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Greenhouse Gas Emissions and Removals From Forest Land, Woodlands, Urban Trees, and Harvested Wood Products in the United States, 1990–2020

Introduction

As a signatory to the United Nations Framework Convention on Climate Change (UNFCCC), the United States has reported an inventory of greenhouse gas (GHG) emissions and removals by Intergovernmental Panel on Climate Change (IPCC) sector since the mid-1990s (U.S. Environmental Protection Agency 2022). In 2020, National Inventory Report net GHG emissions decreased substantially due, in large part, to the global pandemic. Forest land, harvested wood products (HWP), woodlands, and urban trees within the land sector collectively continue to represent the largest net carbon (C) sink in the United States, offsetting the equivalent of more than 12.9 percent of total (i.e., gross) GHG emissions in 2020 (U.S. EPA 2022). Estimates of GHG emissions and removals are compiled by U.S. Department of Agriculture (USDA), Forest Service researchers and partners and are based primarily on National Forest Inventory (NFI) data collected and maintained by the Forest Inventory and Analysis (FIA) program within the Forest Service. This Resource Update provides an overview of the status and trends of GHG emissions and removals from forest land, woodlands in the grassland category, HWP, and urban trees in settlements in the United States from 1990 to 2020. The estimates for the United States summarized here are based on the compilation reported in the "Land Use, Land-Use Change, and Forestry" chapter of the U.S. EPA (2022) submission to the UNFCCC. Most of the national scale estimates are also developed and reported at the individual State level (Fig. 1) for the entire 1990–2020 time series and are available in a published research dataset (Walters et al. 2022). New in this report are regional C stock and stock change estimates by broad ownership category and National Forest System region.

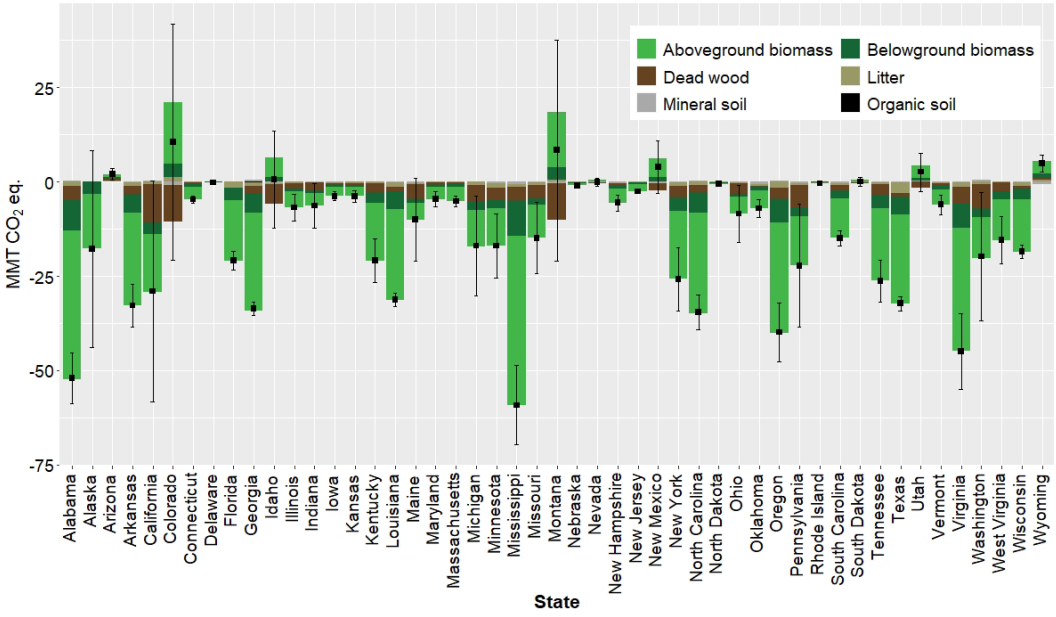

Figure 1.—Estimated annual C stock changes by ecosystem pool for forest land remaining forest land and land converted to forest land in each of the conterminous 48 States and Alaska in 2020 (million metric tons of carbon dioxide equivalent CO_2 Eq.). Note that points and uncertainties represented by confidence intervals (95 percent) reflect net flux for all ecosystem pools in each State. Negative estimates indicate net C uptake (i.e., a net removal of C from the atmosphere or transfer of C between ecosystem pools or land use categories).

Forest Carbon Cycle

In forests, carbon is continuously 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., harvesting, thinning, and replanting). As trees photosynthesize and grow, C is removed from the atmosphere and stored in living tree biomass. As trees die and otherwise deposit litter and debris on the forest floor, C is released to the atmosphere and is also transferred to litter, dead wood, and soil pools by organisms that facilitate decomposition.

The net change in forest C 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 C to the atmosphere. Instead, following harvesting, a portion of the C stored in wood is transferred to a "product pool." Once in a product pool, the C 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 C in the product may be transferred and stored in solid waste disposal sites (SWDS). The rate of emission varies considerably among different product pools and SWDS.

Carbon Pools

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

- Aboveground biomass—all living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. This pool includes live understory.
- 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 C (SOC)—all organic material in soil to a depth of 1 meter but excluding the coarse roots of the belowground pools.

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

- Harvested wood products (HWP) in use.
- HWP in solid waste disposal sites (SWDS).

Total Emissions and Removals

Forest land, HWP, woodlands, and urban trees in settlements individually and collectively represent a net GHG sink over the 1990-2020 time series, with interannual variability driven, in large part, by natural and anthropogenic forest disturbances (e.g., wildfire, harvesting), fluxes resulting from land conversions (e.g., forest land converted to cropland and settlements, reforestation/afforestation), and changes in HWP stocks in use and transfers to SWDS (Table 1) (U.S. EPA 2022). In 2020, forest land, HWP, woodlands, and urban trees in settlements collectively represented an estimated net increase in C stocks of 768.1 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 584.4 MMT CO_2 Eq. For categories included in this report, the largest source of emissions and/or transfers of C was from the conversion of forest land, with estimated losses of 126.9 MMT CO_2 Eq. (Table 1) (U.S. EPA 2022).

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	2018	2019	2020
Forest land remaining forest land[b]	(650.2)	(646.0)	(622.7)	(581.2)	(606.7)	(583.0)	(546.0)	(584.4)
Non-CO_2 emissions from fire	4.1	0.8	8.8	12.8	3.2	11.9	2.5	25.3
N_2O emissions from forest soils	0.1	0.3	0.5	0.5	0.5	0.5	0.5	0.5
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]	118.3	120.1	121.8	123.7	125.3	127.0	127.0	126.9
Nonforest land converted to forest land[b]	(98.6)	(98.7)	(98.8)	(99.1)	(99.2)	(99.5)	(99.5)	(99.5)
Harvested wood products	(123.8)	(112.2)	(93.4)	(106.0)	(69.1)	(94.1)	(88.8)	(83.6)
Woodlands remaining woodlands[c]	2.8	2.8	2.8	2.7	2.6	2.5	2.5	2.4
Urban trees in settlements[d]	(96.4)	(103.3)	(110.4)	(117.4)	(124.6)	(129.8)	(129.8)	(129.8)
Total carbon stock change[e]	**(847.9)**	**(837.4)**	**(800.8)**	**(777.3)**	**(771.6)**	**(777.0)**	**(734.7)**	**(768.1)**
Total net emissions and removals[f]	**(843.6)**	**(836.3)**	**(791.4)**	**(764.0)**	**(768.0)**	**(764.5)**	**(731.7)**	**(742.2)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net C uptake (i.e., a net removal of C from the atmosphere or transfer to or from nonforest land categories).

[a] For details on how estimates were compiled, see U.S. EPA (2022).

[b] Estimated emissions and removals include the net changes to C stocks stored in all ecosystem pools.

[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 C 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.

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 belowground live biomass and dead wood (Table 2). Harvested wood products in use and in solid waste disposal sites (SWDS) are also an important contributor to the net sink in the land sector, and 2020 estimates for both pools decreased slightly from previous years. Private forest land accounted for nearly 84 percent (-478.1 MMT CO_2 Eq.) of the estimated net sink strength in the conterminous 48 States and coastal Alaska (ownership information was not available for forest land in Interior Alaska so those lands were excluded from these estimates) in 2020, and the private working forests of the Southern United States continued to account for the majority of C uptake (Fig. 2). Public forest land makes up a relatively small but important part of the U.S. forest C sink.

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	2018	2019	2020
Forest	**(650.2)**	**(646.0)**	**(622.7)**	**(581.2)**	**(606.7)**	**(583.0)**	**(546.0)**	**(584.4)**
Aboveground biomass	(462.5)	(450.9)	(435.4)	(416.3)	(421.4)	(406.6)	(393.1)	(398.7)
Belowground biomass	(94.2)	(91.6)	(88.3)	(84.2)	(84.7)	(80.8)	(78.1)	(79.1)
Dead wood	(96.8)	(98.7)	(98.5)	(96.8)	(100.1)	(102.0)	(97.0)	(101.5)
Litter	0.6	(7.0)	(1.6)	16.0	0.8	1.3	22.8	(1.9)
Soil (mineral)	3.0	2.2	0.9	(0.3)	(1.9)	4.1	(0.6)	(4.1)
Soil (organic)	(0.9)	(0.8)	(0.5)	(0.3)	(0.1)	0.3	(0.7)	0.2
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)**	**(94.1)**	**(88.8)**	**(83.6)**
Products in use	(54.8)	(51.7)	(31.9)	(42.6)	(7.4)	(29.0)	(24.4)	(20.0)
SWDS	(69.0)	(60.5)	(61.5)	(63.4)	(61.7)	(65.1)	(64.5)	(63.6)
Total net flux	**(774.0)**	**(758.2)**	**(716.2)**	**(687.3)**	**(675.7)**	**(677.1)**	**(634.8)**	**(668.1)**

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

[a] For details on how estimates were compiled, see U.S. EPA (2022).

Figure 2.—Carbon stock changes for forest land remaining forest land for the conterminous 48 States and and coastal Alaska (ownership information was not available for forest land in Interior Alaska so those lands were excluded from these estimates) by region and ownership (MMT CO_2 Eq.). Negative estimates indicate net C uptake (i.e., a net removal of C from the atmosphere or transfer from another C pool).

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 C from live trees to the dead organic matter pools (i.e., dead wood and litter), altering the capacity of forests to sequester and store C. This is particularly true on forest land within the National Forest System, which accounts for approximately 47 percent (-42.6 MMT CO_2 Eq.) of the public land sink in 2020, although nearly all the annual C sink (-40.7 MMT CO_2 Eq.) is due to transfers from the live biomass C pool to dead wood C pool (Table 3).

Carbon stock estimates for forest ecosystem and harvested wood C storage pools are presented in Table 4. Together, the estimated aboveground biomass and soil C pools account for more than 83 percent of total forest ecosystem C stocks. By maintaining current harvesting practices and regeneration activities on these forested lands, along with continued input of harvested products into the HWP pool, C 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 SWDS rather than by incineration, significant quantities of C in harvested wood are transferred to these long-term storage pools rather than being released rapidly to the atmosphere (Skog 2008).

Table 3.—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	1990	1995	2000	2005	2010	2018	2019	2020
Alaska	(1.4)	(1.4)	(1.5)	(1.6)	(1.8)	(1.9)	(1.9)	(1.9)
Eastern	(12.4)	(12.0)	(11.7)	(11.8)	(11.9)	(11.7)	(11.6)	(11.5)
Intermountain	8.6	9.0	9.4	9.8	10.4	10.5	10.8	10.9
Northern	(1.6)	(1.2)	(0.7)	(0.2)	0.2	0.7	0.7	0.8
Pacific Northwest	(26.3)	(25.3)	(25.6)	(26.1)	(27.2)	(28.5)	(28.7)	(28.8)
Pacific Southwest	(8.9)	(8.7)	(8.4)	(8.1)	(7.8)	(6.6)	(6.4)	(6.2)
Rocky Mountain	12.7	12.9	13.1	13.2	13.3	11.9	12.0	11.9
Southern	(29.4)	(28.5)	(27.6)	(26.7)	(26.1)	(24.9)	(24.7)	(24.5)
Southwestern	5.0	5.2	5.4	5.6	5.9	6.5	6.6	6.7
Net emissions and removals	**(53.6)**	**(50.1)**	**(47.7)**	**(45.9)**	**(44.9)**	**(44.1)**	**(43.2)**	**(42.6)**

Note**:** Negative estimates indicate net C uptake (i.e., a net removal of C from the atmosphere or transfers from another C pool).

Table 4.—Carbon stocks in forest land remaining forest land and harvested wood pools (MMT C) by year

Carbon pool[a]	1990	1995	2000	2005	2010	2018	2019	2020
Forest	**53,148**	**54,039**	**54,909**	**55,721**	**56,538**	**57,848**	**58,007**	**58,156**
Aboveground biomass	12,062	12,687	13,294	13,874	14,445	15,361	15,472	15,579
Belowground biomass	2,375	2,502	2,625	2,743	2,858	3,041	3,064	3,085
Dead wood	2,060	2,194	2,328	2,460	2,595	2,814	2,842	2,868
Litter	3,838	3,845	3,852	3,834	3,829	3,816	3,815	3,809
Soil (mineral)	25,458	25,454	25,452	25,452	25,453	25,458	25,457	25,457
Soil (organic)	7,355	7,357	7,358	7,358	7,358	7,357	7,357	7,357
Harvested wood	**1,895**	**2,061**	**2,218**	**2,353**	**2,462**	**2,645**	**2,671**	**2,695**
Products in use	1,249	1,326	1,395	1,447	1,471	1,515	1,523	1,530
SWDS	646	735	823	906	991	1,129	1,147	1,165
Total stocks	**55,043**	**56,101**	**57,128**	**58,074**	**59,000**	**60,493**	**60,678**	**60,851**

Notes: Totals may not sum due to independent rounding. Forest C stock estimates include all forest land remaining forest land in the conterminous 48 States and Alaska. Forest ecosystem C stocks do not include U.S. territories because managed forest land for U.S. territories is not currently included in Section 6.1, Representation of the U.S. Land Base, of the report. Forest ecosystem C stocks also do not include Hawaii because there is not sufficient National Forest Inventory data to support inclusion at this time. Forest ecosystem C stocks on managed forest land in Alaska were compiled using the gain-loss method because there are no remeasurements for forest land in Interior Alaska. These methods are described in the report in Annex 3.13 (see page A-414). Harvested wood product stocks include exports, even if the logs are processed in other countries, and excludes imports. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding. 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 2020 require C stocks for 2020 and 2021.

[a]For details on these estimates and how they were compiled, see U.S. EPA (2022).

Forest Land Conversions

Land use conversions to and from forest land result in substantial C stock changes each year. This section includes all C stock changes for land conversions to and from forest land, as reported in U.S. EPA (2022) (Table 5). It is important to note that in some cases the reported C stock changes from one land use category are transfers to another land use category. Forest land conversion to settlements was the largest source of C stock changes in the conversion categories, while cropland conversion to forest land resulted in the largest annual uptake. Considering all forest land conversions included in the U.S. EPA (2022) report, there have been net losses each year throughout the reporting period. Estimated net losses of approximately 27.4 MMT CO_2 Eq. were recorded for the last 3 reporting years.

Table 5.—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	2018	2019	2020
Forest land converted to cropland	46.3	46.5	46.5	46.6	46.9	47.3	47.3	47.3
Forest land converted to grassland	19.4	19.4	19.5	19.4	19.0	18.1	18.1	18.1
Forest land converted to settlements	52.6	54.2	55.8	57.7	59.4	61.6	61.6	61.5
Cropland converted to forest land	(39.6)	(39.6)	(39.5)	(39.5)	(39.5)	(39.6)	(39.6)	(39.6)
Grassland converted to forest land	(11.5)	(11.6)	(11.6)	(11.6)	(11.7)	(11.8)	(11.8)	(11.8)
Other land converted to forest land	(10.1)	(10.2)	(10.4)	(10.7)	(10.8)	(10.9)	(10.9)	(10.9)
Settlements converted to forest land	(34.2)	(34.2)	(34.1)	(34.1)	(34.1)	(34.1)	(34.1)	(34.1)
Wetlands converted to forest land	(3.2)	(3.2)	(3.2)	(3.2)	(3.2)	(3.2)	(3.2)	(3.2)
Net emissions and removals	**19.7**	**21.4**	**23.0**	**24.6**	**26.1**	**27.5**	**27.5**	**27.4**

[a]For details on these estimates and how they were compiled, see U.S. EPA (2022).

Notes: Totals may not sum due to independent rounding. Parentheses indicate net C uptake (i.e., a net removal of C from the atmosphere or transfer between land use categories). Carbon stock changes from forest land converted to other lands are not currently included in the U.S. EPA (2022) report; forest land converted to wetlands estimates were not compiled by the Forest Service.

Land Area

The land area covered in the U.S. EPA (2022) report includes lands directly influenced by human intervention. Direct intervention mostly occurs in areas accessible to human activity and includes altering or maintaining the 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 and Alaska comprise an estimated 282 million hectares (ha) of forest land that are considered managed and are included in this report along with an additional 1 million ha of nonforest land converted to forest land (see Walters et al. 2022 for detailed land conversion area estimates). Some differences exist in forest land area estimates in the latest update to the Resources Planning Act Assessment (Oswalt et al. 2019) and the forest land area estimates included in the U.S. EPA (2022) report, which are based on annual FIA data through 2020 for all States (USDA Forest Service 2022). These differences are mainly due to the separation of land categories and the managed land definition used in the U.S. EPA (2022) report (Nelson et al. 2020). Sufficient annual inventory data are not yet available for Hawaii, but estimates of these areas are included in Oswalt et al. (2019). Even though Hawaii and U.S. territories have relatively small areas of forest land that may not substantially influence the overall C budget for forest land, these regions will be added to the forest C estimates as sufficient data become available. Agroforestry systems that meet the definition of forest land are also not currently included in the U.S. EPA (2022) report since they are not explicitly inventoried (i.e., they are classified as agroforestry system) by either the FIA program or the Natural 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 (2022) report as a subcategory of grasslands. Combined, managed forest land and woodland area accounts for more than 303 million ha (Table 6).

Table 6.—Annual estimates of forest land and woodland area (1,000 ha) by year

Land area category[a]	1990	1995	2000	2005	2010	2018	2019	2020
Forest land remaining forest land	282,585	282,621	282,575	282,250	282,243	282,312	282,177	282,061
Nonforest land converted to forest land	1,100	1,114	1,166	1,124	1,173	1,044	1,053	1,053
Woodland remaining woodland[b]	23,480	23,224	22,913	22,401	21,730	20,322	20,122	19,922
Total area	**307,165**	**306,958**	**306,653**	**305,775**	**305,146**	**303,678**	**303,352**	**303,036**

Notes: Totals may not sum due to independent rounding. The estimates reported here may differ from the Land Representation section of the U.S. EPA (2022) but are consistent with estimates used to compile emissions and removals in these categories. See Annex 3.13 in the U.S. EPA (2022) for more details.

[a]For details on these estimates and how they were compiled, see U.S. EPA (2022).

[b]Woodland area is included in the grassland remaining grassland category and is not explicitly separated in the U.S. EPA (2022) report.

Fire Emissions and Area Burned

Carbon dioxide emissions from wild and prescribed fire on forest land are inherently captured in the C stock change estimates described in Tables 1 and 2. Fire emissions estimates from forest land are also compiled separately in the U.S. EPA (2022) report using field inventories, remotely sensed information, and models and are reported for each year in the time series (Fig. 3) and by individual State in Walters et al. (2022). There is substantial interannual variability in forest land area burned and associated GHG emissions resulting from fire over the last three decades. In 2020, the area of forest land burned was more than 1.7 million ha, and GHG emissions reached a new high over the reported time series (Fig. 3).

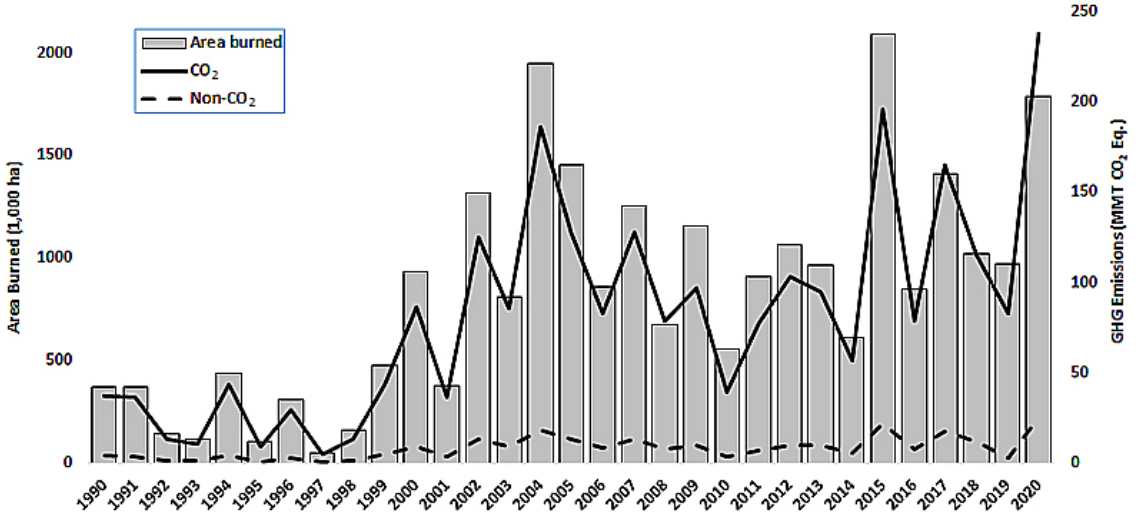

Figure 3.—Estimated annual emissions from wild and prescribed fire on forest land in the conterminous 48 States and Alaska, 1990–2020.

Planned Improvements

Planned improvements to estimation and reporting include the following general topics: development of a robust estimation and reporting system, individual C 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, and 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 eliminate latency in population estimates from the NFI, 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 HWP 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.

2020 Estimates at a Glance

Summary statistics for 2020 from the compilation of the forest land, woodlands, HWP, and urban trees in settlements in the U.S. EPA (2022) report:

- Economywide emissions declined substantially from 2019 to 2020 due, in large part, to the effects of the coronavirus (COVID-19) pandemic on travel and economic activity, as well as long-term trends in many other factors.
- Forest land, HWP, woodlands, and urban trees in settlements resulted in a net increase in C stocks (i.e., net CO_2 removals) offsetting the equivalent of approximately 12.9 percent (768.1 MMT CO_2 Eq.) of total (i.e., gross) GHG emissions or 16.3 percent of CO_2 emissions in 2020.
- Private forest land accounts for nearly 84 percent (-478.1 MMT CO_2 Eq.) of the estimated net sink strength in the conterminous 48 States and coastal Alaska (ownership information was not available for forest land in Interior Alaska so those lands were excluded from these estimates) in 2020.
- Land conversions to and from forest land continue to result in net emissions and/or transfers of C to other land uses (27.4 MMT CO_2 Eq.).
- Soils store more than 56 percent of all the carbon in forest ecosystems, with small stock changes annually.
- Managed forest land area burned was more than 1.7 million ha, and GHG emissions reached a new high over the reported time series from 1990 to 2020.
- Forest uptake averages 0.6 metric tons of C per hectare per year (MT C ha^{-1} yr^{-1}) with live vegetation accounting for more than 84 percent (0.5 MT C ha^{-1} yr^{-1}) of the uptake.

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