Greenhouse Gas Emissions and Removals From Forest Land, Woodlands, and Urban Trees in the United States, 1990–2019

Introduction

As a signatory to the United Nations Framework Convention on Climate Change (UNFCCC), the United States has reported an economy-wide inventory of greenhouse gas (GHG) emissions and removals since the mid-1990s (U.S. EPA 2021). Forest land, harvested wood products (HWP), woodlands, and urban trees within the land sector collectively represent the largest net carbon (C) sink in the United States, offsetting more than 11 percent of total GHG emissions in 2019 (U.S. EPA 2021). Estimates of GHG emissions and removals are compiled by U.S. Department of Agriculture (USDA) Forest Service researchers 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 report 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 2019. 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 (2021) submission to the UNFCCC. Most of the National scale estimates are also reported by individual State (Fig. 1) and are available online for the entire 1990-2019 time series (see appendix 1). New in this report are uncertainty estimates (see appendix 2) compiled for individual States (Fig. 1) and a published research dataset (Walters et al. 2021).
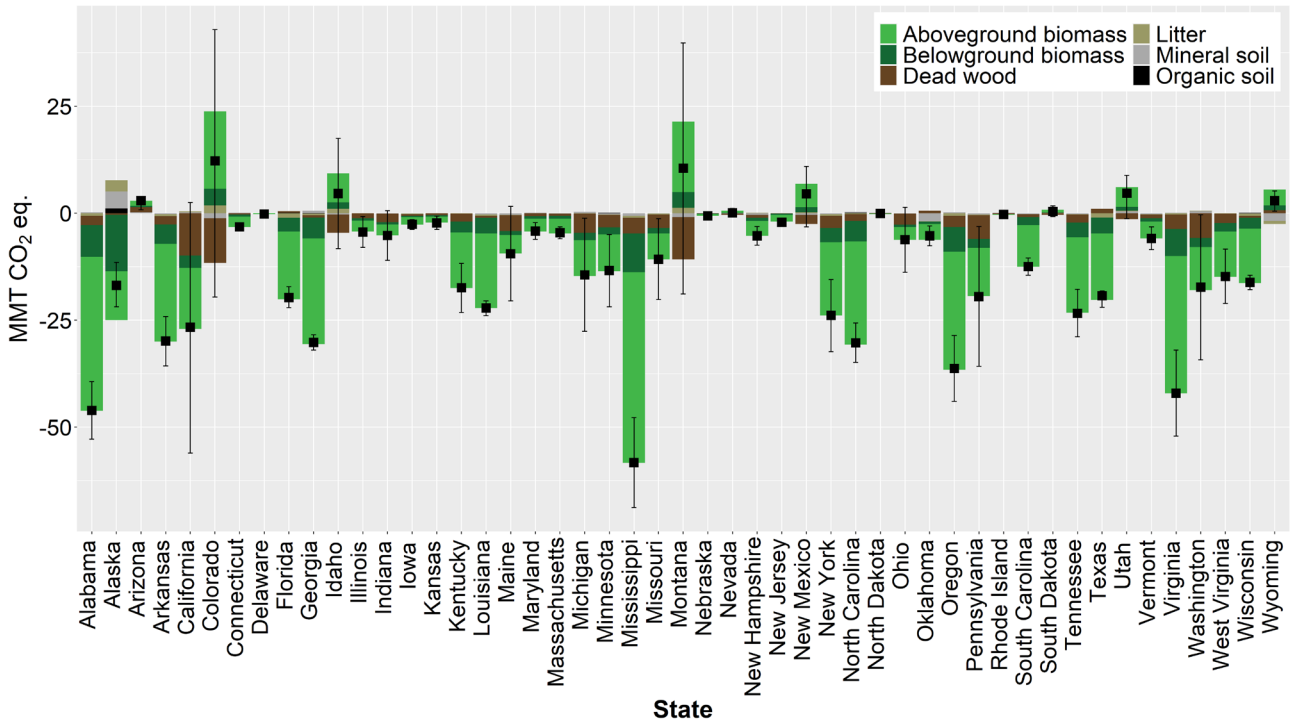

Figure 1.—Estimated annual emissions and removals by carbon pool for forest land remaining forest land in each of the conterminous 49 States in 2019 (MMT CO_2 Eq.). Note that points and uncertainties represented by confidence intervals (95 percent) reflect net flux for all carbon pools in each State. Negative estimates indicate net C uptake (i.e., a net removal of C from the atmosphere).

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 collectively represent a net GHG sink over the UNFCCC reporting period, with interannual variability driven, in large part, by natural and anthropogenic forest disturbances (e.g., wildfire, harvesting), fluxes resulting from land conversions, and changes in HWP in use and transfers to SWDS (table 1) (U.S. EPA 2021). In 2019, forest land, HWP, woodlands, and urban trees in settlements collectively represented an estimated net uptake of 775.7 million metric tons of carbon dioxide equivalent (MMT CO_2 Eq.). The category "forest land remaining forest land" was the largest net sink in the land sector, with an estimated uptake of 583.3 MMT CO_2 Eq. For categories included in this report, the largest source of emissions was from the conversion of forest land, with estimated emissions of 125.3 MMT CO_2 Eq. (table 1) (U.S. EPA 2021).

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	2017	2018	2019
Forest land remaining forest land[b]	(663.8)	(647.1)	(624.5)	(555.5)	(611.8)	(564.0)	(599.8)	(583.3)
Non-CO_2 emissions from fire	1.5	0.5	2.9	8.2	4.7	18.3	15.7	15.7
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 non-forest land[b]	117.3	119.0	121.0	122.9	124.5	125.3	125.3	125.3
Non-forest land converted to forest land[b]	(98.2)	(98.3)	(98.4)	(98.7)	(98.8)	(99.1)	(99.1)	(99.1)
Harvested wood products	(123.8)	(112.2)	(93.4)	(106.0)	(69.1)	(95.7)	(98.8)	(108.5)
Woodlands remaining woodlands[c]	4.1	4.1	4.0	3.9	3.8	3.5	3.5	3.5
Urban trees in settlements[d]	(96.4)	(103.3)	(110.4)	(117.4)	(124.6)	(129.8)	(129.8)	(129.8)
Total Emissions and Removals	**(859.1**	**(837.0)**	**(798.3)**	**(742.0)**	**(770.8)**	**(740.9)**	**(782.4)**	**(775.7)**

[a] For details on how estimates were compiled, see U.S. EPA (2021).
[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.
Notes: Totals may not sum due to independent rounding. Parentheses indicate net C uptake (i.e., a net removal of C from the atmosphere).

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 2019 estimates for both pools increased from previous years.

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	2017	2018	2019
Forest ecosystem total	**(663.8)**	**(647.1)**	**(624.5)**	**(555.5)**	**(611.8)**	**(564.0)**	**(599.8)**	**(583.3)**
Aboveground biomass	(456.4)	(442.3)	(426.0)	(401.3)	(415.4)	(395.1)	(402.4)	(394.0)
Belowground biomass	(103.7)	(100.7)	(97.3)	(92.0)	(94.2)	(89.2)	(90.9)	(89.2)
Dead wood	(97.3)	(97.9)	(98.1)	(93.5)	(99.9)	(97.1)	(101.7)	(99.3)
Litter	(8.1)	(7.2)	(3.1)	32.2	0.7	0.2	(2.3)	(0.5)
Soil (mineral)	1.5	0.7	(0.5)	(1.5)	(3.0)	14.3	(4.5)	(2.4)
Soil (organic)	(0.6)	(0.5)	(0.4)	(0.2)	(0.9)	2.1	1.2	1.2
Drained organic soil	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Harvested wood total	**(123.8)**	**(112.2)**	**(93.4)**	**(106.0)**	**(69.1)**	**(95.7)**	**(98.8)**	**(108.5)**
Products in use	(54.8)	(51.7)	(31.9)	(42.6)	(7.4)	(30.3)	(31.5)	(39.2)
SWDS	(69.0)	(60.5)	(61.5)	(63.4)	(61.7)	(65.5)	(67.2)	(69.3)
Total Net Flux	**(787.6)**	**(759.3)**	**(717.9)**	**(661.5)**	**(680.9)**	**(659.7)**	**(698.6)**	**(691.8)**

[a] For details on these estimates and how they were compiled, see U.S. EPA (2021).
Notes: Totals may not sum due to independent rounding. Parentheses indicate net C uptake (i.e., a net removal of C from the atmosphere).

Carbon stock estimates for forest ecosystem and harvested wood C storage pools are presented in table 3. Together, the estimated aboveground biomass and soil C pools account for a large proportion 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 stocks in forest land remaining forest land and harvested wood pools (MMT C) by year

Carbon Pool[a]	1990	1995	2000	2005	2010	2017	2018	2019
Forest total	**50,913**	**51,808**	**52,681**	**53,489**	**54,302**	**55,610**	**55,774**	**55,933**
Aboveground biomass	11,810	12,424	13,019	13,584	14,144	15,043	15,152	15,260
Belowground biomass	2,319	2,459	2,594	2,723	2,851	3,054	3,079	3,103
Dead wood	2,049	2,182	2,316	2,446	2,580	2,798	2,825	2,852
Litter	3,656	3,665	3,673	3,655	3,645	3,637	3,638	3,638
Soil (mineral)	25,145	25,144	25,143	25,145	25,147	25,145	25,146	25,147
Soil (organic)	5,934	5,934	5,935	5,936	5,936	5,934	5,933	5,933
Harvested wood total	**1,895**	**2,061**	**2,218**	**2,353**	**2,462**	**2,642**	**2,669**	**2,699**
Products in use	1,249	1,326	1,395	1,447	1,471	1,513	1,521	1,532
SWDS	646	735	823	906	991	1,129	1,148	1,167
Total stocks	**52,808**	**53,870**	**54,899**	**55,842**	**56,764**	**58,252**	**58,443**	**58,632**

[a] For details on these estimates and how they were compiled, see U.S. EPA (2021).
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. Forest ecosystem C stocks also do not include Hawaii because there is not sufficient NFI data to support inclusion at this time. Forest ecosystem C stocks on managed forest land in Alaska were compiled using the gain-loss method as described in Annex 3.13. 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 FIA 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 2019 require C stocks for 2019 and 2020.

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 (2021) (table 4). 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 cropland conversion to forest land resulted in the largest annual uptake. Considering all forest land conversions included in the U.S. EPA (2021) report, there have been net emissions each year throughout the reporting period. Estimated net emissions of ~26.2 MMT CO_2 Eq. were recorded for the last 3 reporting years.

Table 4.—Emissions and removals (net flux) from conversions to and from forest land (MMT CO_2 Eq.) by year

Land Conversions[a]	1990	1995	2000	2005	2010	2017	2018	2019
Forest land converted to cropland	46.3	46.5	46.6	46.8	47.0	47.6	47.6	47.6
Forest land converted to grassland	16.3	16.3	16.4	16.3	15.9	14.9	14.9	14.8
Forest land converted to settlements	54.6	56.3	58.0	59.9	61.6	62.9	62.9	62.9
Cropland converted to forest land	(39.8)	(39.8)	(39.7)	(39.7)	(39.7)	(39.8)	(39.8)	(39.8)
Grassland converted to forest land	(10.3)	(10.3)	(10.3)	(10.3)	(10.4)	(10.5)	(10.5)	(10.5)
Other land converted to forest land	(10.2)	(10.4)	(10.6)	(10.8)	(11.0)	(11.0)	(11.0)	(11.0)
Settlements converted to forest land	(34.6)	(34.6)	(34.6)	(34.5)	(34.5)	(34.5)	(34.5)	(34.5)
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	**19.1**	**20.7**	**22.5**	**24.3**	**25.7**	**26.3**	**26.2**	**26.2**

[a] For details on these estimates and how they were compiled, see U.S. EPA (2021).
Notes: Totals may not sum due to independent rounding. Parentheses indicate net C uptake (i.e., a net removal of C from the atmosphere). Emissions and removals from forest land converted to other lands are not currently included in the U.S. EPA (2021) report; forest land converted to wetlands estimates were not compiled by Forest Service.

Land Area

The land area covered in the U.S. EPA (2021) 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 279 million hectares (ha) of forest land that are considered managed and are included in this report along with an additional 1 million ha of non-forest land converted to forest land. 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 (2021) report, which are based on annual FIA data through 2019 for all States (USDA Forest Service 2021). These differences are mainly due to the separation of land categories and the managed land definition used in the U.S. EPA (2021) 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 (2021) 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" and "land converted to grassland" categories and is not explicitly separated in the U.S. EPA (2021) report as a subcategory of grasslands. Combined, forest land and woodland area accounts for nearly 301 million ha (table 5).

Table 5.—Annual estimates of forest land and woodland area (1,000 ha) by year

Land Area Category[a]	1990	1995	2000	2005	2010	2018	2019
Forest land remaining forest land	279,661	279,755	279,795	279,491	279,537	279,483	279,386
Non-forest land converted to forest land	1,026	1,046	1,062	1,039	1,084	1,031	1,031
Woodland remaining woodland[b]	23,736	23,434	23,096	22,521	21,818	20,294	20,077
Non-woodland converted to woodland[b]	579	567	539	536	490	378	378
Total Area	**305,002**	**304,802**	**304,492**	**303,587**	**302,929**	**301,187**	**300,872**

[a] For details on these estimates and how they were compiled, see U.S. EPA (2021).
[b] Woodland area is included in the "remaining grassland" and "land converted to grassland" categories and is not explicitly separated in the U.S. EPA (2021) report.
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 (2021) but are consistent with estimates used to compile emissions and removals in these categories. See Annex 3.13 in the U.S. EPA (2021) for more details.

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.

2021 Estimates at a Glance

Summary statistics from the compilation of the forest land, woodlands, HWP, and urban trees in settlements in the U.S. EPA (2021) report:

- **Forest land, HWP, and urban trees in settlements collectively offset more than 11 percent (765.5 MMT CO_2 Eq.) of total GHG emissions annually or 14 percent of CO_2 emissions.**

- **Live vegetation in forests and urban trees account for nearly 80 percent of the C sink strength.**

- **Land conversions to and from forest land continue to result in net emissions (22.1 MMT CO_2 Eq.).**

- **More than 55 percent of all carbon in forest ecosystems is stored in the soil with small stock changes annually.**

- **Carbon storage in HWP has continued to increase annually since the Great Recession with substantial increases occurring between 2018 and 2019.**

- **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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