux) from forest land remaining forest land within the National Forest System (NFS) by NFS region and year (MMT CO_2 Eq.)

NFS Region	2005	2010	2015	2018	2019	2020	2021	2022
Alaska	(5.1)	(5.4)	(5.6)	(5.5)	(5.4)	(5.2)	(5.2)	(5.0)
Eastern	(17.1)	(17.6)	(18.0)	(18.1)	(18.0)	(17.9)	(17.7)	(17.6)
Intermountain	8.4	8.8	9.2	9.6	9.7	9.9	10.0	10.2
Northern	(5.3)	(5.3)	(5.3)	(4.9)	(4.7)	(4.6)	(4.5)	(4.3)
Pacific Northwest	(26.7)	(28.2)	(29.7)	(30.0)	(30.0)	(30.1)	(30.2)	(30.3)
Pacific Southwest	(9.4)	(9.7)	(9.6)	(8.4)	(8.0)	(7.7)	(7.2)	(6.9)
Rocky Mountain	8.0	8.3	8.4	8.0	7.9	7.8	7.7	7.6
Southern	(27.1)	(26.6)	(26.1)	(25.9)	(25.7)	(25.4)	(25.1)	(24.7)
Southwestern	6.0	6.5	7.0	7.4	7.5	7.7	7.8	8.0
Net emissions and removals	**(68.1)**	**(69.2)**	**(69.8)**	**(67.7)**	**(66.6)**	**(65.5)**	**(64.3)**	**(63.1)**

Parentheses indicate net carbon uptake (i.e., a net removal of carbon from the atmosphere or transfers from another carbon pool).

Carbon density

There is increasing interest in using information and estimates from UNFCCC reporting efforts for State, local, and entity-level carbon and GHG assessments. To support those activities, mean total forest ecosystem carbon density estimates from the most recent NFI measurements used in the compilation of the U.S. EPA (2024) report and mean annual total forest ecosystem carbon stock change estimates from the most recent FIA remeasurements have been summarized by forest type group. Forest type groups are defined in the latest FIA Database manual (USDA Forest Service 2024a).

The estimated total forest ecosystem carbon density across all forest type groups was 215.7 metric tons carbon per hectare (MT C ha^{-1}), with the redwood forest type group containing the largest mean total forest ecosystem carbon density (484.3 MT C ha^{-1}) and the pinyon/juniper forest type group containing the smallest total forest ecosystem carbon density (128.5 MT C ha^{-1}; table 6). The mean annual total forest ecosystem carbon stock change across all forest type groups was 1.0 metric tons carbon per hectare per year (MT C ha^{-1} yr^{-1}), with the redwood forest type group representing the largest net gain (removal from the atmosphere or transfer from another land use) of -4.7 MT C ha^{-1} yr^{-1} (table 7). The nonstocked forest type group represented the largest net losses (transfer from the forest ecosystem to the harvested wood products category, another land use, or emission to the atmosphere (table 7). The estimates of mean total forest ecosystem carbon stocks and carbon stock changes represent the average conditions over all forest land remaining forest land classified into forest type groups. These mean estimates may inherently include natural (e.g., wildfires) and/or anthropogenic (e.g., harvesting) disturbances and may not represent any particular set of forest conditions for the forest types included in tables 6 and 7.

Table 6—Mean carbon density (MT C ha^{-1}) estimates by forest type group from the most recent Nationwide Forest Inventory measurements on forest land remaining forest land

Forest type group	Aboveground biomass	Belowground biomass	Dead wood	Litter	Soil	Total forest ecosystem
White/red/jack pine	81.9	16.2	8.4	13.3	110.8	230.6
Spruce/fir	46.1	7.4	8.4	13.3	143.0	218.3
Longleaf/slash pine	57.1	11.1	5.8	7.5	82.5	163.9
Loblolly/shortleaf pine	68.8	13.9	7.7	7.7	78.9	177.0
Other eastern softwoods	46.6	7.3	5.9	7.9	104.8	172.6
Pinyon/juniper	16.8	3.1	2.4	5.0	101.2	128.5
Douglas-fir	139.5	29.4	30.0	13.5	133.9	346.4
Ponderosa pine	54.1	9.9	9.9	11.6	115.8	201.4
Western white pine	64.7	10.5	20.4	12.4	131.0	239.0
Fir/spruce/mountain hemlock	89.9	16.5	30.2	16.9	132.5	286.0
Lodgepole pine	46.5	8.0	19.3	13.0	116.6	203.5
Hemlock/Sitka spruce	156.3	34.9	42.9	24.9	148.2	407.2
Western larch	70.4	14.2	19.6	18.6	115.4	238.3
Redwood	271.2	58.9	32.5	8.3	113.4	484.3
Other western softwoods	27.8	4.5	6.9	8.4	126.8	174.3
California mixed conifer	126.9	23.5	27.0	18.5	125.1	320.9
Exotic softwoods	75.2	14.6	11.6	9.6	121.2	232.2
Oak/pine	68.4	12.4	7.2	8.5	90.8	187.3
Oak/hickory	83.1	14.1	8.3	8.1	99.3	212.8
Oak/gum/cypress	75.6	13.8	7.7	7.2	101.1	205.3
Elm/ash/cottonwood	63.2	10.4	7.5	6.9	121.4	209.3
Maple/beech/birch	81.6	14.4	8.6	13.5	131.1	249.3
Aspen/birch	45.2	7.4	8.5	11.8	117.6	190.5

Forest type group	Aboveground biomass	Belowground biomass	Dead wood	Litter	Soil	Total forest ecosystem
Alder/maple	136.0	27.4	17.0	8.1	140.0	328.4
Western oak	47.3	7.9	8.4	5.8	114.9	184.4
Tanoak/laurel	175.2	35.2	21.0	8.0	134.7	374.1
Other hardwoods	45.2	7.8	8.8	11.2	135.2	208.1
Woodland hardwoods	14.2	2.2	4.0	3.9	110.7	135.1
Tropical hardwoods	49.1	6.4	9.5	13.3	101.6	179.9
Exotic hardwoods	31.1	5.1	4.4	6.9	102.5	150.0
Nonstocked	6.5	0.9	11.4	5.8	112.8	137.5
All forest type groups	**71.7**	**13.2**	**11.2**	**9.9**	**109.8**	**215.7**

See USDA Forest Service (2024b) for details on each forest type group.

Table 7—Mean annual carbon stock change (MT C ha^{-1} yr^{-1}) estimates by forest type group from the most recent Nationwide Forest Inventory remeasurements on forest land remaining forest land

Forest type group	Aboveground biomass	Belowground biomass	Dead wood	Litter	Soil	Total forest ecosystem
White/red/jack pine	(1.2)	(0.3)	(0.2)	(0.1)	0.2	(1.6)
Spruce/fir	(0.6)	(0.1)	(0.3)	(0.0)	(0.1)	(1.0)
Longleaf/slash pine	(1.6)	(0.3)	(0.1)	0.0	0.1	(1.9)
Loblolly/shortleaf pine	(2.2)	(0.5)	(0.2)	(0.0)	0.0	(2.9)
Other eastern softwoods	(1.1)	(0.2)	(0.2)	(0.1)	(0.3)	(1.9)
Pinyon/juniper	(0.0)	(0.0)	(0.0)	(0.0)	0.0	(0.1)
Douglas-fir	(0.8)	(0.2)	(0.3)	(0.0)	(0.0)	(1.4)
Ponderosa pine	(0.4)	(0.1)	(0.0)	(0.0)	0.0	(0.5)
Western white pine	0.2	0.0	(0.0)	0.1	0.4	0.7
Fir/spruce/mountain hemlock	(0.0)	(0.0)	(0.3)	0.0	(0.0)	(0.4)
Lodgepole pine	0.2	0.0	(0.4)	0.0	0.1	0.0
Hemlock/Sitka spruce	0.4	0.1	(0.4)	(0.1)	(0.0)	0.0
Western larch	(0.3)	(0.1)	0.0	(0.1)	0.3	(0.0)
Redwood	(3.6)	(0.8)	(0.3)	0.0	(0.0)	(4.7)
Other western softwoods	(0.1)	(0.0)	(0.1)	0.0	(0.0)	(0.3)
California mixed conifer	(0.7)	(0.1)	(0.5)	(0.1)	0.0	(1.3)
Exotic softwoods	(1.5)	(0.3)	(0.5)	0.0	0.2	(2.2)
Oak/pine	(0.9)	(0.2)	(0.1)	(0.1)	(0.0)	(1.2)
Oak/hickory	(0.9)	(0.1)	(0.1)	(0.0)	0.0	(1.1)
Oak/gum/cypress	(0.7)	(0.1)	(0.1)	0.0	(0.1)	(1.0)
Elm/ash/cottonwood	(0.6)	(0.1)	(0.2)	0.0	(0.1)	(1.0)
Maple/beech/birch	(0.6)	(0.1)	(0.1)	(0.0)	(0.0)	(0.9)
Aspen/birch	(0.5)	(0.1)	(0.1)	(0.0)	0.1	(0.6)
Alder/maple	(1.6)	(0.3)	0.0	0.1	0.0	(1.7)
Western oak	(0.1)	(0.0)	(0.2)	0.0	0.0	(0.3)
Tanoak/laurel	(3.3)	(0.8)	(0.2)	0.0	(0.0)	(4.3)
Other hardwoods	0.2	0.0	(0.1)	(0.0)	(0.6)	(0.4)
Woodland hardwoods	0.0	0.0	(0.0)	0.0	(0.0)	0.0
Tropical hardwoods	(0.8)	(0.1)	(0.1)	(0.0)	(0.0)	(1.0)
Exotic hardwoods	0.1	0.0	0.1	0.0	(0.1)	0.1
Nonstocked	2.4	0.5	0.1	0.2	0.1	3.3
All forest type groups	**(0.7)**	**(0.1)**	**(0.1)**	**(0.0)**	**(0.0)**	**(1.0)**

Parentheses indicate net carbon uptake (i.e., a net removal of carbon from the atmosphere or transfers from another carbon pool).
See USDA Forest Service (2024b) for details on each forest type group.

Forest Land Conversions

Land use conversions to and from forest land result in substantial emissions and removals each year. This section includes all emissions and removals for land conversions to and from forest land, as reported in U.S. EPA (2024) (table 8). It is important to note that in some cases the reported emissions or removals from one land use category are transfers to another land use category. Forest land conversion to settlements was the largest source of emissions in the conversion categories, while grassland conversion to forest land resulted in the largest annual uptake/transfer. Considering all forest land conversions included in the U.S. EPA (2024) report, there have been net emissions each year throughout the reporting period. Estimated net emissions around 36 MMT CO_2 Eq. were recorded for each of the last 3 reporting years (table 8).

condition of the land for the following reasons: to produce commercial or noncommercial products or services; to serve as transportation corridors or locations for buildings, landfills, or other developed areas for commercial or noncommercial purposes; to extract resources or facilitate acquisition of resources; or to provide social functions for personal, community, or societal objectives where these areas are readily accessible to society. FIA data from each of the conterminous 48 States, Alaska, Hawaii, and the U.S. Territories comprise an estimated 282 million ha of forest land that are considered managed and are included in this report along with an additional 1.1 million ha of nonforest land converted to forest land (table 9, fig. 2). Some differences exist in forest land area estimates in a supporting publication for the latest Resources Planning Act Assessment (Nelson et al. 2020) and the forest land area estimates included in the U.S.

Table 8—Carbon stock changes (net flux) from conversions to and from forest land (MMT CO_2 Eq.) by year

Land conversions[a]	1990	1995	2000	2005	2010	2020	2021	2022
Forest land converted to cropland	19.1	19.1	19.2	19.2	19.3	19.7	19.7	19.6
Forest land converted to grassland	50.1	49.8	49.3	48.9	48.1	46.7	46.7	46.7
Forest land converted to other land	2.3	2.3	2.1	2.0	2.0	2.6	2.6	2.6
Forest land converted to settlements	49.3	50.6	52.1	53.7	55.4	58.3	58.3	58.3
Forest land converted to wetlands	9.0	9.1	9.1	9.2	9.4	9.4	9.4	9.4
Cropland converted to forest land	(17.6)	(17.6)	(17.5)	(17.5)	(17.4)	(17.2)	(17.2)	(17.2)
Grassland converted to forest land	(36.7)	(36.8)	(36.9)	(36.9)	(37.0)	(37.2)	(37.2)	(37.2)
Other land converted to forest land	(5.1)	(5.0)	(5.0)	(5.2)	(5.3)	(5.4)	(5.5)	(5.5)
Settlements converted to forest land	(31.9)	(31.8)	(31.7)	(31.6)	(31.5)	(31.4)	(31.4)	(31.4)
Wetlands converted to forest land	(8.8)	(8.8)	(8.8)	(8.9)	(8.9)	(9.0)	(9.0)	(9.0)
Net emissions and removals	**29.7**	**30.9**	**31.9**	**32.9**	**34.1**	**36.5**	**36.4**	**36.3**

Totals may not sum due to independent rounding. Parentheses indicate net carbon uptake (i.e., a net removal of carbon from the atmosphere or transfer from another carbon pool). Emissions and removals from forest land converted to other lands are not currently included in the U.S. EPA (2024) report; forest land converted to wetlands estimates were not compiled by the Forest Service in the U.S EPA (2024) report but are included here based on methods used to compile estimates for other land conversion categories. Estimates of organic soil carbon are not included for any of the land conversion categories and mineral soil carbon change is not included for forest land converted to other lands and forest land converted to wetlands.

[a] For details on these estimates and how they were compiled, see U.S. EPA (2024).

Land Area

The land area covered in the U.S. EPA (2024) report includes lands directly influenced by human intervention. Direct intervention mostly occurs in areas accessible to human activity and includes altering or maintaining the

EPA (2024) report, which are based on annual FIA data through 2022 for all States (USDA Forest Service 2024b). These differences are mainly due to the separation of land categories and the managed land definition used in the U.S. EPA (2024) report (Nelson et al. 2020). Agroforestry systems that meet the definition of forest land

Table 9—Annual estimates of forest land and woodland area (1,000 ha) by year

Land area category[a]	1990	1995	2000	2005	2010	2020	2021	2022	2023
Forest land remaining forest land	283,500	283,285	283,096	282,521	282,343	281,779	281,780	281,752	281,725
Nonforest land converted to forest land	1,075	1,108	1,097	1,080	1,132	1,129	1,132	1,132	1,132
Woodland remaining woodland[b]	24,360	23,756	23,143	22,350	21,433	21,224	20,979	20,734	20,489
Forest land converted to nonforest land	1,126	1,144	1,128	1,114	1,138	1,155	1,159	1,159	1,159
Total area	**308,935**	**308,149**	**307,336**	**305,951**	**304,908**	**304,132**	**303,891**	**303,618**	**303,346**

Totals may not sum due to independent rounding. The estimates reported here may differ from the land representation section of the U.S. EPA (2024) but are consistent with estimates used to compile emissions and removals in these categories. See Annex 3.13 in the U.S. EPA (2024) for more details.
[a] For details on these estimates and how they were compiled, see U.S. EPA (2024).
[b] Woodland area is included in the grassland remaining grassland category and is not explicitly separated in the U.S. EPA (2024) report.

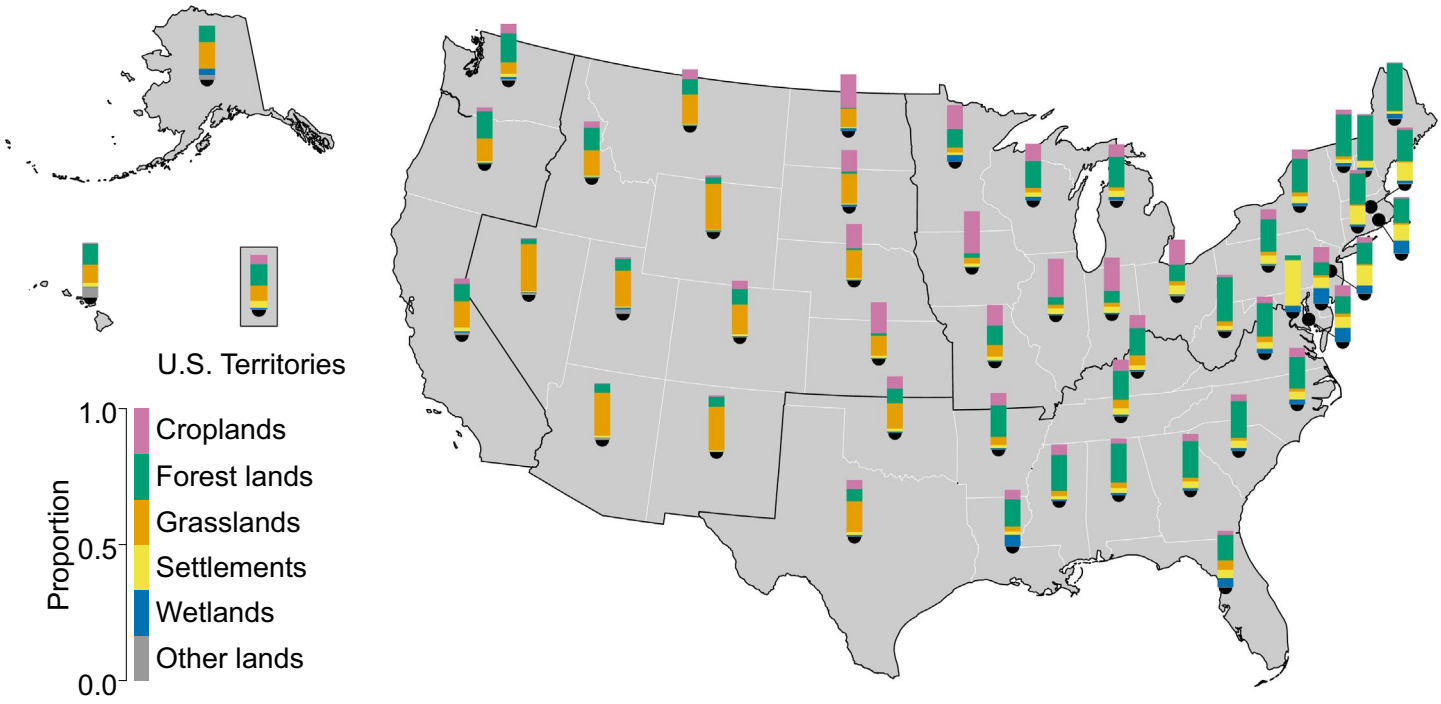


Figure 2—Proportion of managed land by IPCC land use categories for each State and U.S. Territory.

are not currently included in the U.S. EPA (2024) report since they are not explicitly inventoried (i.e., they are classified as agroforestry systems) by either the FIA Program or the National Resources Inventory of the USDA Natural Resources Conservation Service. Woodland area is included in the grassland remaining grassland category and is not explicitly separated in the U.S. EPA (2024) report as a subcategory of grasslands. Combined, managed forest land and woodland area account for more than 303 million ha (table 9). There is also forest land converted to nonforest land, which has increased slightly over the 1990–2022 time series and in 2022 accounted for nearly 1.2 million ha (table 9).

Fire Emissions and Area Burned

Carbon dioxide emissions from wildfire and prescribed fire on forest land are inherently captured in the carbon stock change estimates described in tables 1 and 2. Fire emissions estimates from forest land are also compiled separately in the U.S. EPA (2024) report using a combination of field inventories, remotely sensed information, and models. These estimates are reported for each year in the time series (fig. 3) and by individual State in Walters et al. (2024). There is substantial interannual variability in forest land area burned and associated GHG emissions resulting from fire over the last three decades. In 2022, the area of forest land burned was nearly 1.1 million ha, CO_2 emissions were 129.2 MMT CO_2 Eq., and non-CO_2 emissions estimates were 14.8 MMT CO_2 Eq. (fig. 3).

Planned Improvements

Planned improvements to estimation and reporting include the following general topics: continued development and refinement of a robust estimation and reporting system, individual carbon pool estimation, coordination with other land use categories, and annual inventory data incorporation. Research is underway to leverage auxiliary information (i.e., remotely sensed information) to operate at finer spatial and temporal scales. As in past submissions, emissions and removals associated with natural (e.g., wildfire, insects, disease) and human (e.g., harvesting) disturbances are implicitly included in the report given the design of the annual NFI but are not explicitly estimated. In addition to integrating auxiliary information into the estimation framework, alternative estimators are also being evaluated that will reduce or eliminate lag bias in population estimates from the NFI,[1] improve annual estimation and characterization of interannual variability, facilitate attribution of fluxes to particular activities, and allow for easier harmonization of NFI data with auxiliary data products. Investments are also being made to leverage State-level wood products and harvest information to allow for the disaggregation of harvested wood products estimates at the State level. Collectively, these improvements are expected to reduce uncertainties in the estimates at the national and State scales and facilitate entity-level estimation and reporting (e.g., individual national forest estimates).

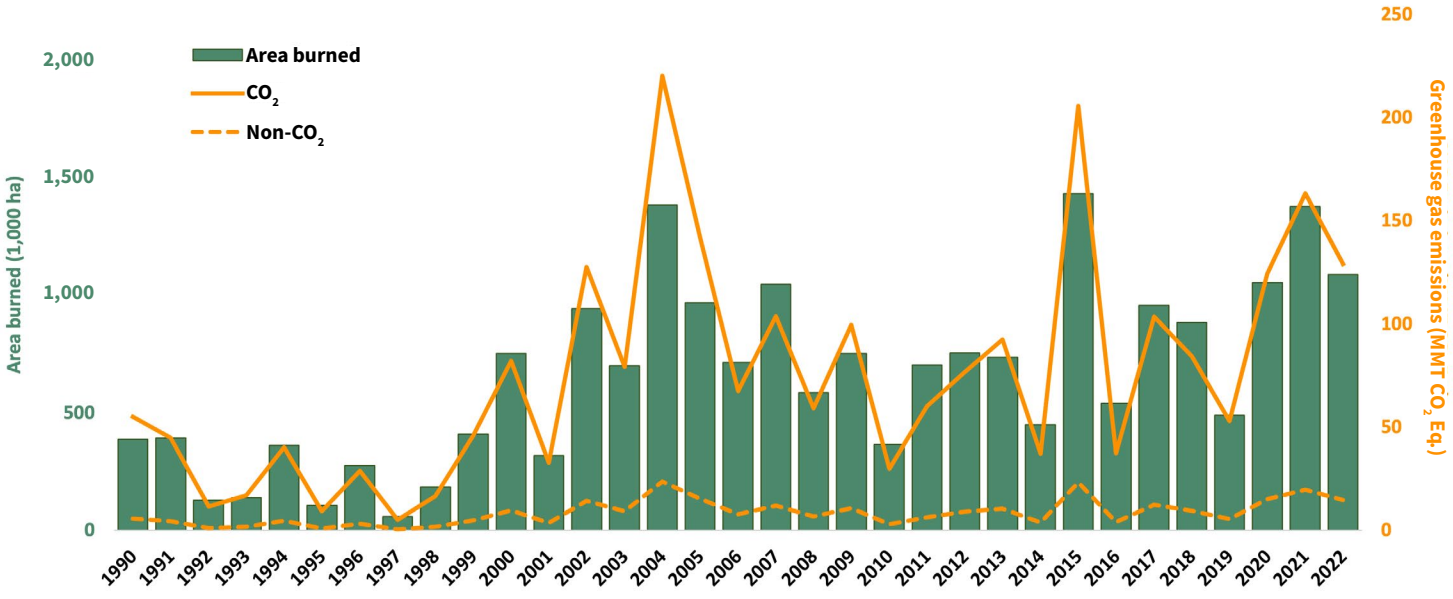


Figure 3—Estimated annual area burned and associated CO_2 and non-CO_2 (N_2O and CH_4) emissions from wildfire and prescribed fire on forest land in the conterminous 48 States and Alaska, 1990–2022.

[1] Traditional estimators rely on multiple panels of data collected over several (5–10) years, which may smooth trends by obscuring annual fluctuations (Bechtold and Patterson 2005).

2022 Estimates at a Glance

Summary results for 2022 from the compilation of the forest land, woodlands, harvested wood products, and urban trees in settlements in the U.S. EPA (2024) report:

- Economywide net GHG emissions increased from 2021 to 2022 by approximately 1.3 percent.
- Several improvements in the methods and models used in the latest inventory resulted in substantial changes in estimates over the time series for several key categories included in this resource bulletin.
- Hawaii and the U.S. Territories of American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands were included for the first time.
- Carbon stock and stock change estimates were compiled for Tribal forest lands and each national forest using the latest methods, models, and compilation system for the first time (Walters et al. 2024).
- Forest lands, harvested wood products, woodlands, and urban trees in settlements collectively removed the equivalent of more than 14 percent (874.1 MMT CO_2 Eq.) of total GHG emissions or 17.6 percent of CO_2 emissions in 2022.
- Private forest land accounts for nearly 78 percent (-565 MMT CO_2 Eq.) of the estimated net sink strength in the conterminous 48 States and coastal Alaska in 2022.
- Land conversions to and from forest land continue to result in net emissions and/or transfers of carbon to other land uses (36.3 MMT CO_2 Eq.).
- Soils store more than 55 percent of all the carbon in forest ecosystems, with small stock changes annually.
- Forest land area burned was nearly 1.1 million ha, and non-CO_2 emissions were 14.81 MMT CO_2 Eq.
- Forest uptake averages 1.0 MT C ha^{-1} yr^{-1}, with live vegetation accounting for more than 84 percent (0.9 MT C ha^{-1} yr^{-1}) of the uptake.

Literature Cited

Bechtold, W.A.; Patterson, P.L., eds. 2005. **The enhanced Forest Inventory and Analysis Program--national sampling design and estimation procedures.** Gen. Tech. Rep. SRS-80. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 85 p. https://doi.org/10.2737/SRS-GTR-80.

Intergovernmental Panel on Climate Change [IPCC]. 2006. 2**006 IPCC guidelines for national greenhouse gas inventories.** Hayma, Japan: Institute for Global Environmental Strategies. https://www.ipcc-nggip.iges.or.jp/ public/2006gl/. (accessed 31 January 2023).

Nelson, M.D.; Riitters, K.H.; Coulston, J.W. [et al.]. 2020. **Defining the United States land base: a technical document supporting the USDA Forest Service 2020 RPA Assessment.** Gen. Tech. Rep. NRS-191. Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 70 p. https://doi.org/10.2737/ NRS-GTR-191.

Skog, K.E. 2008. **Sequestration of carbon in harvested wood products for the United States.** Forest Products Journal. 58(6): 56–72.

U.S. Department of Agriculture [USDA], Forest Service. 2024a. **Forest Inventory and Analysis Database: FIADB user guides, volume database description (version 9.2).** Washington, DC: U.S. Department of Agriculture, Forest Service. https://research.fs.usda.gov/understory/forest-inventory-and-analysis-database-user-guide-nfi. (accessed 11 June 2024).

U.S. Department of Agriculture [USDA], Forest Service. 2024b. **Forest Inventory and Analysis national program: FIA DataMart.** Washington, DC: U.S. Department of Agriculture, Forest Service. https://research.fs.usda.gov/products/dataandtools/tools/fia-datamart. (accessed 5 September 2024).

U.S. Environmental Protection Agency [U.S. EPA]. 2024. **Inventory of U.S. greenhouse gas emissions and sinks: 1990–2022.** EPA 430-R-24-004. Washington, DC: U.S. Environmental Protection Agency. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022. (accessed 10 June 2024).

Walters, B.F.; Domke, G.M.; Greenfield, E.J. [et al.]. 2024. **Greenhouse gas emissions and removals from forest land, woodlands, and urban trees in the United States, 1990–2022: estimates and quantitative uncertainty for individual states, regional ownerships, national forests, and Tribal ownership.** Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Research Data Archive. https://doi.org/10.2737/RDS-2024-0065.

Westfall, J.A.; Coulston, J.W.; Gray, A.N. [et al.]. 2024. **A national-scale tree volume, biomass, and carbon modeling system for the United States.** Gen. Tech. Rep. WO-104. Washington, DC: U.S. Department of Agriculture, Forest Service. 37 p. https://doi.org/10.2737/WO-GTR-104.

How to Cite This Publication

Domke, Grant M.; Walters, Brian F.; Smith, James E.; Greenfield, Eric J.; Giebink, Courtney L.; Ogle, Stephen M.; Steller, John; Rewcastle, Kenna; Knott, Jonathan A.; Coulston, John W.; Heilman, Kelly A.; Lang, Ashley K. 2024. Greenhouse gas emissions and removals from forest land, woodlands, urban trees, and harvested wood products in the United States, 1990–2022. Resour. Bull. WO-102. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office. 13 p. https://doi.org/10.2737/WO-RB-102.

Contact Information

Grant M. Domke, Research Forester
USDA Forest Service, Northern Research Station
1992 Folwell Ave.
St. Paul, MN 55108
Ph: 651–649–5138 Fax: 651–649–5140
grant.m.domke@usda.gov
Northern FIA: https://research.fs.usda.gov/nrs/programs/fia
National FIA: https://research.fs.usda.gov/programs/fia

The published report and disaggregated estimates are available online at https://doi.org/10.2737/RDS-2024-0065.