USDA
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RESOURCE UPDATE FS-227

Greenhouse Gas Emissions and Removals from Forest Land, Woodlands, and Urban Trees in the United States, 1990-2018

Introduction

As a signatory to the United Nations Framework Convention on Climate Change (UNFCCC), the United States has been reporting an economy-wide Inventory of greenhouse gas (GHG) emissions and removals since the mid-1990s (US EPA 2020). Forest land, harvested wood products (HWPs), 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 annually (US EPA 2020). 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 USDA Forest Service. This report—the second in a new series of annual updates—provides an overview of the status and trends of GHG emissions and removals from forest land, woodlands in the grassland category, HWPs, and urban trees in settlements in the United States from 1990 to 2018. 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 US EPA (2020) submission to the UNFCCC. New in this report, most of the national scale estimates are also reported by individual U.S. state (Fig. 1) and are available online for the entire 1990-2018 time series (see appendix).

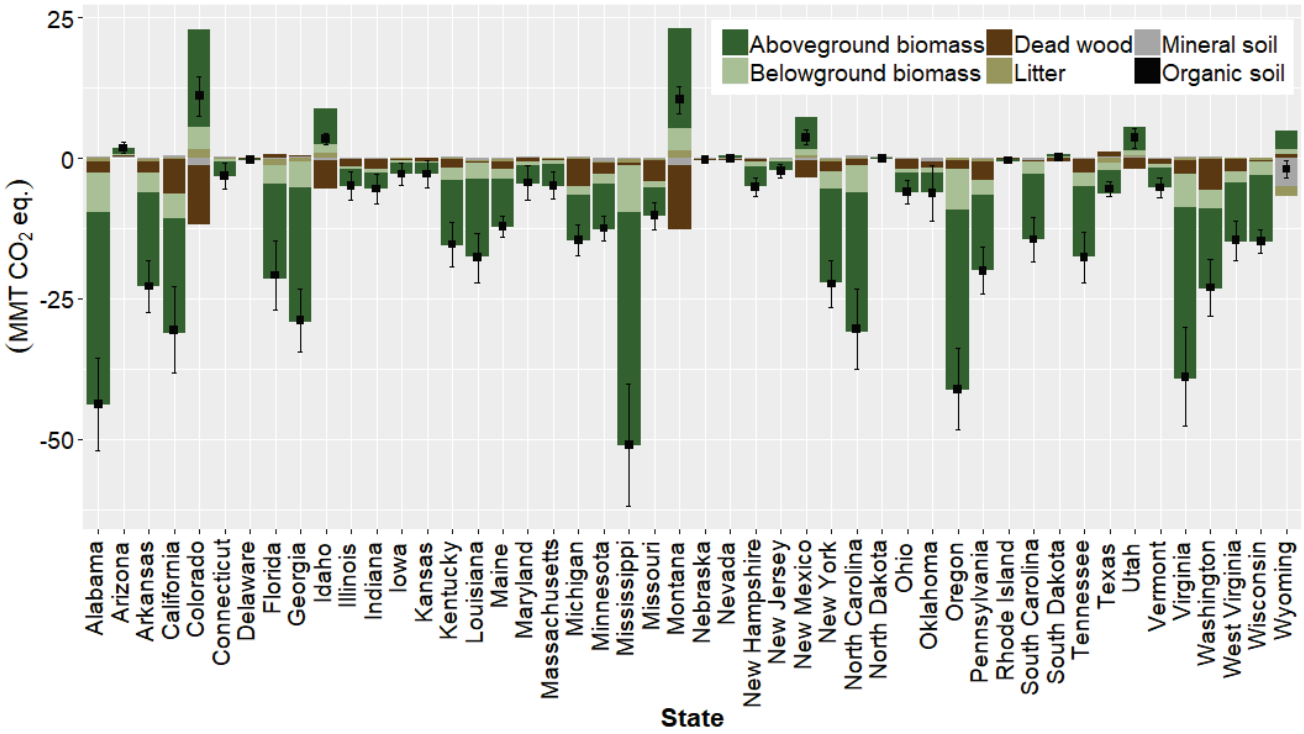

Figure 1.—Estimated annual emissions and removals from forest land remaining forest land by carbon pool for each of the conterminous 48 states in 2018 (MMT CO_2 Eq.). Note that points and confidence intervals (95 percent) reflect net flux for all carbon pools in each state. Negative estimates indicate net C uptake (i.e., a net removal of C from the atmosphere).

Forest Carbon Cycle

Carbon is continuously cycled among ecosystem pools and the atmosphere as a result of biogeochemical processes in forests (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 the 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 flux 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. The rate of emission varies considerably among different product pools.

Carbon Pools

For estimating 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 greater than 2 millimeters (mm) diameter.
- Dead wood—all nonliving woody biomass either standing, lying on the ground (but not including litter), or in the soil.
- Litter—the litter, fumic, and humic layers, and all nonliving biomass with a diameter less than 7.5 centimeters (cm) at transect intersection, lying on the ground.
- Soil organic C (SOC)—all organic material in soil to a depth of 1 meter but excluding the coarse roots of the belowground pools.

In addition, two harvested wood pools are included when estimating C flux:

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

Total Emissions and Removals

Forest land, HWPs, 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 disturbances (e.g., wildfire, harvesting), land conversions, and changes in HWPs in use (Table 1.; US EPA 2020). In 2018, forest land, HWPs, woodlands, and urban trees in settlements collectively represented an estimated net uptake of 752.9 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 564.5 MMT CO_2 Eq. Conversions from forest land were the largest source of emissions within the categories included in this report, with estimated emissions of 127.4 MMT CO_2 Eq. (Table 1; US EPA 2020).

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

Emissions and Removals Category[a]	1990	1995	2000	2005	2010	2016	2017	2018
Forest land remaining forest land[b]	(610.1)	(598.7)	(572.1)	(572.6)	(556.2)	(565.5)	(552.0)	(564.5)
Non-CO_2 emissions from fire	1.5	0.6	2.9	8.2	4.6	5.6	18.8	18.8
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]	119.1	120.8	122.5	124.4	126.0	127.4	127.4	127.4
Non-forest land converted to forest land[b]	(109.4)	(109.7)	(109.9)	(110.2)	(110.4)	(110.6)	(110.6)	(110.6)
Harvested wood products	(123.8)	(112.2)	(93.4)	(106.0)	(69.1)	(92.4)	(95.7)	(98.8)
Woodlands remaining woodlands[c]	5.0	4.9	4.8	4.6	4.4	4.1	4.0	4.0
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	**(813.9)**	**(797.2)**	**(755.0)**	**(768.4)**	**(724.7)**	**(760.6)**	**(737.3)**	**(752.9)**

[a] For details on how estimates were compiled see US EPA 2020.
[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 2018 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.)

Carbon Pool[a]	1990	1995	2000	2005	2010	2016	2017	2018
Forest ecosystem	**(610.1)**	**(598.7)**	**(572.1)**	**(572.6)**	**(556.2)**	**(565.5)**	**(552.0)**	**(564.5)**
Aboveground biomass	(425.1)	(416.1)	(392.7)	(391.3)	(391.3)	(397.0)	(381.2)	(385.2)
Belowground biomass	(98.6)	(96.6)	(91.5)	(90.8)	(90.3)	(91.1)	(87.6)	(88.6)
Dead wood	(81.9)	(82.8)	(82.7)	(84.1)	(83.4)	(87.6)	(83.1)	(86.4)
Litter	(5.0)	(3.5)	(4.5)	(5.2)	(1.4)	(0.9)	(3.5)	(3.1)
Soil (mineral)	0.3	(0.1)	(1.0)	(1.8)	4.6	8.2	1.4	(3.3)
Soil (organic)	(0.6)	(0.5)	(0.3)	(0.1)	4.9	2.3	1.4	1.4
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)**	**(92.4)**	**(95.7)**	**(98.8)**
Products in use	(54.8)	(51.7)	(31.9)	(42.6)	(7.4)	(27.8)	(30.3)	(31.5)
SWDS	(69.0)	(60.5)	(61.5)	(63.4)	(61.7)	(64.6)	(65.5)	(67.2)
Total Net Flux	**(733.9)**	**(710.9)**	**(665.5)**	**(678.6)**	**(625.3)**	**(657.9)**	**(647.7)**	**(663.2)**

[a] For details on these estimates and how they were compiled see US EPA 2020.

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)

Carbon Pool[a]	1990	1995	2000	2005	2010	2017	2018	2019
Forest	**51,527**	**52,358**	**53,161**	**53,886**	**54,663**	**55,746**	**55,897**	**56,051**
Aboveground biomass	11,833	12,408	12,962	13,484	14,020	14,780	14,884	14,989
Belowground biomass	2,350	2,483	2,612	2,734	2,858	3,033	3,056	3,081
Dead wood	2,120	2,233	2,346	2,454	2,568	2,731	2,753	2,777
Litter	3,662	3,670	3,676	3,647	3,646	3,639	3,640	3,641
Soil (mineral)	25,636	25,636	25,637	25,639	25,641	25,637	25,637	25,638
Soil (organic)	5,927	5,928	5,928	5,929	5,929	5,926	5,926	5,926
Harvested wood	**1,895**	**2,061**	**2,218**	**2,353**	**2,462**	**2,616**	**2,642**	**2,669**
Products in use	1,249	1,326	1,395	1,447	1,471	1,505	1,513	1,521
SWDS	646	735	823	906	991	1,112	1,129	1,148
Total stocks	**53,423**	**54,419**	**55,380**	**56,239**	**57,124**	**58,362**	**58,539**	**58,720**

[a] For details on these estimates and how they were compiled see US EPA 2020.

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 2018 require C stocks for 2018 and 2019.

Forest Land Conversions

Land use conversions to and from forest land result in substantial emissions and removals each year. In this section all emissions and removals included for land conversions to and from forest land, as reported in US EPA (2020), are included in Table 4. 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 US EPA (2020) report, over the reporting period there have been net emissions each year, with estimated net emissions of 16.7 MMT CO_2 Eq. for the most recent year.

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

Land Conversions[a]	1990	1995	2000	2005	2010	2016	2017	2018
Forest land converted to cropland	48.6	48.7	48.5	48.4	48.3	48.7	48.7	48.7
Forest land converted to grassland	15.9	15.8	16.0	16.0	16.0	15.9	15.9	15.9
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	(45.9)	(45.9)	(46.0)	(46.1)	(46.2)	(46.3)	(46.3)	(46.3)
Grassland converted to forest land	(9.8)	(9.7)	(9.7)	(9.6)	(9.6)	(9.7)	(9.7)	(9.7)
Other land converted to forest land	(14.3)	(14.5)	(14.6)	(14.8)	(14.9)	(14.9)	(14.9)	(14.9)
Settlements converted to forest land	(38.6)	(38.6)	(38.7)	(38.7)	(38.8)	(38.9)	(38.9)	(38.9)
Wetlands converted to forest land	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)
Net Emissions and Removals	**9.6**	**11.2**	**12.6**	**14.3**	**15.6**	**16.7**	**16.7**	**16.7**

[a] For details on these estimates and how they were compiled see US EPA 2020.

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 currently not included in US EPA (2020). Forest land converted to wetlands estimates were not compiled by the Forest Service.

Land Area

The land area included in the US EPA (2020) report includes lands directly influenced by human intervention. Direct intervention occurs mostly in areas accessible to human activity and includes altering or maintaining the condition of the land 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. Forest Inventory and Analysis data from each of the conterminous 48 states and Alaska comprise an estimated 280 million hectares (ha) of forest land that are considered managed and are included in this report along with an additional 10 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 US EPA (2020) report, which are based on annual FIA data through 2018 for all states (USDA Forest Service 2019). These differences are due, in large part, to the separation of land categories and the managed land definition used in the US EPA (2020) 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 US EPA (2020) 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 US EPA (2020) report as a subcategory of grasslands. Combined, forest land and woodland area accounts for more than 311 million ha (Table 5).

Table 5.—Annual estimates of forest land and woodland area (1000 ha)

Land Area Category[a]	1990	1995	2000	2005	2010	2018	2019
Forest land remaining forest land	279,748	279,840	280,025	279,749	279,918	279,787	279,682
Non-forest land converted to forest land	9,622	9,654	9,689	9,725	9,761	9,796	9,796
Woodland remaining woodland[b]	19,891	19,669	19,255	18,630	17,733	16,000	15,776
Non-woodland converted to woodland[b]	5,782	5,702	5,552	5,322	4,994	4,607	4,607
Total Area	**315,043**	**314,865**	**314,521**	**313,426**	**312,405**	**312,209**	**311,880**

[a] For details on these estimates and how they were compiled see US EPA 2020.

[b]Woodland area is included in the "remaining grassland" and "land converted to grassland" categories and is not explicitly separated in the US EPA (2020) report.

Notes: Totals may not sum due to independent rounding. The estimates reported here may differ from the Land Representation section of US EPA (2020) but are consistent with estimates used to compile emissions and removals in these categories. See Annex 3.13 in US EPA (2020) for more details.

Planned Improvements

Planned improvements to estimation and reporting include the following general topics: development of a more 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. There are also investments being made to leverage state-level wood products and harvest information to allow for the disaggregation of HWPs 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

Below are summary statistics from the compilation of the forest land, woodlands, HWPs, and urban trees in settlements in the US EPA (2020) report.

- Forest land, HWPs, and urban trees in settlements collectively offset more than 11 percent (752.9 MMT CO_2 Eq.) of total GHG emissions annually, or 14 percent of CO_2 emissions.
- Forest land accounts for more than 95 percent of the net C sink within the land sector.
- 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 (16.7 MMT CO_2 Eq.).
- More than 56 percent of all carbon in forest ecosystems is stored in the soil with small stock changes annually.
- Carbon storage in HWPs continues to increase annually since the Great Recession.
- Forests 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 85 percent (0.5 MT C ha^{-1} yr^{-1}) of the uptake.

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