6. Land Use, Land-Use Change, and Forestry

This chapter provides an assessment of the greenhouse gas fluxes resulting from land use and land-use change in the United States.[1] The Intergovernmental Panel on Climate Change's *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) recommends reporting fluxes according to changes within and conversions between all land-use types including: Forest Land, Cropland, Grassland, Wetlands, and Settlements (as well as Other Land).

The greenhouse gas flux from *Forest Land Remaining Forest Land* is reported for all forest ecosystem carbon (C) pools (i.e., aboveground biomass, belowground biomass, dead wood, litter, and mineral and organic soils), harvested wood pools, and non-carbon dioxide (non-CO_2) emissions from forest fires, the application of synthetic nitrogen fertilizers to forest soils, and the draining of organic soils. Fluxes from *Land Converted to Forest Land* are included for aboveground biomass, belowground biomass, dead wood, litter, and C stock changes from mineral soils, while C stock changes from drained organic soils and all non-CO_2 emissions from *Land Converted to Forest Land* are included in the fluxes from *Forest Land Remaining Forest Land* as it is not currently possible to separate these fluxes by conversion category.

Fluxes are reported for four agricultural land use/land-use change categories: *Cropland Remaining Cropland,* Land Converted to Cropland, Grassland Remaining Grassland, and *Land Converted to Grassland*. The reported greenhouse gas fluxes from these agricultural lands include changes in soil organic C stocks in mineral and organic soils due to land use and management, and for the subcategories of Forest Land Converted to Cropland and Forest Land Converted to Grassland, the changes in aboveground biomass, belowground biomass, dead wood, and litter C stocks are also reported. The greenhouse gas flux from Grassland Remaining Grassland also includes estimates of non-CO_2 emissions from grassland fires occurring on both Grassland Remaining Grassland and *Land Converted to Grassland*.

Fluxes from *Wetlands Remaining Wetlands* include changes in C stocks and methane (CH_4) and nitrous oxide (N_2O) emissions from managed peatlands, aboveground and belowground biomass, dead organic matter, soil C stock changes and CH_4 emissions from coastal wetlands, as well as N_2O emissions from aquaculture. In addition, CH_4 emissions from reservoirs and other constructed waterbodies are included for the subcategory Flooded Land Remaining Flooded Land. Estimates for Land Converted to Wetlands include aboveground and belowground biomass, dead organic matter and soil C stock changes, and CH_4 emissions from land converted to vegetated coastal wetlands. Carbon dioxide (CO_2) and CH_4 emissions are included for reservoirs and other constructed waterbodies under the subcategory Land Converted to Flooded Land.

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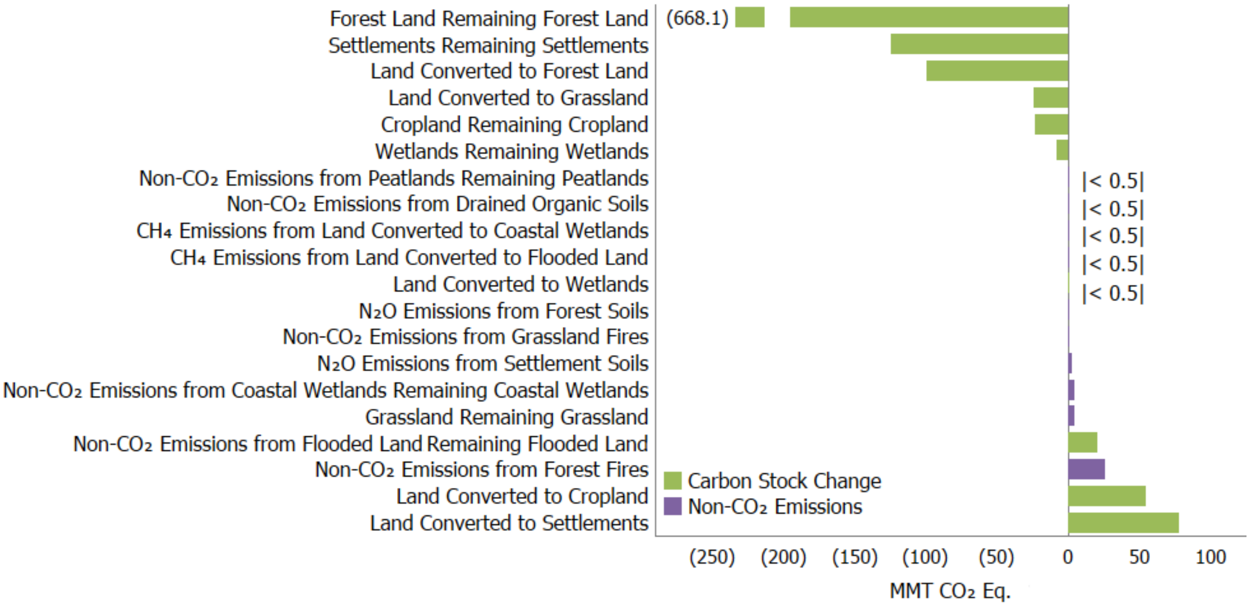
[1] The term "flux" is used to describe the exchange of CO_2 to and from the atmosphere, with net flux being either positive or negative depending on the overall balance. Removal and long-term storage of CO_2 from the atmosphere is also referred to as "carbon sequestration."

Fluxes from *Settlements Remaining Settlements* include changes in C stocks from organic soils, N_2O emissions from nitrogen fertilizer additions to soils, and CO_2 fluxes from settlement trees and landfilled yard trimmings and food scraps. The reported greenhouse gas flux from *Land Converted to Settlements* includes changes in C stocks in mineral and organic soils due to land use and management for all land use conversions to settlements, and the C stock changes in aboveground biomass, belowground biomass, dead wood, and litter are also included for the subcategory *Forest Land Converted to Settlements*.

In 2020 the land use, land-use change, and forestry (LULUCF) sector resulted in a net increase in C stocks (i.e., net CO_2 removals) of 812.2 MMT CO_2 Eq.[2] This represents an offset of approximately 13.6 percent of total (i.e., gross) greenhouse gas emissions in 2020. Emissions of CH_4 and N_2O from LULUCF activities in 2020 were 38.1 and 15.2 MMT CO_2 Eq., respectively, and combined represent 0.9 percent of total greenhouse gas emissions.[3] In 2020 the overall net flux from LULUCF resulted in a removal of 758.9 MMT CO_2 Eq. Emissions, removals and net greenhouse gas flux from LULUCF are summarized in Figure 6-1 and Table 6-1 by land-use and category, and Table 6-2 and Table 6-3 by gas in MMT CO_2 Eq. and kt, respectively. Trends in LULUCF sources and sinks over the 1990 to 2020 time series are shown in Figure 6-2.

Figure 6-1: 2020 LULUCF Chapter Greenhouse Gas Sources and Sinks



Note: Parentheses in horizontal axis indicate net sequestration.

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[2] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland*, Land Converted to Cropland, Grassland Remaining Grassland, *Land Converted to Grassland, Wetlands Remaining Wetlands*, Land Converted to Wetlands, *Settlements Remaining Settlements,* and Land Converted to Settlements.

[3] LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to Coastal Wetlands*, Flooded Land Remaining Flooded Land, and Land Converted to Flooded Land; and N_2O emissions from Forest Soils and Settlement Soils.

Figure 6-2: Trends in Emissions and Removals (Net CO_2 Flux) from Land Use, Land-Use Change, and Forestry

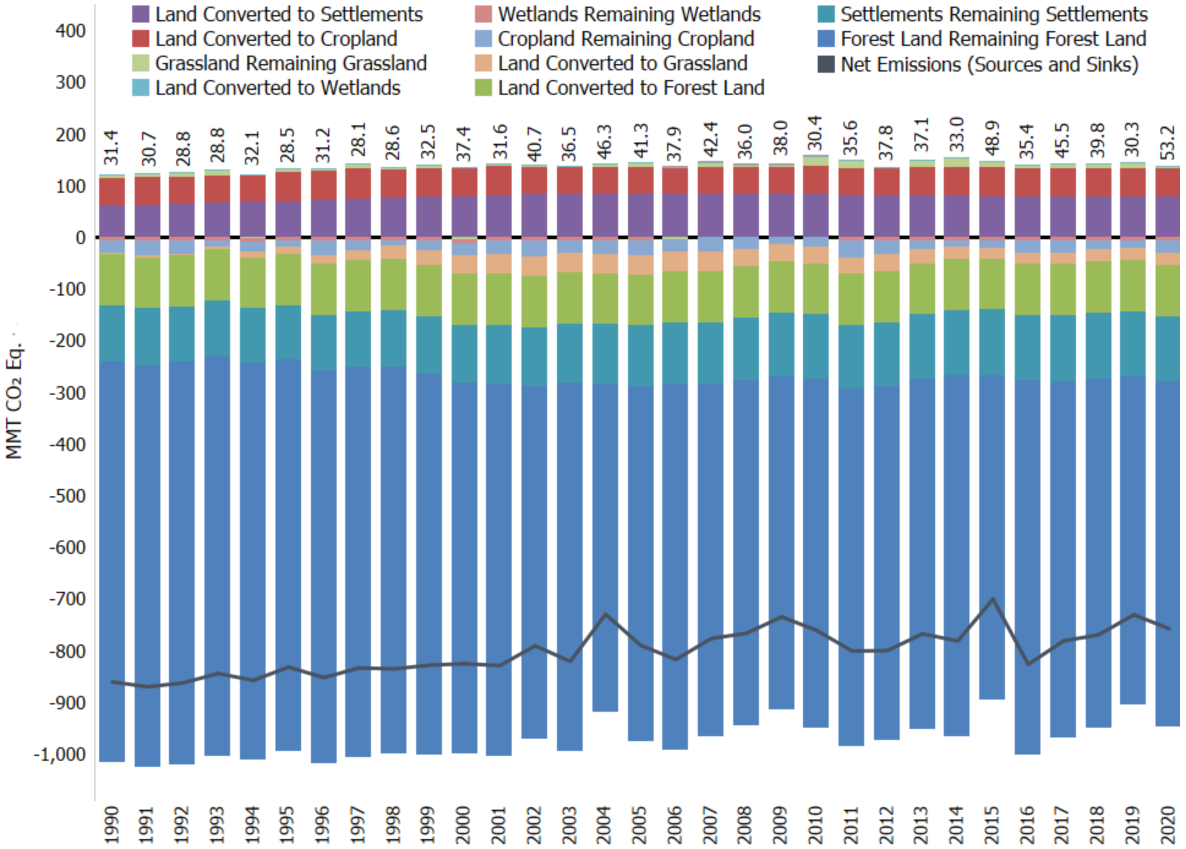

Table 6-1: Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2016	2017	2018	2019	2020
Forest Land Remaining Forest Land	**(769.7)**	**(674.0)**	**(717.3)**	**(670.1)**	**(664.6)**	**(631.8)**	**(642.2)**
Changes in Forest Carbon Stocks[a]	(774.0)	(687.3)	(725.6)	(688.3)	(677.1)	(634.8)	(668.1)
Non-CO_2 Emissions from Forest Fires[b]	4.1	12.8	7.8	17.7	11.9	2.5	25.3
N_2O Emissions from Forest Soils[c]	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Non-CO_2 Emissions from Drained Organic Soils[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Land Converted to Forest Land	**(98.6)**	**(99.1)**	**(99.5)**	**(99.5)**	**(99.5)**	**(99.5)**	**(99.5)**
Changes in Forest Carbon Stocks[e]	(98.6)	(99.1)	(99.5)	(99.5)	(99.5)	(99.5)	(99.5)
Cropland Remaining Cropland	**(23.2)**	**(29.0)**	**(22.7)**	**(22.3)**	**(16.6)**	**(14.5)**	**(23.3)**
Changes in Mineral and Organic Soil Carbon Stocks	(23.2)	(29.0)	(22.7)	(22.3)	(16.6)	(14.5)	(23.3)
Land Converted to Cropland	**51.8**	**52.0**	**54.1**	**54.3**	**54.0**	**53.9**	**54.4**
Changes in all Ecosystem Carbon Stocks[f]	51.8	52.0	54.1	54.3	54.0	53.9	54.4
Grassland Remaining Grassland	**7.1**	**9.4**	**8.6**	**9.9**	**10.3**	**13.1**	**5.1**
Changes in Mineral and Organic Soil Carbon Stocks	6.9	8.7	8.0	9.3	9.7	12.4	4.5
Non-CO_2 Emissions from Grassland Fires[g]	0.2	0.7	0.6	0.6	0.6	0.6	0.6
Land Converted to Grassland	**(3.1)**	**(37.0)**	**(22.6)**	**(22.7)**	**(22.4)**	**(21.5)**	**(24.1)**
Changes in all Ecosystem Carbon Stocks[f]	(3.1)	(37.0)	(22.6)	(22.7)	(22.4)	(21.5)	(24.1)
Wetlands Remaining Wetlands	**14.7**	**17.2**	**15.8**	**15.9**	**15.9**	**15.9**	**15.8**

Changes in Organic Soil Carbon Stocks in Peatlands	1.1	1.1	0.7	0.8	0.8	0.8	0.7
Non-CO_2 Emissions from Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Changes in Biomass, DOM, and Soil Carbon Stocks in Coastal Wetlands	(8.5)	(7.6)	(8.8)	(8.8)	(8.8)	(8.8)	(8.8)
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	3.7	3.8	3.8	3.8	3.8	3.8	3.8
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.2	0.2	0.2
CH_4 Emissions from Flooded Land Remaining Flooded Land	18.2	19.8	19.9	19.9	19.9	19.9	19.9
Land Converted to Wetlands	**7.2**	**1.3**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Changes in Biomass, DOM, and Soil Carbon Stocks in Land Converted to Coastal Wetlands	0.5	0.5	(+)	(+)	(+)	(+)	(+)
CH_4 Emissions from Land Converted to Coastal Wetlands	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Changes in Land Converted to Flooded Land	3.9	0.3	0.3	0.3	0.3	0.3	0.3
CH_4 Emissions from Land Converted to Flooded Land	2.6	0.2	0.2	0.2	0.2	0.2	0.2
Settlements Remaining Settlements	**(107.6)**	**(113.5)**	**(121.5)**	**(125.3)**	**(124.9)**	**(124.5)**	**(123.7)**
Changes in Organic Soil Carbon Stocks	11.3	12.2	16.0	16.0	15.9	15.9	15.9
Changes in Settlement Tree Carbon Stocks	(96.4)	(117.4)	(129.8)	(129.8)	(129.8)	(129.8)	(129.8)
N_2O Emissions from Settlement Soils[h]	2.0	3.1	2.2	2.3	2.4	2.4	2.5
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	(24.5)	(11.4)	(10.0)	(13.8)	(13.4)	(13.1)	(12.2)
Land Converted to Settlements	**60.8**	**82.8**	**77.8**	**77.9**	**78.0**	**77.9**	**77.9**
Changes in all Ecosystem Carbon Stocks[f]	60.8	82.8	77.8	77.9	78.0	77.9	77.9
LULUCF Emissions[i]	**31.4**	**41.3**	**35.4**	**45.5**	**39.8**	**30.3**	**53.2**
CH_4	27.2	30.9	28.3	34.0	30.7	25.5	38.1
N_2O	4.2	10.5	7.1	11.5	9.1	4.8	15.2
LULUCF Carbon Stock Change[j]	**(892.0)**	**(831.1)**	**(862.0)**	**(826.7)**	**(809.0)**	**(760.8)**	**(812.2)**
LULUCF Sector Net Total[k]	**(860.6)**	**(789.8)**	**(826.6)**	**(781.2)**	**(769.3)**	**(730.5)**	**(758.9)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Includes the net changes to carbon stocks stored in all forest ecosystem pools (estimates include C stock changes from drained organic soils from both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*) and harvested wood products.

[b] Estimates include CH_4 and N_2O emissions from fires on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[c] Estimates include N_2O emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[d] Estimates include CH_4 and N_2O emissions from drained organic soils on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.* Carbon stock changes from drained organic soils are included with the *Forest Land Remaining Forest Land* forest ecosystem pools.

[e] Includes the net changes to carbon stocks stored in all forest ecosystem pools.

[f] Includes changes in mineral and organic soil carbon stocks for all land use conversions to cropland, grassland, and settlements. Also includes aboveground/belowground biomass, dead wood, and litter carbon stock changes for conversion of forest land to cropland, grassland, and settlements.

[g] Estimates include CH_4 and N_2O emissions from fires on both Grassland Remaining Grassland and *Land Converted to Grassland.*

[h] Estimates include N_2O emissions from N fertilizer additions on both *Settlements Remaining Settlements* and Land Converted to Settlements because it is not possible to separate the activity data at this time.

[i] LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from *Land Converted to*

Coastal Wetlands, Flooded Land Remaining Flooded Land, and Land Converted to Flooded Land; and N_2O emissions from Forest Soils and Settlement Soils.

[j] LULUCF Carbon Stock Change includes any C stock gains and losses from all land use and land use conversion categories.

[k] The LULUCF Sector Net Total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes in units of MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

The C stock changes and emissions of CH_4 and N_2O from LULUCF are summarized in Table 6-2 (MMT CO_2 Eq.) and Table 6-3 (kt). Total net C sequestration in the LULUCF sector decreased by approximately 9.0 percent between 1990 and 2020. This decrease was primarily due to a decline in the rate of net C accumulation in Forest Land*,* as well as an increase in emissions from Land Converted to Settlements.[4] Specifically, there was a net C accumulation in *Settlements Remaining Settlements*, which increased from 1990 to 2020, while the net C accumulation in *Forest Land Remaining Forest Land* and Land Converted to Wetlands slowed over this period. Net C accumulation remained steady from 1990 to 2020 in *Land Converted to Forest Land, Cropland Remaining Cropland,* Land Converted to Cropland, and *Wetlands Remaining Wetlands*, while net C accumulation fluctuated in Grassland Remaining Grassland.

Flooded Land Remaining Flooded Land*,* included for the first time in this year's estimates, was the largest source of CH_4 emissions from LULUCF in 2020, totaling 19.9 MMT CO_2 Eq. (797kt of CH_4). Forest fires resulted in CH_4 emissions of 13.6MMT CO_2 Eq. (545kt of CH_4). *Coastal Wetlands Remaining Coastal Wetlands* resulted in CH_4 emissions of 3.8MMT CO_2 Eq. (154 kt of CH_4). Grassland fires resulted in CH_4 emissions of 0.3 MMT CO_2 Eq. (12 kt of CH_4). Land Converted to Flooded Land and Land Converted to Wetlands each resulted in CH_4 emissions of 0.2 MMT CO_2 Eq. (7 kt of CH_4). *Drained Organic Soils* on forest lands and Peatlands Remaining Peatlands resulted in CH_4 emissions of less than 0.05 MMT CO_2 Eq. each.

For N_2O emissions, forest fires were the largest source from LULUCF in 2020, totaling 11.7 MMT CO_2 Eq. (39 kt of N_2O). Nitrous oxide emissions from fertilizer application to settlement soils in 2020 totaled to 2.5 MMT CO_2 Eq. (8 kt of N_2O). This represents an increase of 23.2 percent since 1990. Additionally, the application of synthetic fertilizers to forest soils in 2020 resulted in N_2O emissions of 0.5 MMT CO_2 Eq. (2 kt of N_2O). Nitrous oxide emissions from fertilizer application to forest soils have increased by 455.1 percent since 1990, but still account for a relatively small portion of overall emissions. Grassland fires resulted in N_2O emissions of 0.3 MMT CO_2 Eq. (1 kt of N_2O). *Coastal Wetlands Remaining Coastal Wetlands* resulted in N_2O emissions of 0.2 MMT CO_2 Eq. (1 kt of N_2O). Drained Organic Soils on forest lands resulted in N_2O emissions of 0.1 MMT CO_2 Eq. (less than 0.5 kt of N_2O), and Peatlands Remaining Peatlands resulted in N_2O emissions of less than 0.05 MMT CO_2 Eq.

Table 6-2: Emissions and Removals from Land Use, Land-Use Change, and Forestry by Gas (MMT CO_2 Eq.)

Gas/Land-Use Category	1990	2005	2016	2017	2018	2019	2020
Carbon Stock Change (CO_2)[a]	**(892.0)**	**(831.1)**	**(862.0)**	**(826.7)**	**(809.0)**	**(760.8)**	**(812.2)**
Forest Land Remaining Forest Land	(774.0)	(687.3)	(725.6)	(688.3)	(677.1)	(634.8)	(668.1)
Land Converted to Forest Land	(98.6)	(99.1)	(99.5)	(99.5)	(99.5)	(99.5)	(99.5)
Cropland Remaining Cropland	(23.2)	(29.0)	(22.7)	(22.3)	(16.6)	(14.5)	(23.3)
Land Converted to Cropland	51.8	52.0	54.1	54.3	54.0	53.9	54.4
Grassland Remaining Grassland	6.9	8.7	8.0	9.3	9.7	12.4	4.5
Land Converted to Grassland	(3.1)	(37.0)	(22.6)	(22.7)	(22.4)	(21.5)	(24.1)
Wetlands Remaining Wetlands	(7.4)	(6.5)	(8.0)	(8.0)	(8.0)	(8.0)	(8.1)
Land Converted to Wetlands	4.3	0.8	0.3	0.3	0.3	0.3	0.3
Settlements Remaining Settlements	(109.6)	(116.6)	(123.8)	(127.7)	(127.3)	(127.0)	(126.1)
Land Converted to Settlements	60.8	82.8	77.8	77.9	78.0	77.9	77.9
CH_4	**27.2**	**30.9**	**28.3**	**34.0**	**30.7**	**25.5**	**38.1**
Forest Land Remaining Forest Land:	2.3	6.5	3.9	9.5	6.2	1.1	13.6

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[4] Carbon sequestration estimates are net figures. The C stock in a given pool fluctuates due to both gains and losses. When losses exceed gains, the C stock decreases, and the pool acts as a source. When gains exceed losses, the C stock increases, and the pool acts as a sink; also referred to as net C sequestration or removal.

Forest Fires[b]							
Forest Land Remaining Forest Land: Drained Organic Soils[d]	+	+	+	+	+	+	+
Grassland Remaining Grassland: Grassland Fires[c]	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Wetlands Remaining Wetlands: Flooded Land Remaining Flooded Land	18.2	19.8	19.9	19.9	19.9	19.9	19.9
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	3.7	3.8	3.8	3.8	3.8	3.8	3.8
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Land Converted to Wetlands: Land Converted to Flooded Lands	2.6	0.2	0.2	0.2	0.2	0.2	0.2
Land Converted to Wetlands: Land Converted to Coastal Wetlands	0.2	0.2	0.2	0.2	0.2	0.2	0.2
N_2O	**4.2**	**10.5**	**7.1**	**11.5**	**9.1**	**4.8**	**15.2**
Forest Land Remaining Forest Land: Forest Fires[b]	1.8	6.3	3.9	8.2	5.7	1.3	11.7
Forest Land Remaining Forest Land: Forest Soils[f]	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Forest Land Remaining Forest Land: Drained Organic Soils[d]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Grassland Remaining Grassland: Grassland Fires[c]	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.2	0.2	0.2
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Settlements Remaining Settlements: Settlement Soils[e]	2.0	3.1	2.2	2.3	2.4	2.4	2.5
LULUCF Carbon Stock Change[a]	**(892.0)**	**(831.1)**	**(862.0)**	**(826.7)**	**(809.0)**	**(760.8)**	**(812.2)**
LULUCF Emissions[g]	**31.4**	**41.3**	**35.4**	**45.5**	**39.8**	**30.3**	**53.2**
LULUCF Sector Net Total[h]	**(860.6)**	**(789.8)**	**(826.6)**	**(781.2)**	**(769.3)**	**(730.5)**	**(758.9)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland,* Land Converted to Cropland, Grassland Remaining Grassland, *Land Converted to Grassland, Wetlands Remaining Wetlands*, Land Converted to Wetlands, *Settlements Remaining Settlements,* and Land Converted to Settlements.

[b] Estimates include CH_4 and N_2O emissions from fires on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[c] Estimates include CH_4 and N_2O emissions from drained organic soils on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[d] Estimates include CH_4 and N_2O emissions from fires on both Grassland Remaining Grassland and *Land Converted to Grassland*.

[e] Estimates include N_2O emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[f] Estimates include N_2O emissions from N fertilizer additions on both *Settlements Remaining Settlements* and Land Converted to Settlements.

[g] LULUCF emissions include the CH_4 and N_2O emissions reported for Peatlands Remaining Peatlands, Forest Fires, Drained Organic Soils, Grassland Fires, and *Coastal Wetlands Remaining Coastal Wetlands*; CH_4 emissions from Flooded Land Remaining Flooded Land, Land Converted to Flooded Land, and *Land Converted to Coastal Wetlands*; and N_2O emissions from Forest Soils and Settlement Soils.

[h] The LULUCF Sector Net Total is the net sum of all LULUCF CH_4 and N_2O emissions to the atmosphere plus net carbon stock changes in units of MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-3: Emissions and Removals from Land Use, Land-Use Change, and Forestry by Gas (kt)

Gas/Land-Use Category	1990	2005	2016	2017	2018	2019	2020
Carbon Stock Change (CO_2)[a]	**(892,027)**	**(831,126)**	**(862,045)**	**(826,667)**	**(809,026)**	**(760,820)**	**(812,176)**
Forest Land Remaining Forest Land	(773,993)	(687,271)	(725,571)	(688,301)	(677,101)	(634,824)	(668,057)
Land Converted to Forest Land	(98,585)	(99,068)	(99,454)	(99,523)	(99,518)	(99,520)	(99,521)
Cropland Remaining Cropland	(23,176)	(29,002)	(22,731)	(22,293)	(16,597)	(14,544)	(23,335)
Land Converted to Cropland	51,784	52,032	54,107	54,273	53,975	53,935	54,380
Grassland Remaining Grassland	6,940	8,734	7,958	9,308	9,670	12,425	4,497
Land Converted to Grassland	(3,141)	(36,951)	(22,553)	(22,693)	(22,397)	(21,485)	(24,101)
Wetlands Remaining Wetlands	(7,399)	(6,549)	(8,046)	(7,954)	(7,994)	(8,034)	(8,084)
Land Converted to Wetlands	4,329	807	254	258	265	271	279
Settlements Remaining Settlements	(109,567)	(116,642)	(123,794)	(127,679)	(127,299)	(126,977)	(126,128)
Land Converted to Settlements	60,793	82,784	77,784	77,938	77,970	77,932	77,895
CH_4	**1,088**	**1,235**	**1,131**	**1,359**	**1,226**	**1,022**	**1,522**
Forest Land Remaining Forest Land: Forest Fires[b]	92	260	154	381	249	45	545
Forest Land Remaining Forest Land: Drained Organic Soils[d]	1	1	1	1	1	1	1
Grassland Remaining Grassland: Grassland Fires[c]	3	13	11	12	12	12	12
Wetlands Remaining Wetlands: Flooded Land Remaining Flooded Land	729	792	797	797	797	797	797
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	149	151	153	153	153	153	154
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Land Converted to Wetlands: Land Converted to Flooded Lands	103	9	7	7	7	7	7
Land Converted to Wetlands: Land Converted to Coastal Wetlands	10	10	8	8	7	7	7
N_2O	**14**	**35**	**24**	**39**	**31**	**16**	**51**
Forest Land Remaining Forest Land: Forest Fires[b]	6	21	13	27	19	4	39
Forest Land Remaining Forest Land: Forest Soils[f]	+	2	2	2	2	2	2
Forest Land Remaining Forest Land: Drained Organic Soils[d]	+	+	+	+	+	+	+
Grassland Remaining Grassland: Grassland Fires[c]	+	1	1	1	1	1	1
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	+	1	+	+	1	1	1
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Settlements Remaining Settlements: Settlement Soils[e]	7	10	8	8	8	8	8

+ Absolute value does not exceed 0.5 kt.

[a] LULUCF Carbon Stock Change is the net C stock change from the following categories: *Forest Land Remaining Forest Land, Land Converted to Forest Land, Cropland Remaining Cropland,* Land Converted to Cropland, Grassland Remaining Grassland, *Land Converted to Grassland, Wetlands Remaining Wetlands*, Land Converted to Wetlands, *Settlements Remaining Settlements,* and Land Converted to Settlements.

[b] Estimates include CH_4 and N_2O emissions from fires on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[c] Estimates include CH_4 and N_2O emissions from drained organic soils on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[d] Estimates include CH_4 and N_2O emissions from fires on both Grassland Remaining Grassland and *Land Converted to Grassland*.

[e] Estimates include N_2O emissions from N fertilizer additions on both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[f] Estimates include N_2O emissions from N fertilizer additions on both *Settlements Remaining Settlements* and Land Converted to Settlements.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Each year, some emission and sink estimates in the LULUCF sector of the Inventory are recalculated and revised with improved methods and/or data. In general, recalculations are made to the U.S. greenhouse gas emissions and sinks estimates either to incorporate new methodologies or, most commonly, to update recent historical data. These improvements are implemented consistently across the previous Inventory's time series (i.e., 1990 to 2019) to ensure that the trend is accurate. Of the updates implemented for this Inventory, the most significant include (1) Flooded Land Remaining Flooded Land and Land Converted to Flooded Land: new categories included for the first time based on new guidance in the *2019 Refinement to the 2006 IPCC Guidelines for National GHG Inventories*, (2) Forest Lands: use of new data from the National Forest Inventory (NFI), compiling population estimates of carbon stocks and stock changes using NFI data from each U.S. state and summing over all states to obtain the national estimates, refined estimates in the Digital General Soil Map, and new data on area burned from the Monitoring Trends in Burn Severity (MTBS) data product; and (3) Coastal Wetlands: an updated NOAA report on fisheries data was released in 2021 and was used in estimating N_2O emissions from aquaculture. Together, these updates for 2019 decreased total sequestration of CO_2 by 51.6 MMT CO_2 Eq. (5.7 percent) and decreased total non-CO_2 emissions by 16.2 MMT CO_2 Eq. (81.5 percent), compared to the previous Inventory (i.e., 1990 to 2019). For more information on specific methodological updates, please see the Recalculations discussion within the respective source category section of this chapter.

Emissions and removals reported in the LULUCF chapter include those from all states, however, for Hawaii and Alaska some emissions and removals from land use and land use change are not included (see chapter sections on Uncertainty and Planned Improvements for more details). In addition, U.S. Territories are not included. EPA continues to review available data on an ongoing basis to include emissions and removals from U.S. Territories in future inventories to the extent they are occurring (e.g., see Box 6-2). See Annex 5 for more information on EPA's assessment of the emissions and removals not included in this Inventory.

Box 6-1: Methodological Approach for Estimating and Reporting U.S. Emissions and Removals

In following the United Nations Framework Convention on Climate Change (UNFCCC) requirement under Article 4.1 to develop and submit national greenhouse gas emission inventories, the gross emissions total presented in this report for the United States excludes emissions and removals from LULUCF. The LULUCF Sector Net Total presented in this report for the United States includes emissions and removals from LULUCF. All emissions and removals estimates are calculated using internationally accepted methods provided by the IPCC in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006 IPCC Guidelines), 2013 Supplement to the 2006 IPCC Guidelines for National GHG Inventories: Wetlands,* and the *2019 Refinement to the 2006 IPCC Guidelines for National GHG Inventories*. Additionally, the calculated emissions and removals in a given year for the United States are presented in a common manner in line with the UNFCCC reporting guidelines for the reporting of inventories under this international agreement.[5] The use of consistent methods to calculate emissions and removals by all nations providing their inventories to the UNFCCC ensures that these reports are comparable. The presentation of emissions and removals provided in the Land Use Land-Use Change and Forestry chapter does not preclude alternative examinations, but rather, this Chapter presents emissions and removals in a common format consistent with how countries are to report Inventories under the UNFCCC. The report itself,

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[5] See http://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf.

and this chapter, follows this standardized format, and provides an explanation of the application of methods used to calculate emissions and removals.

6.1 Representation of the U.S. Land Base

A national land-use representation system that is consistent and complete, both temporally and spatially, is needed in order to assess land use and land-use change status and the associated greenhouse gas fluxes over the Inventory time series. This system should be consistent with IPCC (2006), such that all countries reporting on national greenhouse gas fluxes to the UNFCCC should: (1) describe the methods and definitions used to determine areas of managed and unmanaged lands in the country (Table 6-4), (2) describe and apply a consistent set of definitions for land-use categories over the entire national land base and time series (i.e., such that increases in the land areas within particular land-use categories are balanced by decreases in the land areas of other categories unless the national land base is changing) (Table 6-5), and (3) account for greenhouse gas fluxes on all managed lands. The IPCC (2006, Vol. IV, Chapter 1) considers all anthropogenic greenhouse gas emissions and removals associated with land use and management to occur on managed land, and all emissions and removals on managed land should be reported based on this guidance (See IPCC (2010), Ogle et al. (2018) for further discussion). Consequently, managed land serves as a proxy for anthropogenic emissions and removals. This proxy is intended to provide a practical framework for conducting an inventory, even though some of the greenhouse gas emissions and removals on managed land are influenced by natural processes that may or may not be interacting with the anthropogenic drivers. Guidelines for factoring out natural emissions and removals may be developed in the future, but currently the managed land proxy is considered the most practical approach for conducting an inventory in this sector (IPCC 2010). This section of the Inventory has been developed in order to comply with this guidance.

Three databases are used to track land management in the United States and are used as the basis to classify United States land area into the thirty-six IPCC land-use and land-use change categories (Table 6-5) (IPCC 2006). The three primary databases are the U.S. Department of Agriculture (USDA) National Resources Inventory (NRI),[6] the USDA Forest Service (USFS) Forest Inventory and Analysis (FIA)[7] Database, and the Multi-Resolution Land Characteristics Consortium (MRLC) National Land Cover Dataset (NLCD).[8]

The total land area included in the United States Inventory is 936 million hectares across the 50 states.[9] Approximately 886 million hectares of this land base is considered managed and 50 million hectares is unmanaged, which has not changed much over the time series of the Inventory (Table 6-5). In 2020, the United States had a total of 282 million hectares of managed Forest Land (0.03 percent decrease compared to 1990). There are 162 million hectares of cropland (7.2 percent decrease compared to 1990), 337 million hectares of managed Grassland (0.01 percent increase compared to 1990), 39 million hectares of managed Wetlands (1.8 percent increase compared to 1990), 45 million hectares of Settlements (34 percent increase compared to 1990), and 22 million hectares of managed Other Land (2.4 percent increase compared to 1990) (Table 6-5).

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[6] NRI data are available at https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/.

[7] FIA data are available at http://www.fia.fs.fed.us/tools-data/default.asp.

[8] NLCD data are available at http://www.mrlc.gov/ and MRLC is a consortium of several U.S. government agencies.

[9] The current land representation does not include areas from U.S. Territories, but there are planned improvements to include these regions in future Inventories. U.S. Territories represent approximately 0.1 percent of the total land base for the United States. See Box 6-2.

Wetlands are not differentiated between managed and unmanaged with the exception of remote areas in Alaska, and so are reported mostly as managed.[10] In addition, C stock changes are not currently estimated for the entire managed land base, which leads to discrepancies between the managed land area data presented here and in the subsequent sections of the Inventory (e.g., Grassland Remaining Grassland within interior Alaska).[11,12] There are also discrepancies in the inventory emissions data and the land representation section because new FIA data were used in the inventory analysis, but were not incorporated into the land representation analysis due to timing of data availability and resources to complete the analysis. The land representation analysis will incorporate the new time series of FIA data int the next Inventory. In addition, planned improvements are under development to estimate C stock changes and greenhouse gas emissions on all managed land and ensure consistency between the total area of managed land in the land-representation description and the remainder of the Inventory.

Dominant land uses vary by region, largely due to climate patterns, soil types, geology, proximity to coastal regions, and historical settlement patterns (Figure 6-3). Forest Land tends to be more common in the eastern United States, mountainous regions of the western United States, and Alaska. Cropland is concentrated in the mid-continent region of the United States, and Grassland is more common in the western United States and Alaska. Wetlands are fairly ubiquitous throughout the United States, though they are more common in the upper Midwest and eastern portions of the country, as well as coastal regions. Settlements are more concentrated along the coastal margins and in the eastern states.

Table 6-4: Managed and Unmanaged Land Area by Land-Use Categories for All 50 States (Thousands of Hectares)

Land Use Categories	1990	2005	2016	2017	2018	2019[a]	2020[a]
Managed Lands	**886,515**	**886,513**	**886,513**	**886,513**	**886,513**	**886,513**	**886,513**
Forest	281,621	281,681	281,796	281,652	281,546	281,546	281,546
Croplands	174,471	165,727	161,933	161,933	161,933	161,933	161,933
Grasslands	336,840	337,621	336,657	336,781	336,863	336,863	336,863
Settlements	33,446	40,469	44,795	44,797	44,797	44,797	44,797
Wetlands	38,422	39,017	39,089	39,108	39,132	39,132	39,132
Other	21,715	21,997	22,243	22,243	22,243	22,243	22,243
Unmanaged Lands	**49,681**	**49,684**	**49,683**	**49,683**	**49,683**	**49,683**	**49,683**
Forest	9,243	8,829	8,208	8,208	8,208	8,208	8,208
Croplands	0	0	0	0	0	0	0
Grasslands	25,530	25,962	26,608	26,608	26,608	26,608	26,608
Settlements	0	0	0	0	0	0	0
Wetlands	4,166	4,166	4,165	4,165	4,165	4,165	4,165
Other	10,742	10,727	10,701	10,701	10,701	10,701	10,701
Total Land Areas	**936,196**	**936,196**	**936,196**	**936,196**	**936,196**	**936,196**	**936,196**
Forest	290,864	290,510	290,004	289,860	289,754	289,754	289,754
Croplands	174,471	165,727	161,933	161,933	161,933	161,933	161,933
Grasslands	362,370	363,583	363,266	363,389	363,471	363,471	363,471
Settlements	33,446	40,469	44,795	44,797	44,797	44,797	44,797
Wetlands	42,589	43,183	43,254	43,273	43,297	43,297	43,297
Other	32,457	32,725	32,944	32,944	32,944	32,944	32,944

[a] Land use data were not updated in this Inventory and the data for 2019 and 2020 were assumed to be the same as in 2018.

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[10] According to the IPCC (2006), wetlands are considered managed if they are created through human activity, such as dam construction, or the water level is artificially altered by human activity. Distinguishing between managed and unmanaged wetlands in the conterminous United States and Alaska is difficult due to limited data availability. Wetlands are not characterized within the NRI with information regarding water table management. As a result, all Wetlands in the conterminous United States and Hawaii are reported as managed. See the Planned Improvements section of the Inventory for future refinements to the Wetland area estimates.

[11] Other discrepancies occur because the coastal wetlands analysis is based on another land use product (NOAA C-CAP) that is not currently incorporated into the land representation analysis for this section, which relies on the NRI and NLCD for wetland areas. EPA anticipates addressing these discrepancies in the next Inventory.

[12] These “managed area” discrepancies also occur in the Common Reporting Format (CRF) tables submitted to the UNFCCC.

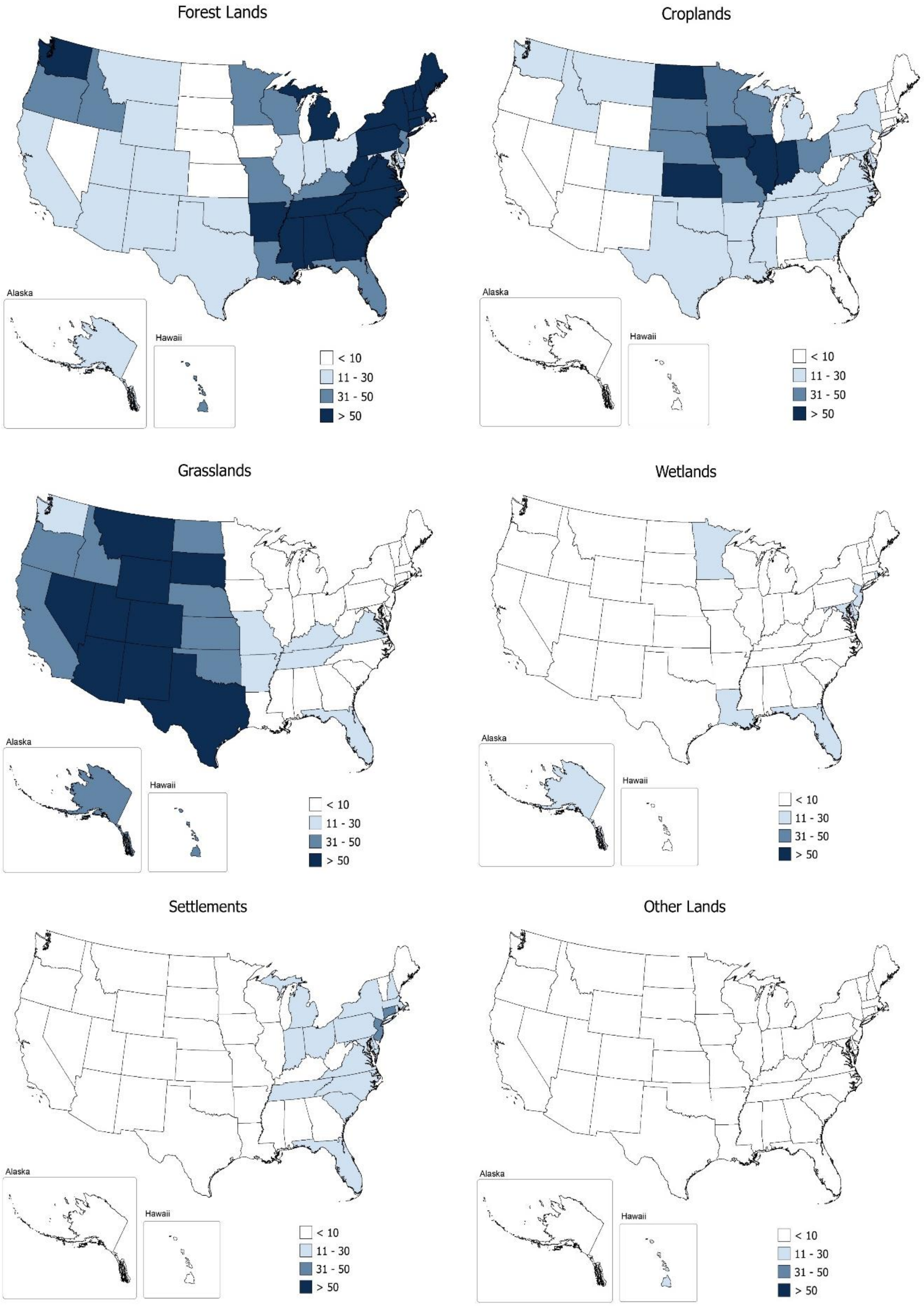
Table 6-5: Land Use and Land-Use Change for the U.S. Managed Land Base for All 50 States (Thousands of Hectares)

Land Use & Land-Use Change Categories[a]	1990	2005	2016	2017	2018	2019	2020
Total Forest Land	**281,621**	**281,681**	**281,796**	**281,652**	**281,546**	**281,546**	**281,546**
FF	280,393	280,207	280,529	280,380	280,274	280,274	280,274
CF	169	167	134	135	135	135	135
GF	919	1,162	989	992	992	992	992
WF	77	28	25	25	25	25	25
SF	12	24	26	26	26	26	26
OF	50	93	93	93	93	93	93
Total Cropland	**174,471**	**165,727**	**161,933**	**161,933**	**161,933**	**161,933**	**161,933**
CC	162,163	150,304	148,885	148,884	148,884	148,884	148,884
FC	182	86	58	58	58	58	58
GC	11,738	14,820	12,609	12,609	12,609	12,609	12,609
WC	118	178	104	104	104	104	104
SC	75	100	99	99	99	99	99
OC	195	239	179	179	179	179	179
Total Grassland	**336,840**	**337,621**	**336,657**	**336,781**	**336,863**	**336,863**	**336,863**
GG	327,446	315,161	316,408	316,502	316,622	316,622	316,622
FG	593	560	553	583	545	545	545
CG	8,237	17,523	16,600	16,600	16,600	16,600	16,600
WG	176	542	308	308	308	308	308
SG	43	509	346	346	346	346	346
OG	345	3,328	2,442	2,442	2,442	2,442	2,442
Total Wetlands	**38,422**	**39,017**	**39,089**	**39,108**	**39,132**	**39,132**	**39,132**
WW	37,860	37,035	37,616	37,634	37,658	37,658	37,658
FW	83	59	54	54	54	54	54
CW	132	566	440	440	440	440	440
GW	297	1,187	836	836	836	836	836
SW	0	38	25	25	25	25	25
OW	50	133	118	118	118	118	118
Total Settlements	**33,446**	**40,469**	**44,795**	**44,797**	**44,797**	**44,797**	**44,797**
SS	30,585	31,522	38,210	38,210	38,210	38,210	38,210
FS	310	549	539	541	541	541	541
CS	1,237	3,602	2,452	2,452	2,452	2,452	2,452
GS	1,255	4,499	3,352	3,352	3,352	3,352	3,352
WS	4	61	46	46	46	46	46
OS	54	235	197	197	197	197	197
Total Other Land	**21,715**	**21,997**	**22,243**	**22,243**	**22,243**	**22,243**	**22,243**
OO	20,953	18,231	19,007	19,007	19,007	19,007	19,007
FO	41	70	90	90	90	90	90
CO	301	590	678	678	678	678	678
GO	391	2,965	2,331	2,331	2,331	2,331	2,331
WO	26	121	121	121	121	121	121
SO	2	20	16	16	16	16	16
Grand Total	**886,515**	**886,513**	**886,513**	**886,513**	**886,513**	**886,513**	**886,513**

[a] The abbreviations are "F" for Forest Land, "C" for Cropland, "G" for Grassland, "W" for Wetlands, "S" for Settlements, and "O" for Other Lands. Lands remaining in the same land-use category are identified with the land-use abbreviation given twice (e.g., "FF" is Forest Land Remaining Forest Land), and land-use change categories are identified with the previous land use abbreviation followed by the new land-use abbreviation (e.g., "CF" is Cropland Converted to Forest Land).

Notes: All land areas reported in this table are considered managed. A planned improvement is underway to deal with an exception for Wetlands, which based on the definitions for the current U.S. Land Representation assessment includes both managed and unmanaged lands. U.S. Territories have not been classified into land uses and are not included in the U.S. Land Representation Assessment. See the Planned Improvements section for discussion on plans to include territories in future Inventories. In addition, C stock changes are not currently estimated for the entire land base, which leads to discrepancies between the managed land area data presented here and in the subsequent sections of the Inventory (see land use chapters e.g., Forest Land Remaining Forest Land for more information). Totals may not sum due to independent rounding.

Figure 6-3: Percent of Total Land Area for Each State in the General Land Use Categories for 2020



Methodology and Time-Series Consistency

IPCC Approaches for Representing Land Areas

IPCC (2006) describes three approaches for representing land areas. Approach 1 provides data on the total area for each individual land-use category, but does not provide detailed information on changes of area between categories and is not spatially explicit other than at the national or regional level. With Approach 1, total net conversions between categories can be detected, but not the individual changes (i.e., additions and/or losses) between the land-use categories that led to those net changes. Approach 2 introduces tracking of individual land-use changes between the categories (e.g., Forest Land to Cropland, Cropland to Forest Land, and Grassland to Cropland), using survey samples or other forms of data, but does not provide spatially-explicit location data. Approach 3 extends Approach 2 by providing spatially-explicit location data, such as surveys with spatially identified sample locations and maps derived from remote sensing products. The three approaches are not presented as hierarchical tiers and are not mutually exclusive.

According to IPCC (2006), the approach or mix of approaches selected by an inventory agency should reflect calculation needs and national circumstances. For this analysis, the NRI, FIA, and the NLCD have been combined to provide a complete representation of land use for managed lands. These data sources are described in more detail later in this section. NRI, FIA and NLCD are Approach 3 data sources that provide spatially-explicit representations of land use and land-use conversions. Lands are treated as remaining in the same category (e.g., *Cropland Remaining Cropland*) if a land-use change has not occurred in the last 20 years. Otherwise, the land is classified in a land-use change category based on the current use and most recent use before conversion to the current use (e.g., *Cropland Converted to Forest Land*).

Definitions of Land Use in the United States

Managed and Unmanaged Land

The United States definition of managed land is similar to the general definition of managed land provided by the IPCC (2006), but with some additional elaboration to reflect national circumstances. Based on the following definitions, most lands in the United States are classified as managed:

- *Managed Land*: Land is considered managed if direct human intervention has influenced its condition. Direct intervention occurs mostly in areas accessible to human activity and includes altering or maintaining the condition of the land to produce commercial or non-commercial products or services; to serve as transportation corridors or locations for buildings, landfills, or other developed areas for commercial or non-commercial 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.[13]
- *Unmanaged Land*: All other land is considered unmanaged. Unmanaged land is largely comprised of areas inaccessible to society due to the remoteness of the locations. Though these lands may be influenced

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[13] Wetlands are an exception to this general definition, because these lands, as specified by IPCC (2006), are only considered managed if they are created through human activity, such as dam construction, or the water level is artificially altered by human activity. Distinguishing between managed and unmanaged wetlands in the United States is difficult due to limited data availability. Wetlands are not characterized within the NRI with information regarding water table management or origin (i.e., constructed rather than natural origin). Therefore, unless wetlands are converted into cropland or grassland, it is not possible to know if they are artificially created or if the water table is managed based on the use of NRI data. As a result, most wetlands are reported as managed with the exception of wetlands in remote areas of Alaska, but emissions from managed wetlands are only reported for coastal regions and peatlands due to insufficient activity data to estimate emissions and limited resources to improve the inventory. See the Planned Improvements section of the Inventory for future refinements to the wetland area estimates.

indirectly by human actions such as atmospheric deposition of chemical species produced in industry or CO_2 fertilization, they are not influenced by a direct human intervention.[14]

In addition, land that is previously managed remains in the managed land base for 20 years before re-classifying the land as unmanaged in order to account for legacy effects of management on C stocks. Unmanaged land is also re-classified as managed over time if anthropogenic activity is introduced into the area based on the definition of managed land.

Land-Use Categories

As with the definition of managed lands, IPCC (2006) provides general non-prescriptive definitions for the six main land-use categories: Forest Land, Cropland, Grassland, Wetlands, Settlements and Other Land. In order to reflect national circumstances, country-specific definitions have been developed, based predominantly on criteria used in the land-use surveys for the United States. Specifically, the definition of Forest Land is based on the FIA definition of forest,[15] while definitions of Cropland, Grassland, and Settlements are based on the NRI.[16] The definitions for Other Land and Wetlands are based on the IPCC (2006) definitions for these categories.

- *Forest Land*: A land-use category that includes areas at least 120 feet (36.6 meters) wide and at least one acre (0.4 hectare) in size with at least 10 percent cover (or equivalent stocking) by live trees including land that formerly had such tree cover and that will be naturally or artificially regenerated. Trees are woody plants having a more or less erect perennial stem(s) capable of achieving at least 3 inches (7.6 cm) in diameter at breast height, or 5 inches (12.7 cm) diameter at root collar, and a height of 16.4 feet (5 m) at maturity in situ. Forest Land includes all areas recently having such conditions and currently regenerating or capable of attaining such condition in the near future. Forest Land also includes transition zones, such as areas between forest and non-forest lands that have at least 10 percent cover (or equivalent stocking) with live trees and forest areas adjacent to urban and built-up lands. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if they are less than 120 feet (36.6 m) wide or an acre (0.4 ha) in size. However, land is not classified as Forest Land if completely surrounded by urban or developed lands, even if the criteria are consistent with the tree area and cover requirements for Forest Land. These areas are classified as Settlements. In addition, Forest Land does not include land that is predominantly under an agricultural land use (Oswalt et al. 2014).
- *Cropland*: A land-use category that includes areas used for the production of adapted crops for harvest; this category includes both cultivated and non-cultivated lands. Cultivated crops include row crops or close-grown crops and also pasture in rotation with cultivated crops. Non-cultivated cropland includes continuous hay, perennial crops (e.g., orchards) and horticultural cropland. Cropland also includes land with agroforestry, such as alley cropping and windbreaks,[17] if the dominant use is crop production, assuming the stand or woodlot does not meet the criteria for Forest Land. Lands in temporary fallow or enrolled in conservation reserve programs (i.e., set-asides[18]) are also classified as Cropland, as long as these areas do not meet the Forest Land criteria. Roads through Cropland, including interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads are excluded from Cropland area estimates and are, instead, classified as Settlements.
- *Grassland*: A land-use category on which the plant cover is composed principally of grasses, grass-like plants (i.e., sedges and rushes), forbs, or shrubs suitable for grazing and browsing, and includes both

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[14] There are some areas, such as Forest Land and Grassland in Alaska that are classified as unmanaged land due to the remoteness of their location.

[15] See http://www.fia.fs.fed.us/library/field-guides-methods-proc/docs/2015/Core-FIA-FG-7.pdf, page 22.

[16] See https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/.

[17] Currently, there is no data source to account for biomass C stock change associated with woody plant growth and losses in alley cropping systems and windbreaks in cropping systems, although these areas are included in the Cropland land base.

[18] A set-aside is cropland that has been taken out of active cropping and converted to some type of vegetative cover, including, for example, native grasses or trees, but is still classified as cropland based on national circumstances.

pastures and native rangelands. This includes areas where practices such as clearing, burning, chaining, and/or chemicals are applied to maintain the grass vegetation. Land is also categorized as Grassland if there have been three or fewer years of continuous hay production.[19] Savannas, deserts, and tundra are considered Grassland.[20] Drained wetlands are considered Grassland if the dominant vegetation meets the plant cover criteria for Grassland. Woody plant communities of low forbs, shrubs and woodlands, such as sagebrush, mesquite, chaparral, mountain shrubland, and pinyon-juniper, are also classified as Grassland if they do not meet the criteria for Forest Land. Grassland includes land managed with agroforestry practices, such as silvopasture and windbreaks, if the land is principally grass, grass-like plants, forbs, and shrubs suitable for grazing and browsing, and assuming the stand or woodlot does not meet the criteria for Forest Land. Roads through Grassland, including interstate highways, state highways, other paved roads, gravel roads, dirt roads, and railroads are excluded from Grassland and are, instead, classified as Settlements.

- *Wetlands*: A land-use category that includes land covered or saturated by water for all or part of the year, in addition to lakes, reservoirs, and rivers. Managed Wetlands are those where the water level is artificially changed, or were created by human activity. Certain areas that fall under the managed Wetlands definition are included in other land uses based on the IPCC guidance and national circumstances, including lands that are flooded for most or just part of the year in Croplands (e.g., rice cultivation and cranberry production), Grasslands (e.g., wet meadows dominated by grass cover) and Forest Lands (e.g., Riparian Forests near waterways).
- *Settlements*: A land-use category representing developed areas consisting of units equal to or greater than 0.25 acres (0.1 ha) that includes residential, industrial, commercial, and institutional land; construction sites; public administrative sites; railroad yards; cemeteries; airports; golf courses; sanitary landfills; sewage treatment plants; water control structures and spillways; parks within urban and built-up areas; and highways, railroads, and other transportation facilities. Also included are all tracts that may meet the definition of Forest Land, and tracts of less than 10 acres (4.05 ha) that may meet the definitions for Cropland, Grassland, or Other Land but are completely surrounded by urban or built-up land, and so are included in the Settlements category. Rural transportation corridors located within other land uses (e.g., Forest Land, Cropland, and Grassland) are also included in Settlements.
- *Other Land*: A land-use category that includes bare soil, rock, ice, and all land areas that do not fall into any of the other five land-use categories. Following the guidance provided by the IPCC (2006), C stock changes and non-CO_2 emissions are not estimated for Other Lands because these areas are largely devoid of biomass, litter and soil C pools. However, C stock changes and non-CO_2 emissions are estimated for *Land Converted to Other Land* during the first 20 years following conversion to account for legacy effects.

Land-Use Data Sources: Description and Application to U.S. Land Area Classification

U.S. Land-Use Data Sources

The three main sources for land-use data in the United States are the NRI, FIA, and the NLCD (Table 6-6). These data sources are combined to account for land use in all 50 states. FIA and NRI data are used when available for an area because these surveys contain additional information on management, site conditions, crop types, biometric measurements, and other data that are needed to estimate C stock changes, N_2O, and CH_4 emissions on those

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[19] Areas with four or more years of continuous hay production are Cropland because the land is typically more intensively managed with cultivation, greater amounts of inputs, and other practices. Occasional harvest of hay from grasslands typically does not involve cultivation or other intensive management practices.

[20] *2006 IPCC Guidelines* do not include provisions to separate desert and tundra as land-use categories.

lands. If NRI and FIA data are not available for an area, however, then the NLCD product is used to represent the land use.

Table 6-6: Data Sources Used to Determine Land Use and Land Area for the Conterminous United States, Hawaii, and Alaska

		NRI	FIA	NLCD
Forest Land				
Conterminous United States				
	Non-Federal		•	
	Federal		•	
Hawaii				
	Non-Federal	•		
	Federal			•
Alaska				
	Non-Federal		•	•
	Federal		•	•
Croplands, Grasslands, Other Lands, Settlements, and Wetlands				
Conterminous United States				
	Non-Federal	•		
	Federal			•
Hawaii				
	Non-Federal	•		
	Federal			•
Alaska				
	Non-Federal			•
	Federal			•

National Resources Inventory

For the Inventory, the NRI is the official source of data for land use and land use change on non-federal lands in the conterminous United States and Hawaii, and is also used to determine the total land base for the conterminous United States and Hawaii. The NRI is a statistically-based survey conducted by the USDA Natural Resources Conservation Service and is designed to assess soil, water, and related environmental resources on non-federal lands. The NRI has a stratified multi-stage sampling design, where primary sample units are stratified on the basis of county and township boundaries defined by the United States Public Land Survey (Nusser and Goebel 1997). Within a primary sample unit (typically a 160 acre [64.75 ha] square quarter-section), three sample points are selected according to a restricted randomization procedure. Each point in the survey is assigned an area weight (expansion factor) based on other known areas and land-use information (Nusser and Goebel 1997). The NRI survey utilizes data derived from remote sensing imagery and site visits in order to provide detailed information on land use and management, particularly for Croplands and Grasslands (i.e., agricultural lands), and is used as the basis to account for C stock changes in agricultural lands (except federal Grasslands). The NRI survey was conducted every 5 years between 1982 and 1997, but shifted to annualized data collection in 1998. The land use between five-year periods from 1982 and 1997 are assumed to be the same for a five-year time period if the land use is the same at the beginning and end of the five-year period (Note: most of the data has the same land use at the beginning and end of the five-year periods). If the land use had changed during a five-year period, then the change is assigned at random to one of the five years. For crop histories, years with missing data are estimated based on the sequence of crops grown during years preceding and succeeding a missing year in the NRI history. This gap-filling approach allows for development of a full time series of land-use data for non-federal lands in the conterminous United States and Hawaii. This Inventory incorporates data through 2015 from the NRI. The land use patterns are assumed to remain the same from 2016 through 2020 for this Inventory, but the time series will be updated when new data are integrated into the land representation analysis.

Forest Inventory and Analysis

The FIA program, conducted by the USFS, is the official source of data on Forest Land area and management data for the Inventory and is another statistically-based survey for the conterminous United States in addition to the including southeast and south-central coastal Alaska. FIA engages in a hierarchical system of sampling, with sampling categorized as Phases 1 through 3, in which sample points for phases are subsets of the previous phase. Phase 1 refers to collection of remotely-sensed data (either aerial photographs or satellite imagery) primarily to classify land into forest or non-forest and to identify landscape patterns like fragmentation and urbanization. Phase 2 is the collection of field data on a network of ground plots that enable classification and summarization of area, tree, and other attributes associated with forest-land uses. Phase 3 plots are a subset of Phase 2 plots where data on indicators of forest health are measured. Data from all three phases are also used to estimate C stock changes for Forest Land. Historically, FIA inventory surveys have been conducted periodically, with all plots in a state being measured at a frequency of every five to 14 years. A new national plot design and annual sampling design was introduced by the FIA program in 1998 and is now used in all states. Annualized sampling means that a portion of plots throughout each state is sampled each year, with the goal of measuring all plots once every five to seven years in the eastern United States and once every ten years in the western United States. See Annex 3.13 to see the specific survey data available by state. The most recent year of available data varies state by state (range of most recent data is from 2015 through 2018; see Table A-202 in Annex 3.13).

National Land Cover Dataset

As noted above, while the NRI survey sample covers the conterminous United States and Hawaii, land use data are only collected on non-federal lands. In addition, FIA only records data for forest land across the land base in the conterminous United States and Alaska.[21] Consequently, gaps exist in the land representation when the datasets are combined, such as federal grassland operated by Bureau of Land Management (BLM), USDA, and National Park Service, as well as Alaska.[22] The NLCD is used to account for land use on federal lands in the conterminous United States and Hawaii, in addition to federal and non-federal lands in Alaska with the exception of Forest Lands in Alaska.

NLCD products provide land-cover for 1992, 2001, 2004, 2006, 2008, 2011, 2013, and 2016 in the conterminous United States (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015), and also for Alaska in 2001 and 2011 and Hawaii in 2001. A Land Cover Change Product is also available for Alaska from 2001 to 2011. A NLCD change product is not available for Hawaii because data are only available for one year, i.e., 2001. The NLCD products are based primarily on Landsat Thematic Mapper imagery at a 30-meter resolution, and the land cover categories have been aggregated into the 36 IPCC land-use categories for the conterminous United States and Alaska, and into the six IPCC land-use categories for Hawaii. The land use patterns are assumed to remain the same after the last year of data in the time series, which is 2001 for Hawaii, 2016 for the conterminous United States and 2011 for Alaska, but the time series will be updated when new data are released.

For the conterminous United States, the aggregated maps of IPCC land-use categories derived from the NLCD products were used in combination with the NRI database to represent land use and land-use change for federal lands, with the exception of forest lands, which are based on FIA. Specifically, NRI survey locations designated as federal lands were assigned a land use/land-use change category based on the NLCD maps that had been aggregated into the IPCC categories. This analysis addressed shifts in land ownership across years between federal or non-federal classes as represented in the NRI survey (i.e., the ownership is classified for each survey location in the NRI). The sources of these additional data are discussed in subsequent sections of the report.

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[21] FIA does collect some data on non-forest land use, but these are held in regional databases versus the national database. The status of these data is being investigated.

[22] The NRI survey program does not include U.S. Territories with the exception of non-federal lands in Puerto Rico. The FIA program recently began implementing surveys of forest land in U.S. Territories and those data will be used in the years ahead. Furthermore, NLCD does not include coverage for all U.S. Territories.

Managed Land Designation

Lands are designated as managed in the United States based on the definition provided earlier in this section. The following criteria are used in order to apply the definition in an analysis of managed land:

- All Croplands and Settlements are designated as managed so only Grassland, Forest Land, Wetlands or Other Lands may be designated as unmanaged land;[23]
- All Forest Lands with active fire protection are considered managed;
- All Forest Lands designated for timber harvests are considered managed;
- All Grasslands are considered managed at a county scale if there are grazing livestock in the county;
- Other areas are considered managed if accessible based on the proximity to roads and other transportation corridors, and/or infrastructure;
- Protected lands maintained for recreational and conservation purposes are considered managed (i.e., managed by public and/or private organizations);
- Lands with active and/or past resource extraction are considered managed; and
- Lands that were previously managed but subsequently classified as unmanaged, remain in the managed land base for 20 years following the conversion to account for legacy effects of management on C stocks.

The analysis of managed lands, based on the criteria listed above, is conducted using a geographic information system (Ogle et al. 2018). Lands that are used for crop production or settlements are determined from the NLCD (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015). Forest Lands with active fire management are determined from maps of federal and state management plans from the National Atlas (U.S. Department of Interior 2005) and Alaska Interagency Fire Management Council (1998). It is noteworthy that all forest lands in the conterminous United States have active fire protection, and are therefore designated as managed regardless of accessibility or other criteria. In addition, forest lands with timber harvests are designated as managed based on county-level estimates of timber products in the U.S. Forest Service Timber Products Output Reports (U.S. Department of Agriculture 2012). Timber harvest data do lead to additional designation of managed forest land in Alaska. The designation of grasslands as managed is based on grazing livestock population data at the county scale from the USDA National Agricultural Statistics Service (U.S. Department of Agriculture 2015). Accessibility is evaluated based on a 10-km buffer surrounding road and train transportation networks using the ESRI Data and Maps product (ESRI 2008), and a 10-km buffer surrounding settlements using NLCD.

Lands maintained for recreational purposes are determined from analysis of the Protected Areas Database (U.S. Geological Survey 2012). The Protected Areas Database includes lands protected from conversion of natural habitats to anthropogenic uses and describes the protection status of these lands. Lands are considered managed that are protected from development if the regulations allow for extractive or recreational uses or suppression of natural disturbance. Lands that are protected from development and not accessible to human intervention, including no suppression of disturbances or extraction of resources, are not included in the managed land base.

Multiple data sources are used to determine lands with active resource extraction: Alaska Oil and Gas Information System (Alaska Oil and Gas Conservation Commission 2009), Alaska Resource Data File (U.S. Geological Survey 2012), Active Mines and Mineral Processing Plants (U.S. Geological Survey 2005), and *Coal Production and Preparation Report* (U.S. Energy Information Administration 2011). A buffer of 3,300 and 4,000 meters is established around petroleum extraction and mine locations, respectively, to account for the footprint of operation and impacts of activities on the surrounding landscape. The buffer size is based on visual analysis of disturbance to the landscape for approximately 130 petroleum extraction sites and 223 mines. After applying the criteria identified above, the resulting managed land area is overlaid on the NLCD to estimate the area of managed land by land use for both federal and non-federal lands in Alaska. The remaining land represents the unmanaged

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[23] All wetlands are considered managed in this Inventory with the exception of remote areas in Alaska. Distinguishing between managed and unmanaged wetlands in the conterminous United States and Hawaii is difficult due to limited data availability. Wetlands are not characterized within the NRI with information regarding water table management. Regardless, a planned improvement is underway to subdivide managed and unmanaged wetlands.

land base. The resulting spatial product is also used to identify NRI survey locations that are considered managed and unmanaged for the conterminous United States and Hawaii.[24]

Approach for Combining Data Sources

The managed land base in the United States has been classified into the 36 IPCC land-use/land-use conversion categories (Table 6-5) using definitions developed to meet national circumstances, while adhering to IPCC guidelines (2006).[25] In practice, the land was initially classified into land-use subcategories within the NRI, FIA, and NLCD datasets, and then aggregated into the 36 broad land use and land-use change categories identified in IPCC (2006).

All three datasets provide information on forest land areas in the conterminous United States, but the area data from FIA serve as the official dataset for Forest Land. Therefore, another step in the analysis is to address the inconsistencies in the representation of the Forest Land among the three databases. NRI and FIA have different criteria for classifying Forest Land in addition to different sampling designs, leading to discrepancies in the resulting estimates of Forest Land area on non-federal land in the conterminous United States. Similarly, there are discrepancies between the NLCD and FIA data for defining and classifying Forest Land on federal lands. Any change in Forest Land Area in the NRI and NLCD also requires a corresponding change in other land use areas because of the dependence between the Forest Land area and the amount of land designated as other land uses, such as the amount of Grassland, Cropland, and Wetlands (i.e., areas for the individual land uses must sum to the total managed land area of the country).

FIA is the main database for forest statistics, and consequently, the NRI and NLCD are adjusted to achieve consistency with FIA estimates of Forest Land in the conterminous United States. Adjustments are made in the *Forest Land Remaining Forest Land*, *Land Converted to Forest Land*, and Forest Land converted to other uses (i.e., Grassland, Cropland, Settlements, Other Lands, and Wetlands). All adjustments are made at the state scale to address the discrepancies in areas associated with Forest Land and conversions to and from Forest Land. There are three steps in this process. The first step involves adjustments to *Land Converted to Forest Land* (Grassland, Cropland, Settlements, Other Lands, and Wetlands), followed by a second step in which there are adjustments in Forest Land converted to another land use (i.e., Grassland, Cropland, Settlements, Other Lands, and Wetlands), and finally the last step is to adjust *Forest Land Remaining Forest Land*.

In the first step, *Land Converted to Forest Land* in the NRI and NLCD are adjusted to match the state-level estimates in the FIA data for non-federal and federal *Land Converted to Forest Land*, respectively. FIA data have not provided specific land-use categories that are converted to Forest Land in the past, but rather a sum of all *Land Converted to Forest Land*.[26] The NRI and NLCD provide information on specific land use conversions, such as *Grassland Converted to Forest Land*. Therefore, adjustments at the state level to NRI and NLCD are made proportional to the amount of specific land use conversions into Forest Land for the state, prior to any adjustments. For example, if 50 percent of the land use change to Forest Land is associated with *Grassland Converted to Forest Land* in a state according to NRI or NLCD, then half of the discrepancy with FIA data in the area of *Land Converted to Forest Land* is addressed by increasing or decreasing the area in *Grassland Converted to Forest Land*. Moreover, any increase or decrease in *Grassland Converted to Forest Land* in NRI or NLCD is addressed by a corresponding change in the area of Grassland Remaining Grassland*,* so that the total amount of managed area is not changed within an individual state.

In the second step, state-level areas are adjusted in the NRI and NLCD to address discrepancies with FIA data for Forest Land converted to other uses. Similar to *Land Converted to Forest Land*, FIA have not provided information

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[24] The exception is cropland and settlement areas in the NRI, which are classified as managed, regardless of the managed land base derived from the spatial analysis described in this section.

[25] Definitions are provided in the previous section.

[26] The FIA program has started to collect data on the specific land uses that are converted to Forest Land, which will be further investigated and incorporated into a future Inventory.

on the specific land-use changes in the past,[27] and so areas associated with Forest Land conversion to other land uses in NRI and NLCD are adjusted proportional to the amount of area in each conversion class in these datasets.

In the final step, the area of *Forest Land Remaining Forest Land* in a given state according to the NRI and NLCD is adjusted to match the FIA estimates for non-federal and federal land, respectively. It is assumed that the majority of the discrepancy in *Forest Land Remaining Forest Land* is associated with an under- or over-prediction of Grassland Remaining Grassland and *Wetlands Remaining Wetlands* in the NRI and NLCD. This step also assumes that there are no changes in the land use conversion categories. Therefore, corresponding increases or decreases are made in the area estimates of Grassland Remaining Grassland and *Wetlands Remaining Wetlands* from the NRI and NLCD. This adjustment balances the change in *Forest Land Remaining Forest Land* area, which ensures no change in the overall amount of managed land within an individual state. The adjustments are based on the proportion of land within each of these land-use categories at the state level according to NRI and NLCD (i.e., a higher proportion of Grassland led to a larger adjustment in Grassland area).

The modified NRI data are then aggregated to provide the land-use and land-use change data for non-federal lands in the conterminous United States, and the modified NLCD data are aggregated to provide the land use and land-use change data for federal lands. Data for all land uses in Hawaii are based on NRI for non-federal lands and on NLCD for federal lands. Land use data in Alaska are based on the NLCD data after adjusting this dataset to be consistent with forest land areas in the FIA (Table 6-6). The result is land use and land-use change data for the conterminous United States, Hawaii, and Alaska.

A summary of the details on the approach used to combine data sources for each land use are described below.

- *Forest Land*: Land representation for both non-federal and federal forest lands in the conterminous United States and Alaska are based on the FIA. FIA is used as the basis for both Forest Land area data as well as to estimate C stocks and fluxes on Forest Land in the conterminous United States and Alaska. FIA does have survey plots in Alaska that are used to determine the C stock changes, and the associated area data for this region are harmonized with the NLCD using the methods described above. NRI is used in the current report to provide Forest Land areas on non-federal lands in Hawaii, and NLCD is used for federal lands. FIA data is being collected in Hawaii and U.S. Territories, however there is insufficient data to make population estimates for this Inventory.
- *Cropland*: Cropland is classified using the NRI, which covers all non-federal lands within 49 states (excluding Alaska), including state and local government-owned land as well as tribal lands. NRI is used as the basis for both Cropland area data as well as to estimate soil C stocks and fluxes on Cropland. NLCD is used to determine Cropland area and soil C stock changes on federal lands in the conterminous United States and Hawaii. NLCD is also used to determine croplands in Alaska, but C stock changes are not estimated for this region in the current Inventory.
- *Grassland*: Grassland on non-federal lands is classified using the NRI within 49 states (excluding Alaska), including state and local government-owned land as well as tribal lands. NRI is used as the basis for both Grassland area data as well as to estimate soil C stocks and non-CO_2 greenhouse emissions on Grassland. Grassland area and soil C stock changes are determined using the classification provided in the NLCD for federal land within the conterminous United States. NLCD is also used to estimate the areas of federal and non-federal grasslands in Alaska, and the federal grasslands in Hawaii, but the current Inventory does not include C stock changes in these areas.
- *Wetlands*: NRI captures wetlands on non-federal lands within 49 states (excluding Alaska), while the land representation data for federal wetlands and wetlands in Alaska are based on the NLCD.[28]

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[27] The FIA program has started to collect data on specific land uses following conversion from Forest Land, which will be further investigated and incorporated into a future Inventory.

[28] This analysis does not distinguish between managed and unmanaged wetlands except for remote areas in Alaska, but there is a planned improvement to subdivide managed and unmanaged wetlands for the entire land base.

- *Settlements*: NRI captures non-federal settlement area in 49 states (excluding Alaska). If areas of Forest Land or Grassland under 10 acres (4.05 ha) are contained within settlements or urban areas, they are classified as Settlements (urban) in the NRI database. If these parcels exceed the 10 acres (4.05 ha) threshold and are Grassland, they are classified as Grassland by NRI. Regardless of size, a forested area is classified as non-forest by FIA if it is located within an urban area. Land representation for settlements on federal lands and Alaska is based on the NLCD.
- *Other Land*: Any land that is not classified into one of the previous five land-use categories, is categorized as Other Land using the NRI for non-federal areas in the conterminous United States and Hawaii and using the NLCD for the federal lands in all regions of the United States and for non-federal lands in Alaska.

Some lands can be classified into one or more categories due to multiple uses that meet the criteria of more than one definition. However, a ranking has been developed for assignment priority in these cases. The ranking process is from highest to lowest priority based on the following order:

Settlements > Cropland > Forest Land > Grassland > Wetlands > Other Land

Settlements are given the highest assignment priority because they are extremely heterogeneous with a mosaic of patches that include buildings, infrastructure, and travel corridors, but also open grass areas, forest patches, riparian areas, and gardens. The latter examples could be classified as Grassland, Forest Land, Wetlands, and Cropland, respectively, but when located in close proximity to settlement areas, they tend to be managed in a unique manner compared to non-settlement areas. Consequently, these areas are assigned to the Settlements land-use category. Cropland is given the second assignment priority, because cropping practices tend to dominate management activities on areas used to produce food, forage, or fiber. The consequence of this ranking is that crops in rotation with pasture are classified as Cropland, and land with woody plant cover that is used to produce crops (e.g., orchards) is classified as Cropland, even though these areas may also meet the definitions of Grassland or Forest Land, respectively. Similarly, Wetlands are considered Croplands if they are used for crop production, such as rice or cranberries. Forest Land occurs next in the priority assignment because traditional forestry practices tend to be the focus of the management activity in areas with woody plant cover that are not croplands (e.g., orchards) or settlements (e.g., housing subdivisions with significant tree cover). Grassland occurs next in the ranking, while Wetlands and then Other Land complete the list.

The assignment priority does not reflect the level of importance for reporting greenhouse gas emissions and removals on managed land, but is intended to classify all areas into a discrete land use category. Currently, the IPCC does not make provisions in the guidelines for assigning land to multiple uses. For example, a wetland is classified as Forest Land if the area has sufficient tree cover to meet the stocking and stand size requirements. Similarly, wetlands are classified as Cropland if they are used for crop production, such as rice, or as Grassland if they are composed principally of grasses, grass-like plants (i.e., sedges and rushes), forbs, or shrubs suitable for grazing and browsing. Regardless of the classification, emissions and removals from these areas should be included in the Inventory if the land is considered managed, and therefore impacted by anthropogenic activity in accordance with the guidance provided by the IPCC (2006).

QA/QC and Verification

The land base derived from the NRI, FIA, and NLCD was compared to the Topologically Integrated Geographic Encoding and Referencing (TIGER) survey (U.S. Census Bureau 2010). The United States Census Bureau gathers data on the population and economy, and has a database of land areas for the country. The area estimates of land-use categories, based on NRI, FIA, and NLCD, are derived from remote sensing data instead of the land survey approach used by the United States Census Survey. The Census does not provide a time series of land-use change data or land management information, which is needed for estimating greenhouse gas emissions from land use and land use change. Regardless, the Census does provide sufficient information to provide a check on the Inventory data. There are 46 million more hectares of land in the United States according to the Census, compared to the total area estimate of 936 million hectares derived from the combined NRI, FIA, and NLCD data. Much of this difference is associated with open waters in coastal regions and the Great Lakes, which is included in the TIGER Survey of the Census, but not included in the land representation using the NRI, FIA and NLCD. There is only a 0.4

percent difference when open water in coastal regions is removed from the TIGER data. General QC procedures for data gathering and data documentation also were applied consistent with the QA/QC and Verification Procedures described in Annex 8.

Recalculations Discussion

No recalculations were performed for the 1990 through 2019 portion of the time series, thus the land use areas for 2020 are assumed the same as 2019.

Planned Improvements

The next (i.e., 1990 through 2021) Inventory will be improved by using new NRI, FIA and possibly NLCD data to update the time series for land representation, providing consistency between the total area of managed land in the land representation section and the remainder of the Inventory. Another key planned improvement for the Inventory is to fully incorporate area data by land-use type for U.S. Territories. Fortunately, most of the managed land in the United States is included in the current land-use data, but a complete reporting of all lands in the United States is a key goal for the near future. Preliminary land-use area data for U.S. Territories by land-use category are provided in Box 6-2.

Box 6-2: Preliminary Estimates of Land Use in U.S. Territories

Several programs have developed land cover maps for U.S. Territories using remote sensing imagery, including the Gap Analysis Program, Caribbean Land Cover project, National Land Cover Dataset, USFS Pacific Islands Imagery Project, and the National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program (C-CAP). Land-cover data can be used to inform a land-use classification if there is a time series to evaluate the dominate practices. For example, land that is principally used for timber production with tree cover over most of the time series is classified as forest land even if there are a few years of grass dominance following timber harvest. These products were reviewed and evaluated for use in the national Inventory as a step towards implementing a planned improvement to include U.S. Territories in the land representation for the Inventory. Recommendations are to use the NOAA C-CAP Regional Land Cover Database for the smaller island Territories (U.S. Virgin Islands, Guam, Northern Marianas Islands, and American Samoa) because this program is ongoing and therefore will be continually updated. The C-CAP product does not cover the entire territory of Puerto Rico so the NLCD was used for this area. The final selection of land-cover products for these territories is still under discussion. Results are presented below (in hectares). The total land area of all U.S. Territories is 1.05 million hectares, representing 0.1 percent of the total land base for the United States (see Table 6-7).

Table 6-7: Total Land Area (Hectares) by Land-Use Category for U.S. Territories

	Puerto Rico	U.S. Virgin Islands	Guam	Northern Marianas Islands	American Samoa	Total
Cropland	19,712	138	236	289	389	20,764
Forest Land	404,004	13,107	24,650	25,761	15,440	482,962
Grasslands	299,714	12,148	15,449	13,636	1,830	342,777
Other Land	5,502	1,006	1,141	5,186	298	13,133
Settlements	130,330	7,650	11,146	3,637	1,734	154,496
Wetlands	24,525	4,748	1,633	260	87	31,252
Total	**883,788**	**38,796**	**54,255**	**48,769**	**19,777**	**1,045,385**

Note: Totals may not sum due to independent rounding.

Methods in the *2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014) have been applied to estimate emissions and removals from coastal wetlands. Specifically, greenhouse gas emissions from coastal wetlands have been developed for the Inventory using the NOAA C-CAP land cover product.

The NOAA C-CAP product is not used directly in the land representation analysis, however, so a planned improvement for the next (i.e., 1990 through 2021) Inventory is to reconcile the coastal wetlands data from the C-CAP product with the wetlands area data provided in the NRI, FIA and NLCD. In addition, the current Inventory does not include a classification of managed and unmanaged wetlands, except for remote areas in Alaska. Consequently, there is a planned improvement to classify managed and unmanaged wetlands for the conterminous United States and Hawaii, and more detailed wetlands datasets will be evaluated and integrated into the analysis to meet this objective.

6.2 Forest Land Remaining Forest Land (CRF Category 4A1)

Changes in Forest Carbon Stocks (CRF Category 4A1)

Delineation of Carbon Pools

For 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, which includes all living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. This category includes live understory.
- Belowground biomass, which includes all living biomass of coarse living roots greater than 2 millimeters (mm) diameter.
- Dead wood, which includes all non-living woody biomass either standing, lying on the ground (but not including litter), or in the soil.
- Litter, which includes all duff, humus, and fine woody debris above the mineral soil and includes woody fragments with diameters of up to 7.5 cm.
- Soil organic C (SOC), including all organic material in soil to a depth of 1 meter but excluding the coarse roots of the belowground pools.

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

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

Forest Carbon Cycle

Carbon is continuously cycled among the previously defined C storage 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 cause an immediate flux of all harvested biomass C to the atmosphere. Instead, harvesting transfers a portion of the C stored in wood to a "product pool." Once in a product pool, the C is emitted over time as CO_2 in the case of decomposition and as CO_2, CH_4, N_2O, CO, and NO_x when the wood product combusts. The rate of emission varies considerably among different product pools. For example, if timber is harvested to produce energy, combustion releases C immediately, and these emissions are reported for information purposes in the Energy sector while the harvest (i.e., the associated reduction in forest C stocks) and subsequent combustion are implicitly estimated in the Land Use, Land-Use Change, and Forestry (LULUCF) sector (i.e., the portion of harvested timber combusted to produce energy does not enter the HWP pools). Conversely, if timber is harvested and used as lumber in a house, it may be many decades or even centuries before the lumber decays and C is released to the atmosphere. If wood products are disposed of in SWDS, the C contained in the wood may be released many years or decades later or may be stored almost permanently in the SWDS. These latter fluxes, with the exception of CH_4 from wood in SWDS, which is included in the Waste sector, are also estimated in the LULUCF sector.

Net Change in Carbon Stocks within Forest Land of the United States

This section describes the general method for quantifying the net changes in C stocks in the five C storage pools and two harvested wood pools (a more detailed description of the methods and data is provided in Annex 3.13). The underlying methodology for determining C stock and stock change relies on data from the national forest inventory (NFI) conducted by the Forest Inventory and Analysis (FIA) program within the USDA Forest Service. The annual NFI is implemented across all U.S. forest lands within the conterminous 48 states and Alaska and inventories have been initiated in Hawaii and some of the U.S. Territories. The methods for estimation and monitoring are continuously improved and these improvements are reflected in the C estimates (Domke et al. 2016; Domke et al. 2017). First, the total C stocks are estimated for each C storage pool at the individual NFI plot, next the annual net changes in C stocks for each pool are estimated, and then the changes in stocks are summed for all pools to estimate total net flux at the population level (e.g., U.S. state). Changes in C stocks from disturbances, such natural disturbances (e.g., wildfires, insects/disease, wind) or harvesting, are included in the net changes (See Box 6-3 for more information). For instance, an inventory conducted after a fire implicitly includes only the C stocks remaining on the NFI plot. The IPCC (2006) recommends estimating changes in C stocks from forest lands according to several land-use types and conversions, specifically *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*, with the former being lands that have been forest lands for 20 years or longer and the latter being lands (i.e., croplands, grassland, wetlands, settlements and other lands) that have been converted to forest lands for less than 20 years. The methods and data used to delineate forest C stock changes by these two categories continue to improve and in order to facilitate this delineation, a combination of modeling approaches for carbon estimation were used in this Inventory.

Forest Area in the United States

Approximately 32 percent of the U.S. land area is estimated to be forested based on the U.S. definition of forest land as provided in Section 6.1 Representation of the U.S. Land Base. All annual NFI plots included in the public FIA database as of August 2021 (which includes data collected through 2020 – note that the ongoing COVID 19 pandemic has resulted in delays in data collection in many states) were used in this Inventory. Since area estimates for some land use categories were not updated in the Land Representation in the current Inventory there are differences in the area estimates reported in this section and those reported in Section 6.1 Representation of the U.S. Land Base. The NFIs from each of the conterminous 48 states (CONUS; USDA Forest Service 2022a, 2022b) and Alaska comprise an estimated 282 million hectares of forest land that are considered managed and are included in the current Inventory. Some differences also exist in forest land area estimates from the latest update to the Resources Planning Act (RPA) Assessment (Oswalt et al. 2019) and the forest land area estimates included in this report, which are based on the annual NFI data through 2020 for all states (USDA Forest Service 2022b; Nelson et al. 2020). Sufficient annual NFI data are not yet available for Hawaii and the U.S. Territories to include them in this section of the Inventory but estimates of these areas are included in Oswalt et al. (2019). While Hawaii and U.S. Territories have relatively small areas of forest land and thus 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. Since HI was not included in this section of the current Inventory there are small differences in the area estimates reported in this section and those reported in Section 6.1 Representation of the U.S. Land Base.[29] Agroforestry systems that meet the definition of forest land are also not currently included in the current Inventory since they are not explicitly inventoried (i.e., classified as an agroforestry system) by either the FIA program or the Natural Resources Inventory (NRI)[30] of the USDA Natural Resources Conservation Service (Perry et al. 2005).

An estimated 67 percent (208 million hectares) of U.S. forests in Alaska, and Hawaii and the conterminous United States are classified as timberland, meaning they meet minimum levels of productivity and have not been removed from production. Approximately ten percent of Alaska forest land and 73 percent of forest land in the conterminous United States are classified as timberland. Of the remaining non-timberland, nearly 33 million hectares are reserved forest lands (withdrawn by law from management for production of wood products) and 102 million hectares are lower productivity forest lands (Oswalt et al. 2019). Historically, the timberlands in the conterminous 48 states have been more frequently or intensively surveyed than the forest land removed from production because it does not meet the minimum level of productivity.

Since the late 1980s, gross forest land area in Alaska, Hawaii, and the conterminous United States has increased by about 13 million hectares (Oswalt et al. 2019). The southern region of the United States contains the most forest land (Figure 6-4). A substantial portion of this accrued forest land is from the conversion of abandoned croplands to forest (e.g., Woodall et al. 2015b). Estimated forest land area in the CONUS and Alaska represented here is stable but there are substantial conversions as described in Section 6.1 Representation of the U.S. Land Base and each of the land conversion sections for each land use category (e.g., Land Converted to Cropland, *Land Converted to Grassland*). The major influences on the net C flux from forest land across the 1990 to 2020 time series are management activities, natural disturbance, particularly wildfire, and the ongoing impacts of current and previous land-use conversions. These activities affect the net flux of C by altering the amount of C stored in forest ecosystems and also the area converted to forest land. For example, intensified management of forests that leads to an increased rate of growth of aboveground biomass (and possible changes to the other C storage pools) may increase the eventual biomass density of the forest, thereby increasing the uptake and storage of C in the aboveground biomass pool.[31] Though harvesting forests removes much of the C in aboveground biomass (and possibly changes C density in other pools), on average, the estimated volume of annual net growth in aboveground tree biomass in the conterminous United States is about double the volume of annual removals on timberlands (Oswalt et al. 2019). The net effects of forest management and changes in *Forest Land Remaining Forest Land* are captured in the estimates of C stocks and fluxes presented in this section.

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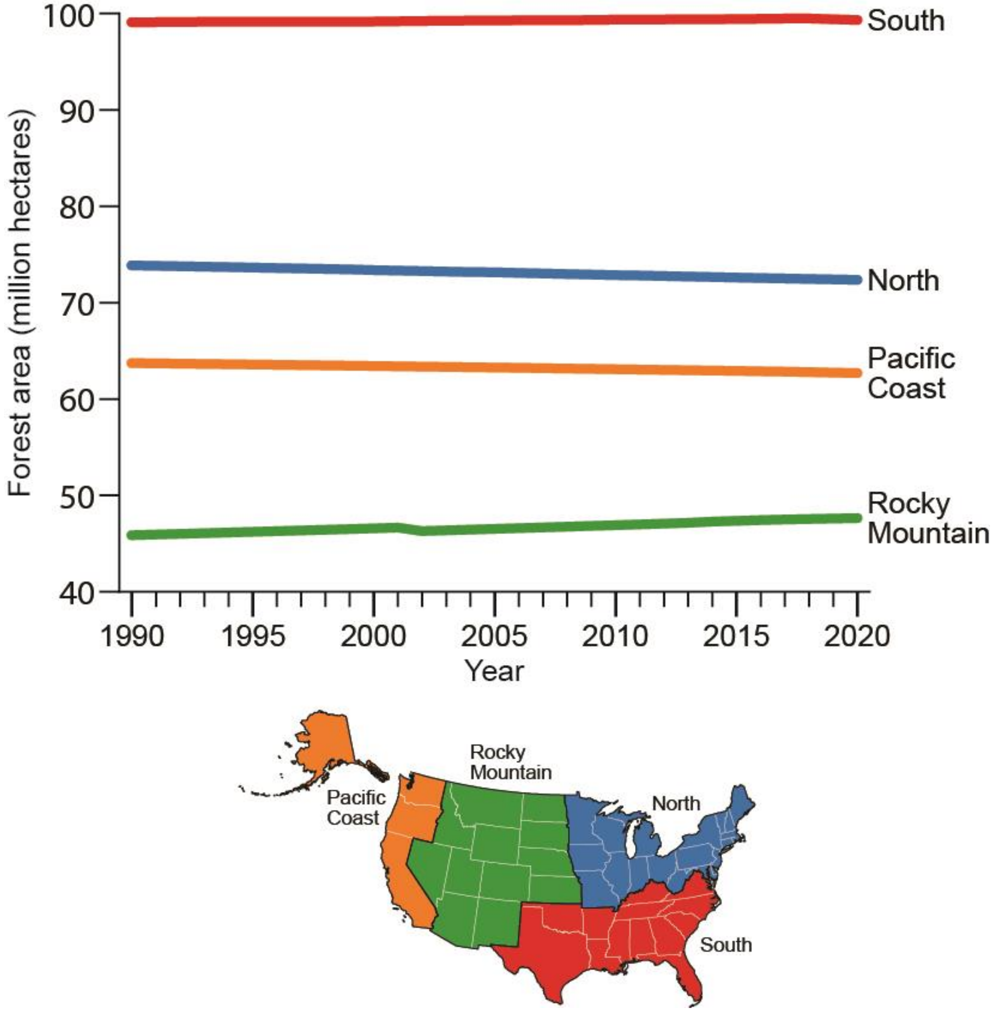
[29] See Annex 3.13, Table A-213 for annual differences between the forest area reported in Section 6.1 Representation of the U.S. Land Base and Section 6.2 Forest Land Remaining Forest Land.

[30] The Natural Resources Inventory of the USDA Natural Resources Conservation Service is described in Section 6.1 Representation of the U.S. Land Base.

[31] The term "biomass density" refers to the mass of live vegetation per unit area. It is usually measured on a dry-weight basis. A carbon fraction of 0.5 is used to convert dry biomass to C (USDA Forest Service 2022d).

Figure 6-4: Changes in Forest Area by Region for *Forest Land Remaining Forest Land* in the conterminous United States and Alaska (1990-2020)



Forest Carbon Stocks and Stock Change

In *Forest Land Remaining Forest Land*, forest management practices, the regeneration of forest areas cleared more than 20 years prior to the reporting year, and timber harvesting have resulted in net uptake (i.e., net sequestration or accumulation) of C each year from 1990 through 2020. The rate of forest clearing in the 17th century following European settlement had slowed by the late 19th century. Through the later part of the 20th century many areas of previously forested land in the United States were allowed to revert to forests or were actively reforested. The impacts of these land-use changes still influence C fluxes from these forest lands. More recently, the 1970s and 1980s saw a resurgence of federally sponsored forest management programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on tree planting, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. In addition to forest regeneration and management, forest harvests and natural disturbance have also affected net C fluxes. 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). 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 the *Forest Land Remaining Forest Land* category are likely to continue to increase in the near term, though possibly at a lower rate. Changes in

C stocks in the forest ecosystem and harvested wood pools associated with *Forest Land Remaining Forest Land* were estimated to result in net uptake of 668.1 MMT CO_2 Eq. (182.2 MMT C) in 2020 (Table 6-8, Table 6-9, Table A-210, Table A-211 and state-level estimates in Table A-214). The estimated net uptake of C in the Forest Ecosystem was 584.4 MMT CO_2 Eq. (159.4 MMT C) in 2020 (Table 6-8 and Table 6-9). The majority of this uptake in 2020, 398.7 MMT CO_2 Eq. (108.7 MMT C), was from aboveground biomass. Overall, estimates of average C density in forest ecosystems (including all pools) increased consistently over the time series with an average of approximately 198 MT C ha^{-1} from 1990 to 2020. This was calculated by dividing the Forest Land area estimates by Forest Ecosystem C Stock estimates for every year (see Table 6-10 and Table A-212) and then calculating the mean across the entire time series, i.e., 1990 through 2020. The increasing forest ecosystem C density when combined with relatively stable forest area results in net C accumulation over time. Aboveground live biomass is responsible for the majority of net C uptake among all forest ecosystem pools (Figure 6-5). These increases may be influenced in some regions by reductions in C density or forest land area due to natural disturbances (e.g., wildfire, weather, insects/disease), particularly in Alaska. The inclusion of all managed forest land in Alaska has increased the interannual variability in carbon stock change estimates over the time series and much of this variability can be attributed to severe fire years. The distribution of carbon in forest ecosystems in Alaska is substantially different from forests in the CONUS. In Alaska, more than 11 percent of forest ecosystem C is stored in the litter carbon pool whereas in the CONUS only 7 percent of the total ecosystem C stocks are in the litter pool. Much of the litter material in forest ecosystems is combusted during fire (IPCC 2006) which is why there are substantial C losses in this pool during severe fire years (Figure 6-5, Table A-227).

The estimated net uptake of C in HWP was 83.6 MMT CO_2 Eq. (22.8 MMT C) in 2020 (Table 6-8, Table 6-9, Table A-210, and Table A-211). The majority of this uptake, 63.6 MMT CO_2 Eq. (17.3 MMT C), was from wood and paper in SWDS. Products in use were an estimated 20.0 MMT CO_2 Eq. (5.5 MMT C) in 2020.

Table 6-8: Net CO_2 Flux from Forest Ecosystem Pools in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT CO_2 Eq.)

Carbon Pool	1990	2005	2016	2017	2018	2019	2020
Forest Ecosystem	**(650.2)**	**(581.2)**	**(630.4)**	**(588.1)**	**(583.0)**	**(546.0)**	**(584.4)**
Aboveground Biomass	(462.5)	(416.3)	(432.7)	(407.7)	(406.6)	(393.1)	(398.7)
Belowground Biomass	(94.2)	(84.2)	(86.3)	(80.9)	(80.8)	(78.1)	(79.1)
Dead Wood	(96.8)	(96.8)	(106.4)	(99.8)	(102.0)	(97.0)	(101.5)
Litter	0.6	16.0	(3.1)	(1.9)	1.3	22.8	(1.9)
Soil (Mineral)	3.0	(0.3)	(5.6)	(1.1)	4.1	(0.6)	(4.1)
Soil (Organic)	(0.9)	(0.3)	3.0	2.5	0.3	(0.7)	0.2
Drained Organic Soil[a]	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Harvested Wood	**(123.8)**	**(106.0)**	**(95.1)**	**(100.2)**	**(94.1)**	**(88.8)**	**(83.6)**
Products in Use	(54.8)	(42.6)	(30.4)	(34.9)	(29.0)	(24.4)	(20.0)
SWDS	(69.0)	(63.4)	(64.8)	(65.3)	(65.1)	(64.5)	(63.6)
Total Net Flux	**(774.0)**	**(687.3)**	**(725.6)**	**(688.3)**	**(677.1)**	**(634.8)**	**(668.1)**

[a] These estimates include C stock changes from drained organic soils from both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. See the section below on CO_2, CH_4, and N_2O Emissions from Drained Organic Soils for the methodology used to estimate the CO_2 emissions from drained organic soils. Also, Table 6-20 and 6-21 for non-CO_2 emissions from drainage of organic soils from both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Notes: Forest ecosystem C stock changes do not include forest stocks in 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. The forest ecosystem C stock changes do not include Hawaii because there is not sufficient NFI data to support inclusion at this time. However, managed forest land area for Hawaii is included in Section 6.1 Representation of the U.S. Land Base so there are small differences in the forest land area estimates in this Section and Section 6.1. See Annex 3.13, Table A-213 for annual differences between the forest area reported in Section 6.1 Representation of the U.S. Land Base and Section 6.2 *Forest Land Remaining Forest Land*. The forest ecosystem C stock changes do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 *Settlements Remaining Settlements* for estimates of C stock change from settlement trees). Forest ecosystem C stocks on managed forest land in Alaska were compiled using the gain-loss method as described in Annex 3.13. Parentheses indicate net C uptake (i.e., a net removal of C from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest C pool and the atmosphere. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding.

Table 6-9: Net C Flux from Forest Ecosystem Pools in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

Carbon Pool	1990	2005	2016	2017	2018	2019	2020
Forest Ecosystem	**(177.3)**	**(158.5)**	**(171.9)**	**(160.4)**	**(159.0)**	**(148.9)**	**(159.4)**
Aboveground Biomass	(126.1)	(113.5)	(118.0)	(111.2)	(110.9)	(107.2)	(108.7)
Belowground Biomass	(25.7)	(23.0)	(23.5)	(22.1)	(22.0)	(21.3)	(21.6)
Dead Wood	(26.4)	(26.4)	(29.0)	(27.2)	(27.8)	(26.5)	(27.7)
Litter	0.2	4.4	(0.9)	(0.5)	0.3	6.2	(0.5)
Soil (Mineral)	0.8	(0.1)	(1.5)	(0.3)	1.1	(0.2)	(1.1)
Soil (Organic)	(0.3)	(0.1)	0.8	0.7	0.1	(0.2)	0.1
Drained Organic Soil[a]	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Harvested Wood	**(33.8)**	**(28.9)**	**(25.9)**	**(27.3)**	**(25.7)**	**(24.2)**	**(22.8)**
Products in Use	(14.9)	(11.6)	(8.3)	(9.5)	(7.9)	(6.6)	(5.5)
SWDS	(18.8)	(17.3)	(17.7)	(17.8)	(17.8)	(17.6)	(17.3)
Total Net Flux	**(211.1)**	**(187.4)**	**(197.9)**	**(187.7)**	**(184.7)**	**(173.1)**	**(182.2)**

[a] These estimates include carbon stock changes from drained organic soils from both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. See the section below on CO_2, CH_4, and N_2O Emissions from Drained Organic Soils for the methodology used to estimate the C flux from drained organic soils. Also, see Table 6-20 and 6-21 for greenhouse gas emissions from non-CO_2 gases changes from drainage of organic soils from *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Notes: Forest ecosystem C stock changes do not include forest stocks in 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. The forest ecosystem C stock changes do not include Hawaii because there is not sufficient NFI data to support inclusion at this time. However, managed forest land area for Hawaii is included in 6.1 Representation of the U.S. Land Base so there are small differences in the forest land area estimates in this Section and Section 6.1. See Annex 3.13, Table A-213 for annual differences between the forest area reported in Section 6.1 Representation of the U.S. Land Base and Section 6.2 *Forest Land Remaining Forest Land*. The forest ecosystem C stock changes do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 *Settlements Remaining Settlements* for estimates of C stock change from settlement trees). Forest ecosystem C stocks on managed forest land in Alaska were compiled using the gain-loss method as described in Annex 3.13. Parentheses indicate net C uptake (i.e., a net removal of C from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest C pool and the atmosphere. Harvested wood estimates are based on results from annual surveys and models. Totals may not sum due to independent rounding.

Stock estimates for forest ecosystem and harvested wood C storage pools are presented in Table 6-10. Together, the estimated aboveground biomass and soil C pools account for a large proportion of total forest ecosystem C stocks. Forest land area estimates are also provided in Table 6-10, but these do not precisely match those in Section 6.1 Representation of the U.S. Land Base for *Forest Land Remaining Forest Land*. This is because the forest land area estimates in Table 6-10 only include managed forest land in the conterminous 48 states and Alaska while the area estimates in Section 6.1 include all managed forest land in Hawaii. Differences also exist because forest land area estimates are based on the latest NFI data through 2020 and woodland areas previously included as forest land have been separated and included in the Grassland categories in this Inventory.[32]

Table 6-10: Forest Area (1,000 ha) and C Stocks in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

	1990	2005	2017	2018	2019	2020	2021
Forest Area (1,000 ha)	***282,585***	***282,250***	***282,352***	***282,312***	***282,177***	***282,061***	***281,951***
Carbon Pools (MMT C)							
Forest Ecosystem	**53,148**	**55,721**	**57,687**	**57,848**	**58,007**	**58,156**	**58,316**
Aboveground Biomass	12,062	13,874	15,250	15,361	15,472	15,579	15,688
Belowground Biomass	2,375	2,743	3,019	3,041	3,064	3,085	3,106
Dead Wood	2,060	2,460	2,787	2,814	2,842	2,868	2,896
Litter	3,838	3,834	3,815	3,816	3,815	3,809	3,810
Soil (Mineral)	25,458	25,452	25,458	25,458	25,457	25,457	25,459
Soil (Organic)	7,355	7,358	7,357	7,357	7,357	7,357	7,357
Harvested Wood	**1,895**	**2,353**	**2,618**	**2,645**	**2,671**	**2,695**	**2,718**
Products in Use	1,249	1,447	1,506	1,515	1,523	1,530	1,536
SWDS	646	906	1,112	1,129	1,147	1,165	1,182
Total C Stock	**55,043**	**58,074**	**60,305**	**60,493**	**60,678**	**60,851**	**61,034**

Notes: Forest area and C stock estimates include all *Forest Land Remaining Forest Land* in the conterminous 48 states and Alaska. Forest ecosystem C stocks do not include forest stocks in 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. The forest ecosystem C stocks do not include Hawaii because there is not sufficient NFI data to support inclusion at this time. However, managed forest land area for Hawaii is included in Section 6.1 Representation of the U.S. Land Base so there are small differences in the forest land area estimates in this Section and Section 6.1. See Annex 3.13, Table A-213 for annual differences between the forest area reported in Section 6.1 Representation of the U.S. Land Base and Section 6.2 *Forest Land Remaining Forest Land*. The forest ecosystem C stocks do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 *Settlements Remaining Settlements* for estimates of C stock change from settlement trees). 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 exclude 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, an estimate of flux for 2020 requires estimates of C stocks for 2020 and 2021.

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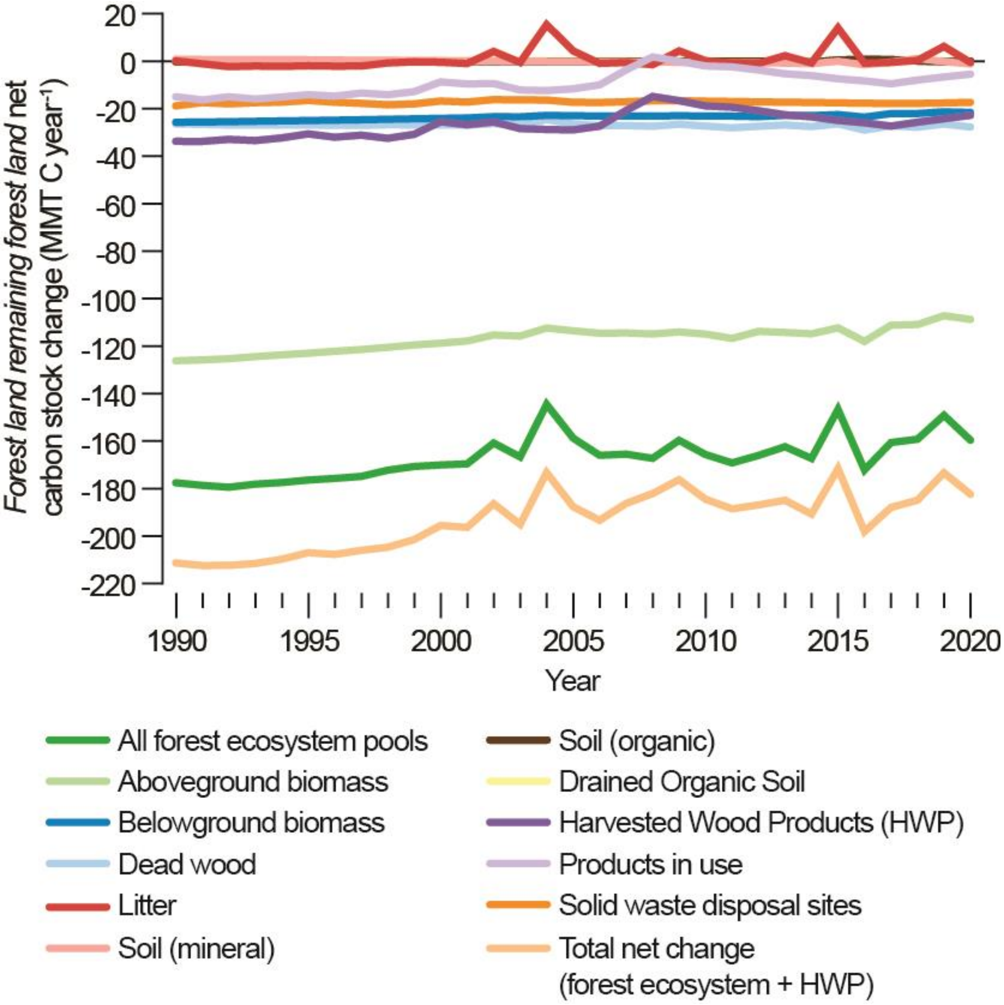
[32] See Annex 3.13, Table A-213 for annual differences between the forest area reported in Section 6.1 Representation of the U.S. Land Base and Section 6.2 Forest Land Remaining Forest Land.

Figure 6-5: Estimated Net Annual Changes in C Stocks for All C Pools in *Forest Land Remaining Forest Land* in the Conterminous United States and Alaska (1990-2020)



Box 6-3: CO_2 Emissions from Forest Fires

As stated previously, the forest inventory approach implicitly includes all C losses due to disturbances such as forest fires, because only C remaining in the forest is estimated. Net C stock change is estimated by subtracting consecutive C stock estimates. A forest fire disturbance removes C from the forest. The inventory data on which net C stock estimates are based already reflect this C loss. Therefore, estimates of net annual changes in C stocks for U.S. forest land already includes CO_2 emissions from forest fires occurring in the conterminous states as well as the portion of managed forest lands in Alaska. Because it is of interest to quantify the magnitude of CO_2 emissions from fire disturbance, these separate estimates are highlighted here. Note that these CO_2 estimates are based on the same methodology as applied for the non-CO_2 greenhouse gas emissions from forest fires that are also quantified in a separate section below as required by IPCC Guidance and UNFCCC reporting requirements.

Emissions estimates are developed consistent with IPCC (2006) methodology and based on U.S.-specific data and models to quantify the primary fire-specific components: area burned; availability and combustibility of fuel: fire severity (or consumption); and CO_2 and non-CO_2 emissions. Estimated CO_2 emissions for fires on forest lands in the conterminous 48 states and in Alaska for 2020 are 237 MMT CO_2 per year (Table 6-11). This estimate is an embedded component of the net annual forest C stock change estimates provided previously (i.e., Table 6-9), but this separate approach to estimate CO_2 emissions is necessary in order to associate these emissions with fire. See the discussion in Annex 3.13 for more details on this methodology. Note that in Alaska a portion of the forest lands are considered unmanaged, therefore the estimates for Alaska provided in Table 6-11 include only managed forest land within the state, which is consistent with C stock change estimates provided above.

Table 6-11: Estimates of CO2 (MMT per Year) Emissions from Forest Fires in the Conterminous 48 States and Alaska[a]

Year	CO_2 emitted from fires on forest land in the Conterminous 48 States (MMT yr^{-1})	CO_2 emitted from fires on forest land in Alaska (MM Tyr^{-1})	Total CO_2 emitted (MMTyr^{-1})
1990	11.2	26.0	**37.1**
2005	33.9	93.5	**127.4**
2016	73.1	5.7	**78.8**
2017	154.8	10.0	**164.8**
2018	108.5	6.7	**115.2**
2019	27.0	55.8	**82.7**
2020	236.8	0.6	**237.4**

[a] These emissions have already been included in the estimates of net annual changes in C stocks, which include the amount sequestered minus any emissions, including the assumption that combusted wood may continue to decay through time.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The methodology described herein is consistent with IPCC (2006). Forest ecosystem C stocks and net annual C stock change were determined according to the stock-difference method for the CONUS, which involved applying C estimation factors to annual forest inventories across time to obtain C stocks and then subtracting between the years to obtain the stock change. The gain-loss method was used to estimate C stocks and net annual C stock changes in Alaska. The approaches for estimating carbon stocks and stock changes on *Forest Land Remaining Forest Land* are described in Annex 3.13. All annual NFI plots available in the public FIA database (USDA Forest Service 2022b) were used in the current Inventory. Additionally, NFI plots established and measured in 2014 as part of a pilot inventory in interior Alaska were also included in this report as were plots established and measured since 2015 as part of the operational NFI in interior Alaska. Some of the data from the pilot and operational NFI in interior Alaska are not yet available in the public FIA database. Only plots which meet the definition of forest land (see Section 6.1 Representation of the U.S. Land Base) are measured in the NFI, as part of the pre-field process in the FIA program, all plots or portions of plots (i.e., conditions) are classified into a land use category. This land use information on each forest and non-forest plot was used to estimate forest land area and land converted to and from forest land over the time series. The estimates in this section of the report are based on land use information from the NFI and they may differ with the other land use categories where area estimates reported in the Land Representation were not updated (see Section 6.1 Representation of the U.S. Land Base) Further, HI was not included in this section of the current Inventory so that also contributes to small differences in the area estimates reported in this section and those reported in Section 6.1 Representation of the U.S. Land Base (See Annex 3.13 for details on differences). To implement the stock-difference approach, forest Land conditions in the CONUS were observed on NFI plots at time t_0 and at a subsequent time $t_1=t_0+s$, where s is the time step (time measured in years) and is indexed by discrete (e.g., 5 year) forest age classes. The inventory from t_0 was then projected from t_1 to 2020. This projection approach requires simulating changes in the age-class distribution resulting from forest aging and disturbance events and then applying C density estimates for each age class to obtain population estimates for the nation. To implement the gain-loss approach in Alaska, forest land conditions in Alaska were observed on NFI plots from 2004 to 2020. Plot-level data from the NFI were harmonized with auxiliary data describing climate, forest structure, disturbance, and other site-specific conditions to develop non-parametric models to predict carbon stocks by forest ecosystem carbon pool as well as fluxes over the entire inventory period, 1990 to 2020. First, carbon stocks for each forest ecosystem carbon pool were predicted for the year 2016 for all base intensity NFI plot locations (representing approximately 2,403 ha) in coastal southeast and southcentral Alaska and for 1/5 intensity plots in interior Alaska (representing 12,015 ha). Next, the chronosequence of sampled NFI plots and auxiliary information (e.g., climate, forest structure, disturbance, and other site-specific data) were used to predict annual gains and losses by forest ecosystem carbon pool. The annual gains and losses were then combined with the stock estimates and disturbance information to compile plot- and population-level carbon stocks and fluxes for each year from 1990 to 2020. To estimate C stock changes in harvested wood, estimates were based on factors such as the allocation of wood to various primary and end-use products as well as half-life (the time at which half of the amount placed in use will have been discarded from use) and expected disposition (e.g., product pool, SWDS, combustion). An overview of the different methodologies and data sources used to estimate the C in forest ecosystems within the conterminous states and Alaska and harvested wood products for all of the United States is provided below. See Annex 3.13 and Domke et al. (In prep) for details and additional information related to the methods and data.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020. Details on the emission/removal trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

Forest Ecosystem Carbon from Forest Inventory

The United States applied the compilation approach described in Woodall et al. (2015a) for the current Inventory which removes the older periodic inventory data, which may be inconsistent with annual inventory data, from the estimation procedures and enables the delineation of forest C accumulation by forest growth, land use change, and natural disturbances such as fire. Development will continue on a system that attributes changes in forest C to disturbances and delineates *Land Converted to Forest Land* from *Forest Land Remaining Forest Land*. As part of this development, C pool science will continue and will be expanded to improve the estimates of C stock transfers from forest land to other land uses and include techniques to better identify land use change (see the Planned Improvements section below).

Unfortunately, the annual FIA inventory system does not extend into the 1970s, necessitating the adoption of a system to estimate carbon stocks prior to the establishment of the annual forest inventory. The estimation of carbon stocks prior to the annual national forest inventory consisted of a modeling framework comprised of a forest dynamics module (age transition matrices) and a land use dynamics module (land area transition matrices). The forest dynamics module assesses forest uptake, forest aging, and disturbance effects (e.g., disturbances such as wind, fire, and floods identified by foresters on inventory plots). The land use dynamics module assesses C stock transfers associated with afforestation and deforestation (Woodall et al. 2015b). Both modules are developed from land use area statistics and C stock change or C stock transfer by age class. The required inputs are estimated from more than 625,000 forest and non-forest observations recorded in the FIA national database (U.S. Forest Service 2022a, b, c). Model predictions prior to the annual inventory period are constructed from the estimation system using the annual estimates. The estimation system is driven by the annual forest inventory system conducted by the FIA program (Frayer and Furnival 1999; Bechtold and Patterson 2005; USDA Forest Service 2022d, 2022a). The FIA program relies on a rotating panel statistical design with a sampling intensity of one 674.5 m^2 ground plot per 2,403 ha of land and water area. A five-panel design, with 20 percent of the field plots typically measured each year within a state, is used in the eastern United States and a ten-panel design, with typically 10 percent of the field plots measured each year within a state, is used in the western United States. The interpenetrating hexagonal design across the U.S. landscape enables the sampling of plots at various intensities in a spatially and temporally unbiased manner. Typically, tree and site attributes are measured with higher sample intensity while other ecosystem attributes such as downed dead wood are sampled during summer months at lower intensities. The first step in incorporating FIA data into the estimation system is to identify annual inventory datasets by state. Inventories include data collected on permanent inventory plots on forest lands and were organized as separate datasets, each representing a complete inventory, or survey, of an individual state at a specified time. Many of the annual inventories reported for states are represented as “moving window” averages, which mean that a portion—but not all—of the previous year’s inventory is updated each year (USDA Forest Service 2022d). Forest C estimates are organized according to these state surveys, and the frequency of surveys varies by state.

Using this FIA data, separate estimates were prepared for the five C storage pools identified by IPCC (2006) and described above. All estimates were based on data collected from the extensive array of permanent, annual forest inventory plots and associated models (e.g., live tree belowground biomass) in the United States (USDA Forest Service 2022b, 2022c). Carbon conversion factors were applied at the disaggregated level of each inventory plot and then appropriately expanded to population estimates.

Carbon in Biomass

Live tree C pools include aboveground and belowground (coarse root) biomass of live trees with diameter at breast height (dbh) of at least 2.54 cm at 1.37 m above the litter. Separate estimates were made for above- and belowground biomass components. If inventory plots included data on individual trees, aboveground and belowground (coarse roots) tree C was based on Woodall et al. (2011a), which is also known as the component ratio method (CRM), and is a function of tree volume, species, and diameter. An additional component of foliage, which was not explicitly included in Woodall et al. (2011a), was added to each tree following the same CRM method.

Understory vegetation is a minor component of biomass, which is defined in the FIA program as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this Inventory, it was assumed that 10 percent of total understory C mass is belowground (Smith et al. 2006). Estimates of C density were based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003). Understory biomass represented over 1 percent of C in biomass, but its contribution rarely exceeded 2 percent of the total carbon stocks or stock changes across all forest ecosystem C pools each year.

Carbon in Dead Organic Matter

Dead organic matter was initially calculated as three separate pools—standing dead trees, downed dead wood, and litter—with C stocks estimated from sample data or from models as described below. The standing dead tree C pool includes aboveground and belowground (coarse root) biomass for trees of at least 12.7 cm dbh. Calculations followed the basic method applied to live trees (Woodall et al. 2011a) with additional modifications to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). Downed dead wood estimates are based on measurement of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008; Woodall et al. 2013). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood C estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter C is the pool of organic C (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter C. A modeling approach, using litter C measurements from FIA plots (Domke et al. 2016) was used to estimate litter C for every FIA plot used in the estimation framework.

Carbon in Forest Soil

Soil carbon is the largest terrestrial C sink with much of that C in forest ecosystems. The FIA program has been consistently measuring soil attributes as part of the annual inventory since 2001 and has amassed an extensive inventory of soil measurement data on forest land in the conterminous United States and coastal Alaska (O’Neill et al. 2005). Observations of mineral and organic soil C on forest land from the FIA program and the International Soil Carbon Monitoring Network were used to develop and implement a modeling approach that enabled the prediction of mineral and organic (i.e., undrained organic soils) soil C to a depth of 100 cm from empirical measurements to a depth of 20 cm and included site-, stand-, and climate-specific variables that yield predictions of soil C stocks specific to forest land in the United States (Domke et al. 2017). This new approach allowed for separation of mineral and organic soils, the latter also referred to as Histosols, in the *Forest Land Remaining Forest Land* category. Note that mineral and organic (i.e., undrained organic soils) soil C stock changes are reported to a depth of 100 cm for *Forest Land Remaining Forest Land* to remain consistent with past reporting in this category, however for consistency across land-use categories mineral (e.g., cropland, grassland, settlements) soil C is reported to a depth of 30 cm in Section 6.3 *Land Converted to Forest Land*. Estimates of C stock changes from organic soils shown in Table 6-8 and Table 6-9 include separately the emissions from drained organic forest soils, the methods used to develop these estimates can be found in the Drained Organic Soils section below.

Harvested Wood Carbon

Estimates of the HWP contribution to forest C sinks and emissions (hereafter called "HWP contribution") were based on methods described in Skog (2008) using the WOODCARB II model. These methods are based on IPCC (2006) guidance for estimating the HWP contribution. IPCC (2006) provides methods that allow for reporting of HWP contribution using one of several different methodological approaches: Production, stock change and atmospheric flow, as well as a default method that assumes there is no change in HWP C stocks (see Annex 3.13 for more details about each approach). The United States uses the production approach to report HWP contribution. Under the production approach, C in exported wood was estimated as if it remains in the United States, and C in imported wood was not included in the estimates. Though reported U.S. HWP estimates are based on the production approach, estimates resulting from use of the two alternative approaches, the stock change and atmospheric flow approaches, are also presented for comparison (see Annex 3.13). Annual estimates of change were calculated by tracking the annual estimated additions to and removals from the pool of products held in end uses (i.e., products in use such as housing or publications) and the pool of products held in SWDS. The C loss from harvest is reported in the Forest Ecosystem component of the *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* sections and for information purposes in the Energy sector, but the non-CO_2 emissions associated with biomass energy are included in the Energy sector emissions (see Chapter 3). EPA includes HWP within the forest chapter because that is the source of wood that goes into the HWP estimates. EPA includes HWP within the forest chapter because that is the source of wood that goes into the HWP estimates.

Solidwood products include lumber and panels. End-use categories for solidwood include single and multifamily housing, alteration and repair of housing, and other end uses. There is one product category and one end-use category for paper. Additions to and removals from pools were tracked beginning in 1900, with the exception of additions of softwood lumber to housing, which began in 1800. Solidwood and paper product production and trade data were taken from USDA Forest Service and other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census 1976; Ulrich 1985, 1989; Steer 1948; AF&PA 2006a, 2006b; Howard 2003, 2007; Howard and Jones 2016; Howard and Liang 2019). Estimates for disposal of products reflects the change over time in the fraction of products discarded to SWDS (as opposed to burning or recycling) and the fraction of SWDS that were in sanitary landfills versus dumps.

There are five annual HWP variables that were used in varying combinations to estimate HWP contribution using any one of the three main approaches listed above. These are:

(1A) annual change of C in wood and paper products in use in the United States,

(1B) annual change of C in wood and paper products in SWDS in the United States,

(2A) annual change of C in wood and paper products in use in the United States and other countries where the wood came from trees harvested in the United States,

(2B) annual change of C in wood and paper products in SWDS in the United States and other countries where the wood came from trees harvested in the United States,

(3) C in imports of wood, pulp, and paper to the United States,

(4) C in exports of wood, pulp and paper from the United States, and

(5) C in annual harvest of wood from forests in the United States.

The sum of variables 2A and 2B yielded the estimate for HWP contribution under the production estimation approach. A key assumption for estimating these variables that adds uncertainty in the estimates was that products exported from the United States and held in pools in other countries have the same half-lives for products in use, the same percentage of discarded products going to SWDS, and the same decay rates in SWDS as they would in the United States.

Uncertainty

A quantitative uncertainty analysis placed bounds on the flux estimates for forest ecosystems through a combination of sample-based and model-based approaches to uncertainty for forest ecosystem CO_2 flux using IPCC Approach 1 (Table 6-12 and Table A-214 for state-level uncertainties). A Monte Carlo Stochastic Simulation of the methods described above, and probabilistic sampling of C conversion factors, were used to determine the HWP uncertainty using IPCC Approach 2. See Annex 3.13 for additional information. The 2020 net annual change for forest C stocks was estimated to be between -744.6 and -592.2 MMT CO_2 Eq. around a central estimate of -668.1 MMT CO_2 Eq. at a 95 percent confidence level. This includes a range of -657.5 to -511.4 MMT CO_2 Eq. around a central estimate of -584.4 MMT CO_2 Eq. for forest ecosystems and -106.4 to -63.1 MMT CO_2 Eq. around a central estimate of -83.6 MMT CO_2 Eq. for HWP.

Table 6-12: Quantitative Uncertainty Estimates for Net CO_2 Flux from *Forest Land Remaining Forest Land*: Changes in Forest C Stocks (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Forest Ecosystem C Pools[a]	CO_2	(584.4)	(657.5)	(511.4)	-12.5%	12.5%
Harvested Wood Products[b]	CO_2	(83.6)	(106.4)	(63.1)	-27.3%	24.5%
Total Forest	**CO_2**	**(668.1)**	**(744.6)**	**(592.2)**	**-11.5%**	**11.4%**

[a] Range of flux estimates predicted through a combination of sample-based and model-based uncertainty for a 95 percent confidence interval, IPCC Approach 1.

[b] Range of flux estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval, IPCC Approach 2.

Notes: Parentheses indicate negative values or net uptake. Totals may not sum due to independent rounding.

QA/QC and Verification

As discussed above, the FIA program has conducted consistent forest surveys based on extensive statistically-based sampling of most of the forest land in the conterminous United States, dating back to 1952. The FIA program includes numerous quality assurance and quality control (QA/QC) procedures, including calibration among field crews, duplicate surveys of some plots, and systematic checking of recorded data. Because of the statistically-based sampling, the large number of survey plots, and the quality of the data, the survey databases developed by the FIA program form a strong foundation for C stock estimates. Field sampling protocols, summary data, and detailed inventory databases are archived and are publicly available on the Internet (USDA Forest Service 2022d).

General quality control procedures were used in performing calculations to estimate C stocks based on survey data. For example, the C datasets, which include inventory variables such as areas and volumes, were compared to standard inventory summaries such as the forest resource statistics of Oswalt et al. (2019) or selected population estimates generated from the FIA database, which are available at an FIA internet site (USDA Forest Service 2022b). Agreement between the C datasets and the original inventories is important to verify accuracy of the data used.

Estimates of the HWP variables and the HWP contribution under the production estimation approach use data from U.S. Census and USDA Forest Service surveys of production and trade and other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census 1976; Ulrich 1985, 1989; Steer 1948; AF&PA 2006a, 2006b; Howard 2003, 2007; Howard and Jones 2016; Howard and Liang 2019; AF&PA 2021; FAO 2021). Factors to convert wood and paper to units of C are based on estimates by industry and Forest Service published sources (see Annex 3.13). The WOODCARB II model uses estimation methods suggested by IPCC (2006). Estimates of annual C change in solidwood and paper products in use were calibrated to meet two independent criteria. The first criterion is that the WOODCARB II model estimate of C in houses standing in 2001 needs to match an independent estimate of C in housing based on U.S. Census and USDA Forest Service survey data. Meeting the first criterion resulted in an estimated half-life of about 80 years for single family housing built in the 1920s, which is confirmed by other U.S. Census data on housing. The second criterion is that the WOODCARB II model estimate of wood and paper being discarded to SWDS needs to match EPA estimates of discards used in the Waste sector each year over the period 1990 to 2000 (EPA 2006). These criteria help reduce uncertainty in estimates of annual change in C in products in use in the United States and, to a lesser degree, reduce uncertainty in estimates of annual change in C in products made from wood harvested in the United States. In addition, WOODCARB II landfill decay rates have been validated by ensuring that estimates of CH_4 emissions from landfills based on EPA (2006) data are reasonable in comparison to CH_4 estimates based on WOODCARB II landfill decay rates.

Recalculations Discussion

The methods used in the current Inventory to compile estimates for forest ecosystem carbon stocks and stock changes and HWPs from 1990 through 2020 are consistent with those used in the previous (1990 through 2019) Inventory. Population estimates of carbon stocks and stock changes were compiled using NFI data from each U.S. state and national estimates were compiled by summing over all states. New NFI data in most states were incorporated in the latest Inventory which contributed to increases in forest land area estimates and carbon stocks, particularly in Alaska where new data from 2018 to 2020 (with the exception of litter and soil) were included (Table 6-13). Fire data sources were also updated for AK through 2020 and this combined with the new NFI data for the years 2018 through 2020 resulted in substantial changes in carbon stocks and stock changes. In 2019, in particular, an estimated 646,276 ha of forest land burned in AK—the fifth largest fire year in the time-series— which resulted in substantial differences in the carbon stock and stock change estimates reported in the previous (i.e., 1990 through 2019) Inventory and those in the current Inventory. Additionally, this report does not include separate emission estimates for prescribed fires (a change from recent annual reports) because the data records do not specify the fire origins allowing for separation of wild and prescribed fire emissions. Soil carbon stocks increased in the latest Inventory relative to the previous Inventory and this change can be attributed to refinements in the Digital General Soil Map of the United States (STATSGO2) dataset where soil orders may have changed in the updated data product (Table 6-13). This resulted in a structural change in the soil organic carbon estimates for mineral and organic soils across the entire time series, particularly in AK where new data on forest area was included for the years 2018 through 2020 (Table 6-8). Finally, recent land use change in AK (since 2015) also contributed to variability in soil carbon stocks and stock changes in recent years in the time series which contributed to differences in estimates in the 2021 Inventory and the current Inventory. New data in the HWP time-series result in a minor decrease (< 1 percent) in carbon stocks in the HWP pools but a substantial decrease (38 percent) in the carbon stock change estimates for Products in Use and to a lesser extent (7 percent) in SWDS between the previous Inventory and the current Inventory. The new HWP data suggest a continued decline in paper products in use over time due to changes in consumer behavior (i.e., more use of electronic information sources) and a small drop in solid wood products in the last year due to a downturn in the economy associated with the global pandemic.

Table 6-13: Recalculations of Forest Area (1,000 ha) and C Stocks in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

	2020 Estimate, Previous Inventory	2020 Estimate, Current Inventory	2021 Estimate, Current Inventory
Forest Area (1000 ha)	***279,289***	***282,061***	***281,951***
Carbon Pools (MMT C)			
Forest	**55,933**	**58,156**	**58,316**
Aboveground Biomass	15,260	15,579	15,688
Belowground Biomass	3,103	3,085	3,106

Dead Wood	2,852	2,868	2,896
Litter	3,638	3,809	3,810
Soil (Mineral)	25,147	25,457	25,459
Soil (Organic)	5,933	7,357	7,357
Harvested Wood	**2,699**	**2,695**	**2,718**
Products in Use	1,532	1,530	1,536
SWDS	1,167	1,165	1,182
Total Stock	**58,632**	**60,851**	**61,034**

Note: Totals may not sum due to independent rounding.

Table 6-14: Recalculations of Net C Flux from Forest Ecosystem Pools in *Forest Land Remaining Forest Land* and Harvested Wood Pools (MMT C)

Carbon Pool (MMT C)	2019 Estimate, Previous Inventory	2019 Estimate, Current Inventory	2020 Estimate, Current Inventory
Forest	**(159.1)**	**(148.9)**	**(159.4)**
Aboveground Biomass	(107.4)	(107.2)	(108.7)
Belowground Biomass	(24.3)	(21.3)	(21.6)
Dead Wood	(27.1)	(26.5)	(27.7)
Litter	(0.1)	6.2	(0.5)
Soil (Mineral)	(0.7)	(0.2)	(1.1)
Soil (Organic)	0.3	(0.2)	0.1
Drained organic soil	0.2	0.2	0.2
Harvested Wood	**(29.6)**	**(24.2)**	**(22.8)**
Products in Use	(10.7)	(6.6)	(5.5)
SWDS	(18.9)	(17.6)	(17.3)
Total Net Flux	**(188.7)**	**(173.1)**	**(182.2)**

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Planned Improvements

Reliable estimates of forest C stocks and changes across the diverse ecosystems of the United States require a high level of investment in both annual monitoring and associated analytical techniques. Development of improved monitoring/reporting techniques is a continuous process that occurs simultaneously with annual Inventory submissions. Planned improvements can be broadly assigned to the following categories: development of a robust estimation and reporting system, individual C pool estimation, coordination with other land-use categories, and annual inventory data incorporation.

While this Inventory submission includes C change by *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* and C stock changes for all IPCC pools in these two categories, there are many improvements that are still necessary. The estimation approach used for the CONUS in the current Inventory for the forest land category operates at the state scale, whereas previously the western United States and southeast and southcentral coastal Alaska operated at a regional scale. While this is an improvement over previous Inventories and led to improved estimation and separation of land use categories in the current Inventory, research is underway to leverage all FIA data and 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 not explicitly estimated. In addition to integrating auxiliary information into the estimation framework and leveraging all NFI plot measurements, alternative estimators are also being evaluated which 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. This will also facilitate separation of prescribed and wildfire emissions in future reports. The transparency and repeatability of estimation and reporting systems will be improved through the dissemination of open source code (e.g., R programming language) in concert with the public availability of the annual NFI (USDA Forest Service 2022b). Also, several FIA database processes are being institutionalized to increase efficiency and

QA/QC in reporting and further improve transparency, completeness, consistency, accuracy, and availability of data used in reporting. Finally, a combination of approaches were used to estimate uncertainty associated with C stock changes in the *Forest Land Remaining Forest Land* category in this report. There is research underway investigating more robust approaches to total uncertainty (Clough et al. 2016), which will be considered in future Inventory reports.

The modeling framework used to estimate downed dead wood within the dead wood C pool (Smith et al. 2022) will be updated similar to the litter (Domke et al. 2016) and soil C pools (Domke et al. 2017). Finally, components of other pools, such as C in belowground biomass (Russell et al. 2015) and understory vegetation (Russell et al. 2014; Johnson et al. 2017), are being explored but may require additional investment in field inventories before improvements can be realized in the Inventory report.

The foundation of forest C estimation and reporting is the annual NFI. The ongoing annual surveys by the FIA program are expected to improve the accuracy and precision of forest C estimates as new state surveys become available (USDA Forest Service 2022b). With the exception of Wyoming and western Oklahoma, all other states in the CONUS now have sufficient annual NFI data to consistently estimate C stocks and stock changes for the future using the state-level compilation system. The FIA program continues to install permanent plots in Alaska as part of the operational NFI and as more plots are added to the NFI they will be used to improve estimates for all managed forest land in Alaska. The methods used to include all managed forest land in Alaska will be used in the years ahead for Hawaii and U.S. Territories as forest C data become available (only a small number of plots from Hawaii are currently available from the annualized sampling design). To that end, research is underway to incorporate all NFI information (both annual and periodic data) and the dense time series of remotely sensed data in multiple inferential frameworks for estimating greenhouse gas emissions and removals as well as change detection and attribution across the entire reporting period and all managed forest land in the United States. Leveraging this auxiliary information will aid not only the interior Alaska effort but the entire inventory system. In addition to fully inventorying all managed forest land in the United States, the more intensive sampling of fine woody debris, litter, and SOC on a subset of FIA plots continues and will substantially improve resolution of C pools (i.e., greater sample intensity; Westfall et al. 2013) as this information becomes available (Woodall et al. 2011b). Increased sample intensity of some C pools and using annualized sampling data as it becomes available for those states currently not reporting are planned for future submissions. The NFI sampling frame extends beyond the forest land use category (e.g., woodlands, which fall into the grasslands land use category, and urban areas, which fall into the settlements land use category) with inventory-relevant information for trees outside of forest land. These data will be utilized as they become available in the NFI.

Non-CO_2 Emissions from Forest Fires

Emissions of non-CO_2 gases from forest fires were estimated using U.S.-specific data and models for annual area of forest burned, fuel, consumption, and emission consistent with IPCC (2006). In 2020, emissions from this source were estimated to be 13.7 MMT CO_2 Eq. of CH_4 and 11.7 MMT CO_2 Eq. of N_2O (Table 6-15; kt units provided in Table 6-16). The estimates of non-CO_2 emissions from forest fires are for the conterminous 48 states and all managed forest land in Alaska (Ogle et al. 2018).

Table 6-15: Non-CO_2 Emissions from Forest Fires (MMT CO_2 Eq.)[a]

Gas	1990	2005	2016	2017	2018	2019	2020
CH_4	2.3	6.5	3.9	9.5	6.2	1.1	13.6
N_2O	1.8	6.3	3.9	8.2	5.7	1.3	11.7
Total	**4.1**	**12.8**	**7.8**	**17.7**	**11.9**	**2.5**	**25.3**

[a] These estimates include Non-CO_2 Emissions from Forest Fires on *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Note: Totals may not sum due to independent rounding

Table 6-16: Non-CO_2 Emissions from Forest Fires (kt)[a]

Gas	1990	2005	2016	2017	2018	2019	2020

CH_4	92		260		154	381	249	45	545
N_2O	6		21		13	27	19	4	39
CO	2,589		7,284		3,775	8,591	5,457	1,095	11,739
NO_x	47		120		87	167	119	30	224

[a] These estimates include Non-CO_2 Emissions from Forest Fires on *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

Methodology and Time-Series Consistency

Non-CO_2 emissions from forest fires—primarily CH_4 and N_2O emissions—were calculated consistent with IPCC (2006) methodology, which included U.S.-specific data and models on area, fuel, consumption, and emission. The annual estimates were calculated by the Wildland Fire Emissions Inventory System (WFEIS, French et al. 2011, 2014) with area burned based on Monitoring Trends in Burn Severity (MTBS, Eidenshink et al. 2007) or MODIS burned area mapping (MODIS MCD64A1, Giglio et al. 2018) data. The MTBS data available for this report (MTBS 2021) included fires through 2018 with only a partial set of the 2019 fires included with the data. The MODIS-based records include 2001 through 2020. Emissions reported here originate from MTBS data for the 1990 to 2018 interval, and the 2019 and 2020 emissions are based on MODIS burned areas. All other parts of calculations—fuels, fire characteristics, and emissions—are via WFEIS and therefore identical throughout the 1990 to 2020 interval. Note that N_2O emissions are not included in WFEIS calculations; the emissions provided here are based on the average N_2O to CO_2 ratio of 0.000166 following Larkin et al. (2014). See Emissions from Forest Fires in Annex 3.13 for further details on all fire-related emissions calculations for forests. Consistent data sources, data processing, and calculation methods were applied to the entire time series to ensure time-series consistency from 1990 through 2020.

Uncertainty

In order to quantify the uncertainties for non-CO_2 emissions from forest fires, a Monte Carlo (IPCC Approach 2) sampling approach was employed to propagate uncertainties in per-fire quantities of fuel and forest area burned. See Annex 3.13 for the quantities and assumptions employed to define and propagate uncertainty. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-17.

Table 6-17: Quantitative Uncertainty Estimates of Non-CO_2 Emissions from Forest Fires (MMT CO_2 Eq. and Percent)[a]

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[b] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Non-CO_2 Emissions from Forest Fires	CH_4	13.6	8.6	19.3	-37%	42%
Non-CO_2 Emissions from Forest Fires	N_2O	11.7	7.6	16.3	-35%	39%

[a] These estimates include Non-CO_2 Emissions from Forest Fires on *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*.

[b] Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for estimating non-CO_2 emissions from forest fires included checking input data, documentation, and calculations to ensure data were properly handled through the inventory process and results were consistent with values expected from those calculations. The QA/QC procedures did not reveal any inaccuracies or incorrect input values.

Recalculations Discussion

The methods used in the current (1990 through 2020) Inventory to compile estimates of non-CO_2 emissions from forest fires represent a change relative to the previous (1990 through 2019) Inventory. The basic components of calculating forest fire emissions (IPCC 2006) remain unchanged, but the WFEIS-based estimates for fuel, combustion, and allocation of emissions provide both increased specificity (for site and fire) and more consistent application of these factors. An additional source of change recalculation are recent updates to the MTBS fire records (post-2000 fires). These recalculations resulted in a 10 percent increase in average annual emissions over the 2014 to 2018 interval as compared to the previous Inventory (interval represents years with emissions estimated via both past and current methods for comparison).

Planned Improvements

Continuing improvements are planned for developing better fire and site-specific estimates for forest fires. The focus will be on addressing three aspects of reporting: best use of WFEIS, better resolution of uncertainty, and identification of forest area burned but not included in the MTBS records.

N_2O Emissions from N Additions to Forest Soils

Of the synthetic nitrogen (N) fertilizers applied to soils in the United States, no more than one percent is applied to forest soils. Application rates are similar to those occurring on cropland soils, but in any given year, only a small proportion of total forested land receives N fertilizer. This is because forests are typically fertilized only twice during their approximately 40-year growth cycle (once at planting and once midway through their life cycle). While the rate of N fertilizer application for the area of forests that receives N fertilizer in any given year is relatively high, the annual application rate is quite low over the entire area of forest land.

N additions to soils result in direct and indirect N_2O emissions. Direct emissions occur on-site due to the N additions. Indirect emissions result from fertilizer N that is transformed and transported to another location through volatilization in the form of ammonia [NH_3] and nitrogen oxide [NO_x], in addition to leaching and runoff of nitrates [NO_3], and later converted into N_2O at the off-site location. The indirect emissions are assigned to forest land because the management activity leading to the emissions occurred in forest land.

Direct soil N_2O emissions from *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*[33] in 2020 were 0.3 MMT CO_2 Eq. (1.2 kt), and the indirect emissions were 0.1 MMT CO_2 Eq. (0.4 kt). Total emissions for 2020 were 0.5 MMT CO_2 Eq. (1.5 kt) and have increased by 455 percent from 1990 to 2020. Total forest soil N_2O emissions are summarized in Table 6-18.

Table 6-18: N_2O Fluxes from Soils in *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* (MMT CO_2 Eq. and kt N_2O)

	1990		2005		2016	2017	2018	2019	2020
Direct N_2O Fluxes from Soils									
MMT CO_2 Eq.	0.1		0.3		0.3	0.3	0.3	0.3	0.3
kt N_2O	+		1.2		1.2	1.2	1.2	1.2	1.2
Indirect N_2O Fluxes from Soils									
MMT CO_2 Eq.	+		0.1		0.1	0.1	0.1	0.1	0.1
kt N_2O	+		+		+	+	+	+	+
Total									
MMT CO_2 Eq.	**0.1**		**0.5**		**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
kt N_2O	**+**		**1.5**		**1.5**	**1.5**	**1.5**	**1.5**	**1.5**

+ Does not exceed 0.05 MMT CO_2 Eq. or 0.5 kt.

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[33] The N_2O emissions from *Land Converted to Forest Land* are included with *Forest Land Remaining Forest Land* because it is not currently possible to separate the activity data by land use conversion category.

Note: Totals may not sum due to independent rounding. The N_2O emissions from *Land Converted to Forest Land* are included with *Forest Land Remaining Forest Land* because it is not currently possible to separate the activity data by land use conversion category.

Methodology and Time-Series Consistency

The IPCC Tier 1 approach is used to estimate N_2O from soils within *Forest Land Remaining Forest Land* and *Land Converted to Forest Land*. According to U.S. Forest Service statistics for 1996 (USDA Forest Service 2001), approximately 75 percent of trees planted are for timber, and about 60 percent of national total harvested forest area is in the southeastern United States. Although southeastern pine plantations represent the majority of fertilized forests in the United States, this Inventory also incorporated N fertilizer application to commercial Douglas-fir stands in western Oregon and Washington. For the Southeast, estimates of direct N_2O emissions from fertilizer applications to forests are based on the area of pine plantations receiving fertilizer in the southeastern United States and estimated application rates (Albaugh et al. 2007; Fox et al. 2007). Fertilizer application is rare for hardwoods and therefore not included in the inventory (Binkley et al. 1995). For each year, the area of pine receiving N fertilizer is multiplied by the weighted average of the reported range of N fertilization rates (121 lbs. N per acre). Area data for pine plantations receiving fertilizer in the Southeast are not available for 2005 through 2020, so data from 2004 are used for these years. For commercial forests in Oregon and Washington, only fertilizer applied to Douglas-fir is addressed in the inventory because the vast majority (approximately 95 percent) of the total fertilizer applied to forests in this region is applied to Douglas-fir (Briggs 2007). Estimates of total Douglas-fir area and the portion of fertilized area are multiplied to obtain annual area estimates of fertilized Douglas-fir stands. Similar to the Southeast, data are not available for 2005 through 2020, so data from 2004 are used for these years. The annual area estimates are multiplied by the typical rate used in this region (200 lbs. N per acre) to estimate total N applied (Briggs 2007), and the total N applied to forests is multiplied by the IPCC (2006) default emission factor of one percent to estimate direct N_2O emissions.

For indirect emissions, the volatilization and leaching/runoff N fractions for forest land are calculated using the IPCC default factors of 10 percent and 30 percent, respectively. The amount of N volatilized is multiplied by the IPCC default factor of one percent for the portion of volatilized N that is converted to N_2O off-site. The amount of N leached/runoff is multiplied by the IPCC default factor of 0.075 percent for the portion of leached/runoff N that is converted to N_2O off-site. The resulting estimates are summed to obtain total indirect emissions.

The same method is applied in all years of this Inventory to ensure time-series consistency from 1990 through 2020.

Uncertainty

The amount of N_2O emitted from forests depends not only on N inputs and fertilized area, but also on a large number of variables, including organic C availability, oxygen gas partial pressure, soil moisture content, pH, temperature, and tree planting/harvesting cycles. The effect of the combined interaction of these variables on N_2O flux is complex and highly uncertain. IPCC (2006) does not incorporate any of these variables into the default methodology, except variation in estimated fertilizer application rates and estimated areas of forested land receiving N fertilizer. All forest soils are treated equivalently under this methodology. Furthermore, only applications of synthetic N fertilizers to forest are captured in this inventory, so applications of organic N fertilizers are not estimated. However, the total quantity of organic N inputs to soils in the United States is included in the inventory for Agricultural Soil Management (Section 5.4) and *Settlements Remaining Settlements* (Section 6.10).

Uncertainties exist in the fertilization rates, annual area of forest lands receiving fertilizer, and the emission factors. Fertilization rates are assigned a default level[34] of uncertainty at ±50 percent, and area receiving fertilizer is assigned a ±20 percent according to expert knowledge (Binkley 2004). The uncertainty ranges around the 2004 activity data and emission factor input variables are directly applied to the 2020 emission estimates. IPCC (2006)

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[34] Uncertainty is unknown for the fertilization rates so a conservative value of ±50 percent is used in the analysis.

provided estimates for the uncertainty associated with direct and indirect N_2O emission factor for synthetic N fertilizer application to soils.

Uncertainty is quantified using simple error propagation methods (IPCC 2006). The results of the quantitative uncertainty analysis are summarized in Table 6-19. Direct N_2O fluxes from soils in 2020 are estimated to be between 0.1 and 1.1 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 59 percent below and 211 percent above the emission estimate of 0.3 MMT CO_2 Eq. for 2020. Indirect N_2O emissions in 2020 are 0.1 MMT CO_2 Eq. and have a range are between 0.02 and 0.4 MMT CO_2 Eq., which is 86 percent below to 238 percent above the emission estimate for 2020.

Table 6-19: Quantitative Uncertainty Estimates of N_2O Fluxes from Soils in *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
Forest Land Remaining Forest Land			**Lower Bound**	**Upper Bound**	**Lower Bound**	**Upper Bound**
Direct N_2O Fluxes from Soils	N_2O	0.3	0.1	1.1	-59%	+211%
Indirect N_2O Fluxes from Soils	N_2O	0.1	+	0.4	-86%	+238%

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding

QA/QC and Verification

The spreadsheet containing fertilizer applied to forests and calculations for N_2O and uncertainty ranges are checked and verified based on the sources of these data.

Recalculations Discussion

No recalculations were performed for the 1990 to 2019 estimates.

CO_2, CH_4, and N_2O Emissions from Drained Organic Soils[35]

Drained organic soils on forest land are identified separately from other forest soils largely because mineralization of the exposed or partially dried organic material results in continuous CO_2 and N_2O emissions (IPCC 2006). In addition, the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014) calls for estimating CH_4 emissions from these drained organic soils and the ditch networks used to drain them.

Organic soils are identified on the basis of thickness of organic horizon and percent organic matter. All organic soils are assumed to have originally been wet, and drained organic soils are further characterized by drainage or the process of artificially lowering the soil water table, which exposes the organic material to drying and the associated emissions described in this section. The land base considered here is drained inland organic soils that are coincident with forest area as identified by the NFI of the USDA Forest Service (USDA Forest Service 2022b).

The estimated area of drained organic soils on forest land is 70,849 ha and did not change over the time series based on the data used to compile the estimates in the current Inventory. These estimates are based on permanent plot locations of the NFI (USDA Forest Service 2022b) coincident with mapped organic soil locations (STATSGO2 2016), which identifies forest land on organic soils. Forest sites that are drained are not explicitly

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[35] Estimates of C and CO_2 emissions from drained organic soils are described in this section but reported in Table 6-8 and Table 6-9 for both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* in order to allow for reporting of all C stock changes on forest lands in a complete and comprehensive manner.

identified in the data, but for this estimate, planted forest stands on sites identified as mesic or xeric (which are identified in USDA Forest Service 2022c, d) are labeled "drained organic soil" sites.

Land use, region, and climate are broad determinants of emissions as are more site-specific factors such as nutrient status, drainage level, exposure, or disturbance. Current data are limited in spatial precision and thus lack site specific details. At the same time, corresponding emissions factor data specific to U.S. forests are similarly lacking. Tier 1 estimates are provided here following IPCC (2014). Total annual non-CO_2 emissions on forest land with drained organic soils in 2020 are estimated as 0.8 MMT CO_2 Eq. per year (Table 6-20; kt units provided in 6-21).

The Tier 1 methodology provides methods to estimate C emission as CO_2 from three pathways: direct emissions primarily from mineralization; indirect, or off-site, emissions associated with dissolved organic carbon releasing CO_2 from drainage waters; and emissions from (peat) fires on organic soils. Data about forest fires specifically located on drained organic soils are not currently available; as a result, no corresponding estimate is provided here. Non-CO_2 emissions provided here include CH_4 and N_2O. Methane emissions generally associated with anoxic conditions do occur from the drained land surface, but the majority of these emissions originate from ditches constructed to facilitate drainage at these sites. Emission of N_2O can be significant from these drained organic soils in contrast to the very low emissions from wet organic soils.

Table 6-20: Non-CO_2 Emissions from Drained Organic Forest Soils[a,b] (MMT CO_2 Eq.)

Source	1990		2005		2016	2017	2018	2019	2020
CH_4	+		+		+	+	+	+	+
N_2O	0.1		0.1		0.1	0.1	0. 1	0.1	0.1
Total	**0.8**		**0.8**		**0.8**	**0.8**	**0.8**	**0.8**	**0.8**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] This table includes estimates from *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[b] Estimates of C and CO_2 emissions from drained organic soils are described in this section but reported in Table 6-8 and Table 6-9 for both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* in order to allow for reporting of all C stock changes on forest lands in a complete and comprehensive manner.

Note: Totals may not sum due to independent rounding.

Table 6-21: Non-CO_2 Emissions from Drained Organic Forest Soils[a,b] (kt)

Source	1990		2005		2016	2017	2018	2019	2020
CH_4	1		1		1	1	1	1	1
N_2O	+		+		+	+	+	+	+

+ Does not exceed 0.5 kt.

[a] This table includes estimates from *Forest Land Remaining Forest Land* and *Land Converted to Forest Land.*

[b] Estimates of C and CO_2 emissions from drained organic soils are described in this section but reported in Table 6-8 and Table 6-9 for both *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* in order to allow for reporting of all C stock changes on forest lands in a complete and comprehensive manner.

Methodology and Time-Series Consistency

The Tier 1 methods for estimating CO_2, CH_4 and N_2O emissions from drained inland organic soils on forest lands follow IPCC (2006), with extensive updates and additional material presented in the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2014). With the exception of quantifying area of forest on drained organic soils, which is user-supplied, all quantities necessary for Tier 1 estimates are provided in Chapter 2, Drained Inland Organic Soils of IPCC (2014).

Estimated area of drained organic soils on forest land is 70,849 ha based on analysis of the permanent NFI of the USDA Forest Service and did not change over the time series. The most recent plot data per state within the inventories were used in a spatial overlay with the STATSGO2 (2016) soils data, and forest plots coincident with the soil order histosol were selected as having organic soils. Information specific to identifying "drained organic" are not in the inventory data so an indirect approach was employed here. Specifically, artificially regenerated forest stands (inventory field STDORGCD=1) on mesic or xeric sites (inventory field 11≤PHYSCLCD≤29) are labeled "drained organic soil" sites. From this selection, forest area and sampling error for forest on drained organic sites are based on the population estimates developed within the inventory data for each state (USDA Forest Service 2022d). Eight states, all temperate forests (including pine forest in northern Florida, which largely display characteristics of temperate forests), were identified as having drained organic soils (Table 6-22).

Table 6-22: States identified as having Drained Organic Soils, Area of Forest on Drained Organic Soils, and Sampling Error

State	Forest on Drained Organic Soil (1,000 ha)	Sampling Error (68.3% as ± Percentage of Estimate)
Florida	2.4	79
Georgia	3.7	71
Michigan	18.7	34
Minnesota	30.2	19
North Carolina	1.3	99
Virginia	2.3	102
Washington	2.1	101
Wisconsin	10.1	30
Total	**70.8**	**14**

Note: Totals may not sum due to independent rounding.

The Tier 1 methodology provides methods to estimate emissions for three pathways of C emission as CO_2. Note that subsequent mention of equations and tables in the remainder of this section refer to Chapter 2 of IPCC (2014). The first pathway–direct CO_2 emissions–is calculated according to Equation 2.3 and Table 2.1 as the product of forest area and emission factor for temperate drained forest land. The second pathway—indirect, or off-site, emissions—is associated with dissolved organic carbon releasing CO_2 from drainage waters according to Equation 2.4 and Table 2.2, which represent a default composite of the three pathways for this flux: (1) the flux of dissolved organic carbon (DOC) from natural (undrained) organic soil; (2) the proportional increase in DOC flux from drained organic soils relative to undrained sites; and (3) the conversion factor for the part of DOC converted to CO_2 after export from a site. The third pathway—emissions from (peat) fires on organic soils—assumes that the drained organic soils burn in a fire but not any wet organic soils. However, this Inventory currently does not include emissions for this pathway because data on the combined fire and drained organic soils information are not available at this time; this may become available in the future with additional analysis.

Non-CO_2 emissions, according to the Tier 1 method, include methane (CH_4), nitrous oxide (N_2O), and carbon monoxide (CO). Emissions associated with peat fires include factors for CH_4 and CO in addition to CO_2, but fire estimates are assumed to be zero for the current Inventory, as discussed above. Methane emissions generally associated with anoxic conditions do occur from the drained land surface, but the majority of these emissions originate from ditches constructed to facilitate drainage at these sites. From this, two separate emission factors are used, one for emissions from the area of drained soils and a second for emissions from drainage ditch waterways. Calculations are according to Equation 2.6 and Tables 2.3 and 2.4, which includes the default fraction of the total area of drained organic soil which is occupied by ditches. Emissions of N_2O can be significant from these drained soils in contrast to the very low emissions from wet organic soils. Calculations are according to Equation 2.7 and Table 2.5, which provide the estimate as kg N per year.

Methodological calculations were applied to the entire set of estimates for 1990 through 2020. Year-specific data are not available. Estimates are based on a single year and applied as the annual estimates over the interval.

Uncertainty

Uncertainties are based on the sampling error associated with forest area of drained organic soils and the uncertainties provided in the Chapter 2 (IPCC 2014) emissions factors (Table 6-23). The estimates and resulting quantities representing uncertainty are based on the IPCC Approach 1–error propagation. However, probabilistic sampling of the distributions defined for each emission factor produced a histogram result that contained a mean and 95 percent confidence interval. The primary reason for this approach was to develop a numerical representation of uncertainty with the potential for combining with other forest components. The methods and parameters applied here are identical to previous inventories, but input values were resampled for this inventory, which results in minor changes in the less significant digits in the resulting estimates, relative to past values. The total non-CO_2 emissions in 2020 from drained organic soils on *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* were estimated to be between -0.006 and 0.162 MMT CO_2 Eq. around a central estimate of 0.073 MMT CO_2 Eq. at a 95 percent confidence level.

Table 6-23: Quantitative Uncertainty Estimates for Non-CO_2 Emissions on Drained Organic Forest Soils (MMT CO_2 Eq. and Percent)[a]

Source	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
CH_4	+	+	+	-69%	+82%
N_2O	0.1	+	0.1	-118%	+132%
Total	**0.1**	**+**	**0.2**	**-109%**	**+123%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of flux estimates predicted through a combination of sample-based and IPCC defaults for a 95 percent confidence interval, IPCC Approach 1.

Note: Totals may not sum due to independent rounding.

QA/QC and Verification

IPCC (2014) guidance cautions of a possibility of double counting some of these emissions. Specifically, the off-site emissions of dissolved organic C from drainage waters may be double counted if soil C stock and change is based on sampling and this C is captured in that sampling. Double counting in this case is unlikely since plots identified as drained were treated separately in this chapter. Additionally, some of the non-CO_2 emissions may be included in either the Wetlands or sections on N_2O emissions from managed soils. These paths to double counting emissions are unlikely here because these issues are taken into consideration when developing the estimates and this chapter is the only section directly including such emissions on forest land.

Recalculations Discussion

No recalculations were performed for the 1990 through 2019 estimates.

Planned Improvements

Additional data will be compiled to update estimates of forest areas on drained organic soils as new reports are made available and new geospatial products become available.

6.3 Land Converted to Forest Land (CRF Source Category 4A2)

The C stock change estimates for *Land Converted to Forest Land* that are provided in this Inventory include all forest land in an inventory year that had been in another land use(s) during the previous 20 years.[36] For example, cropland or grassland converted to forest land during the past 20 years would be reported in this category. Converted lands are in this category for 20 years as recommended in the *2006 IPCC Guidelines* (IPCC 2006), after which they are classified as *Forest Land Remaining Forest Land*. Estimates of C stock changes from all pools (i.e., aboveground and belowground biomass, dead wood, litter and soils), as recommended by IPCC (2006), are included in the *Land Converted to Forest Land* category of this Inventory.

Area of Land Converted to Forest in the United States[37]

Land conversion to and from forests has occurred regularly throughout U.S. history. The 1970s and 1980s saw a resurgence of federally sponsored forest management programs (e.g., the Forestry Incentive Program) and soil conservation programs (e.g., the Conservation Reserve Program), which have focused on tree planting, improving timber management activities, combating soil erosion, and converting marginal cropland to forests. Recent analyses suggest that net accumulation of forest area continues in areas of the United States, in particular the northeastern United States (Woodall et al. 2015b). Specifically, the annual conversion of land from other land-use categories (i.e., Cropland, Grassland, Wetlands, Settlements, and Other Lands) to Forest Land resulted in a fairly continuous net annual accretion of Forest Land area from over the time series at an average rate of 1.0 million ha year^{-1}.

Over the 20-year conversion period used in the *Land Converted to Forest Land* category, the conversion of cropland to forest land resulted in the largest source of C transfer and uptake, accounting for approximately 40 percent of the uptake annually. Estimated C uptake has remained relatively stable over the time series across all conversion categories (see Table 6-24). The net flux of C from all forest pool stock changes in 2020 was -99.5 MMT CO_2 Eq. (-27.1 MMT C) (Table 6-24 and Table 6-25).

Mineral soil C stocks increase slightly over the time series for Land Converted to Forest Land. The small gains are associated with Cropland Converted to Forest Land, Settlements Converted to Forest Land, and Other Land Converted to Forest Land. Much of this conversion is from soils that are more intensively used under annual crop production or settlement management, or are conversions from other land, which has little to no soil C. In contrast, Grassland Converted to Forest Land leads to a loss of soil C across the time series, which negates some of the gain in soil C with the other land use conversions. Managed pasture to Forest Land is the most common conversion. This conversion leads to a loss of soil C because pastures are mostly improved in the United States with fertilization and/or irrigation, which enhances C input to soils relative to typical forest management activities.

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[36] The annual NFI data used to compile estimates of carbon transfer and uptake in this section are based on 5- to 10-yr remeasurements so the exact conversion period was limited to the remeasured data over the time series.

[37] The estimates reported in this section only include the 48 conterminous states in the United States. Land use conversion to forest in Alaska and Hawaii were not included. Since area estimates for some land use categories were not updated in the Land Representation in the current Inventory there are differences in the area estimates reported in this section and those reported in Section 6.1 Representation of the U.S. Land Base. See Annex 3.13, Table A-213 for annual differences between the forest area reported in Section 6.1 Representation of the U.S. Land Base and Section 6.3 Land Converted to Forest Land.

Table 6-24: Net CO_2 Flux from Forest C Pools in *Land Converted to Forest Land* by Land Use Change Category (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2016	2017	2018	2019	2020
Cropland Converted to Forest Land	**(39.6)**	**(39.5)**	**(39.5)**	**(39.6)**	**(39.6)**	**(39.6)**	**(39.6)**
Aboveground Biomass	(23.0)	(23.0)	(23.0)	(23.0)	(23.0)	(23.0)	(23.0)
Belowground Biomass	(4.4)	(4.4)	(4.4)	(4.4)	(4.4)	(4.4)	(4.4)
Dead Wood	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)
Litter	(6.9)	(6.9)	(6.9)	(6.9)	(6.9)	(6.9)	(6.9)
Mineral Soil	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Grassland Converted to Forest Land	**(11.5)**	**(11.6)**	**(11.8)**	**(11.8)**	**(11.8)**	**(11.8)**	**(11.8)**
Aboveground Biomass	(5.9)	(6.0)	(6.1)	(6.1)	(6.1)	(6.1)	(6.1)
Belowground Biomass	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)
Dead Wood	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)
Litter	(3.8)	(3.8)	(3.9)	(3.9)	(3.9)	(3.9)	(3.9)
Mineral Soil	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Other Land Converted to Forest Land	**(10.1)**	**(10.7)**	**(10.9)**	**(10.9)**	**(10.9)**	**(10.9)**	**(10.9)**
Aboveground Biomass	(4.7)	(4.8)	(4.9)	(4.9)	(4.9)	(4.9)	(4.9)
Belowground Biomass	(0.8)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)
Dead Wood	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)
Litter	(2.5)	(2.5)	(2.6)	(2.6)	(2.6)	(2.6)	(2.6)
Mineral Soil	(0.6)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)
Settlements Converted to Forest Land	**(34.2)**	**(34.1)**	**(34.1)**	**(34.1)**	**(34.1)**	**(34.1)**	**(34.1)**
Aboveground Biomass	(20.9)	(20.9)	(20.8)	(20.8)	(20.8)	(20.8)	(20.8)
Belowground Biomass	(4.0)	(4.0)	(4.0)	(4.0)	(4.0)	(4.0)	(4.0)
Dead Wood	(3.9)	(3.9)	(3.9)	(3.9)	(3.9)	(3.9)	(3.9)
Litter	(5.4)	(5.3)	(5.3)	(5.3)	(5.3)	(5.3)	(5.3)
Mineral Soil	(0.1)	(0.04)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Wetlands Converted to Forest Land	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**
Aboveground Biomass	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)
Belowground Biomass	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Dead Wood	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
Litter	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)
Mineral Soil	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Aboveground Biomass Flux	**(55.9)**	**(55.9)**	**(56.1)**	**(56.1)**	**(56.1)**	**(56.1)**	**(56.1)**
Total Belowground Biomass Flux	**(10.5)**	**(10.5)**	**(10.5)**	**(10.5)**	**(10.5)**	**(10.5)**	**(10.5)**
Total Dead Wood Flux	**(11.7)**	**(11.7)**	**(11.8)**	**(11.8)**	**(11.8)**	**(11.8)**	**(11.8)**
Total Litter Flux	**(19.8)**	**(19.8)**	**(19.9)**	**(19.9)**	**(19.9)**	**(19.9)**	**(19.9)**
Total Mineral Soil Flux	**(0.8)**	**(1.1)**	**(1.1)**	**(1.1)**	**(1.1)**	**(1.1)**	**(1.1)**
Total Flux	**(98.6)**	**(99.1)**	**(99.5)**	**(99.5)**	**(99.5)**	**(99.5)**	**(99.5)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net uptake. Forest ecosystem C stock changes from land conversion in Alaska are currently included in the Forest Land Remaining Forest Land section because there is insufficient data to separate the changes at this time. Forest ecosystem C stock changes from land conversion do not include U.S. Territories because managed forest land in U.S. Territories is not currently included in Section 6.1 Representation of the U.S. Land Base. The forest ecosystem C stock changes from land conversion do not include Hawaii because there is insufficient NFI data to support inclusion at this time. See Annex 3.13, Table A-217 for annual differences between the forest area reported in Section 6.1 Representation of the U.S. Land Base and Section 6.3 *Land Converted to Forest Land*. Since area estimates for some land use categories were not updated in the Land Representation in the current Inventory there are differences in the area estimates reported in this section and those reported in Section 6.1 Representation of the U.S. Land Base. The forest ecosystem C stock changes from land conversion do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 *Settlements Remaining Settlements* for estimates of C stock change from settlement trees). It is not possible to separate emissions from drained organic soils between *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* so estimates for all organic soils are included in Table 6-8 and Table 6-9 of the *Forest Land Remaining Forest Land* section of the Inventory.

Table 6-25: Net C Flux from Forest C Pools in *Land Converted to Forest Land* by Land Use Change Category (MMT C)

Land Use/Carbon Pool	1990	2005	2016	2017	2018	2019	2020
Cropland Converted to Forest Land	**(10.8)**	**(10.8)**	**(10.8)**	**(10.8)**	**(10.8)**	**(10.8)**	**(10.8)**
Aboveground Biomass	(6.3)	(6.3)	(6.3)	(6.3)	(6.3)	(6.3)	(6.3)
Belowground Biomass	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)
Dead Wood	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)
Litter	(1.9)	(1.9)	(1.9)	(1.9)	(1.9)	(1.9)	(1.9)
Mineral Soil	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Grassland Converted to Forest Land	**(3.1)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**
Aboveground Biomass	(1.6)	(1.6)	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)
Belowground Biomass	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Dead Wood	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Litter	(1.0)	(1.0)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)
Mineral Soil	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Other Land Converted to Forest Land	**(2.7)**	**(2.9)**	**(3.0)**	**(3.0)**	**(3.0)**	**(3.0)**	**(3.0)**
Aboveground Biomass	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)
Belowground Biomass	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Dead Wood	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
Litter	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)
Mineral Soil	(0.2)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Settlements Converted to Forest Land	**(9.3)**	**(9.3)**	**(9.3)**	**(9.3)**	**(9.3)**	**(9.3)**	**(9.3)**
Aboveground Biomass	(5.7)	(5.7)	(5.7)	(5.7)	(5.7)	(5.7)	(5.7)
Belowground Biomass	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)
Dead Wood	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)
Litter	(1.5)	(1.5)	(1.5)	(1.5)	(1.5)	(1.5)	(1.5)
Mineral Soil	+	+	+	+	+	+	+
Wetlands Converted to Forest Land	**(0.9)**	**(0.9)**	**(0.9)**	**(0.9)**	**(0.9)**	**(0.9)**	**(0.9)**
Aboveground Biomass	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
Belowground Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Wood	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Litter	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Mineral Soil	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Aboveground Biomass Flux	**(15.2)**	**(15.3)**	**(15.3)**	**(15.3)**	**(15.3)**	**(15.3)**	**(15.3)**
Total Belowground Biomass Flux	**(2.9)**	**(2.9)**	**(2.9)**	**(2.9)**	**(2.9)**	**(2.9)**	**(2.9)**
Total Dead Wood Flux	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**	**(3.2)**
Total Litter Flux	**(5.4)**	**(5.4)**	**(5.4)**	**(5.4)**	**(5.4)**	**(5.4)**	**(5.4)**
Total Mineral Soil Flux	**(0.2)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**
Total Flux	**(26.9)**	**(27.0)**	**(27.1)**	**(27.1)**	**(27.1)**	**(27.1)**	**(27.1)**

+ Absolute value does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net uptake. Forest ecosystem C stock changes from land conversion in Alaska are currently included in the *Forest Land Remaining Forest Land* section because there is not sufficient data to separate the changes at this time. Forest ecosystem C stock changes from land conversion do not include U.S. Territories because managed forest land in U.S. Territories is not currently included in Section 6.1 Representation of the U.S. Land Base. The forest ecosystem C stock changes from land conversion do not include Hawaii because there is not sufficient NFI data to support inclusion at this time. See Annex 3.13, Table A-217 for annual differences between the forest area reported in Section 6.1 Representation of the U.S. Land Base and Section 6.3 *Land Converted to Forest Land*. Since area estimates for some land use categories were not updated in the Land Representation in the current Inventory there are differences in the area estimates reported in this section and those reported in Section 6.1 Representation of the U.S. Land Base The forest ecosystem C stock changes from land conversion do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 *Settlements Remaining Settlements* for estimates of C stock change from settlement trees). It is not possible to separate emissions from drained organic soils between *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* so estimates for organic soils are included in Table 6-8 and Table 6-9 of the *Forest Land Remaining Forest Land* section of the Inventory.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate stock changes in all forest C pools for *Land Converted to Forest Land*. National Forest Inventory data and IPCC (2006) defaults for reference C stocks were used to compile separate estimates for the five C storage pools. Estimates for Aboveground and Belowground Biomass, Dead Wood and Litter were based on data collected from the extensive array of permanent, annual NFI plots and associated models (e.g., live tree belowground biomass estimates) in the United States (USDA Forest Service 2022b, 2022c). Carbon conversion factors were applied at the individual plot and then appropriately expanded to population estimates. To ensure consistency in the *Land Converted to Forest Land* category where C stock transfers occur between land-use categories, all soil estimates are based on methods from Ogle et al. (2003, 2006) and IPCC (2006).

The methods used for estimating carbon stocks and stock changes in the *Land Converted to Forest Land* are consistent with those used for *Forest Land Remaining Forest Land*. For land use conversion, IPCC (2006) default biomass C stocks removed due to land use conversion from Croplands and Grasslands were used in the year of conversion on individual plots. All annual NFI plots available through August 2021 were used in this Inventory. Forest Land conditions were observed on NFI plots at time t_0 and at a subsequent time t_1=t_0+s, where s is the time step (time measured in years) and is indexed by discrete (e.g., 5 year) forest age classes. The inventory from t_0 was then projected from t_1 to 2020. This projection approach requires simulating changes in the age-class distribution resulting from forest aging and disturbance events and then applying C density estimates for each age class to obtain population estimates for the nation.

Carbon in Biomass

Live tree C pools include aboveground and belowground (coarse root) biomass of live trees with diameter at breast height (dbh) of at least 2.54 cm at 1.37 m above the forest floor. Separate estimates were made for above and belowground biomass components. If inventory plots included data on individual trees, above- and belowground tree C was based on Woodall et al. (2011a), which is also known as the component ratio method (CRM), and is a function of volume, species, and diameter. An additional component of foliage, which was not explicitly included in Woodall et al. (2011a), was added to each tree following the same CRM method.

Understory vegetation is a minor component of biomass and is defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For the current Inventory, it was assumed that 10 percent of total understory C mass is belowground (Smith et al. 2006). Estimates of C density were based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003). Understory biomass represented over one percent of C in biomass, but its contribution rarely exceeded 2 percent of the total.

Biomass losses associated with conversion from Grassland and Cropland to Forest Land were assumed to occur in the year of conversion. To account for these losses, IPCC (2006) defaults for aboveground and belowground biomass on Grasslands and aboveground biomass on Croplands were subtracted from sequestration in the year of the conversion. For all other land use (i.e., Other Lands, Settlements, Wetlands) conversions to Forest Land no biomass loss data were available, and no IPCC (2006) defaults currently exist to include transfers, losses, or gains of carbon in the year of the conversion, so none were incorporated for these conversion categories. As defaults or country-specific data become available for these conversion categories they will be incorporated.

Carbon in Dead Organic Matter

Dead organic matter was initially calculated as three separate pools—standing dead trees, downed dead wood, and litter—with C stocks estimated from sample data or from models. The standing dead tree C pool includes aboveground and belowground (coarse root) biomass for trees of at least 12.7 cm dbh. Calculations followed the basic method applied to live trees (Woodall et al. 2011a) with additional modifications to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). Downed dead wood estimates are based on measurement of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008; Woodall et al. 2013). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood C estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter C is the pool of organic C (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter C. A modeling approach, using litter C measurements from FIA plots (Domke et al. 2016) was used to estimate litter C for every FIA plot used in the estimation framework.

Mineral Soil Carbon Stock Changes

A Tier 2 method is applied to estimate mineral soil C stock changes for *Land Converted to Forest Land* (Ogle et al. 2003, 2006; IPCC 2006). For this method, land is stratified by climate, soil types, land use, and land management activity, and then assigned reference carbon levels and factors for the forest land and the previous land use. The difference between the stocks is reported as the stock change under the assumption that the change occurs over 20 years. Reference C stocks have been estimated from data in the National Soil Survey Characterization Database (USDA-NRCS 1997), and U.S.-specific stock change factors have been derived from published literature (Ogle et al. 2003, 2006). Land use and land use change patterns are determined from a combination of the Forest Inventory and Analysis Dataset (FIA), the 2015 National Resources Inventory (NRI) (USDA-NRCS 2018), and National Land Cover Dataset (NLCD) (Yang et al. 2018). See Annex 3.12 (Methodology for Estimating N_2O Emissions, CH_4 Emissions and Soil Organic C Stock Changes from Agricultural Soil Management) for more information about this method. Note that soil C in this Inventory is reported to a depth of 100 cm in the Forest Land Remaining Forest Land category (Domke et al. 2017) while other land-use categories report soil C to a depth of 30 cm. However, to ensure consistency in the *Land Converted to Forest Land* category where C stock transfers occur between land-use categories, soil C estimates were based on a 30 cm depth using methods from Ogle et al. (2003, 2006) and IPCC (2006), as described in Annex 3.12.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. Mineral soil organic C stock changes from 2016 to 2020 are estimated using a linear extrapolation method described in Box 6-4 of the Methodology section in *Cropland Remaining Cropland*. The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2015 emissions data and is a standard data splicing method for estimating emissions at the end of a time series if activity data are not available (IPCC 2006). The Tier 2 method described previously will be applied to recalculate the 2016 to 2020 emissions in a future Inventory.

Uncertainty

A quantitative uncertainty analysis placed bounds on the flux estimates for *Land Converted to Forest Land* through a combination of sample-based and model-based approaches to uncertainty for forest ecosystem CO_2 Eq. flux (IPCC Approach 1). Uncertainty estimates for forest pool C stock changes were developed using the same methodologies as described in the *Forest Land Remaining Forest Land* section for aboveground and belowground biomass, dead wood, and litter. The exception was when IPCC default estimates were used for reference C stocks in certain conversion categories (i.e., *Cropland Converted to Forest Land* and *Grassland Converted to Forest Land*). In those cases, the uncertainties associated with the IPCC (2006) defaults were included in the uncertainty calculations. IPCC Approach 2 was used for mineral soils and is described in the *Cropland Remaining Cropland* section.

Uncertainty estimates are presented in Table 6-26 for each land conversion category and C pool. Uncertainty estimates were obtained using a combination of sample-based and model-based approaches for all non-soil C pools (IPCC Approach 1) and a Monte Carlo approach (IPCC Approach 2) was used for mineral soil. Uncertainty estimates were combined using the error propagation model (IPCC Approach 1). The combined uncertainty for all C stocks in *Land Converted to Forest Land* ranged from 11 percent below to 11 percent above the 2020 C stock change estimate of -99.5 MMT CO_2 Eq.

Table 6-26: Quantitative Uncertainty Estimates for Forest C Pool Stock Changes (MMT CO_2 Eq. per Year) in 2020 from *Land Converted to Forest Land* by Land Use Change

Land Use/Carbon Pool	2020 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Range[a]			
		(MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Forest Land	**(39.6)**	**(48.2)**	**(30.9)**	**-22%**	**22%**
Aboveground Biomass	(23.0)	(31.4)	(14.5)	-37%	37%
Belowground Biomass	(4.4)	(5.5)	(3.4)	-24%	24%
Dead Wood	(5.0)	(6.2)	(3.8)	-24%	24%
Litter	(6.9)	(8.0)	(5.8)	-16%	16%
Mineral Soils	(0.2)	(0.5)	0.1	-134%	134%
Grassland Converted to Forest Land	**(11.8)**	**(14.3)**	**(9.4)**	**-21%**	**20%**
Aboveground Biomass	(6.1)	(7.5)	(4.7)	-23%	23%
Belowground Biomass	(1.0)	(1.3)	(0.7)	-28%	28%
Dead Wood	(1.1)	(1.3)	(1.0)	-13%	13%
Litter	(3.9)	(4.4)	(3.4)	-14%	14%
Mineral Soils	0.3	(0.1)	0.6	-136%	136%
Other Lands Converted to Forest Land	**(10.9)**	**(13.2)**	**(8.5)**	**-22%**	**22%**
Aboveground Biomass	(4.9)	(7.0)	(2.8)	-43%	43%
Belowground Biomass	(0.9)	(1.3)	(0.4)	-50%	50%
Dead Wood	(1.4)	(2.0)	(0.8)	-40%	40%
Litter	(2.6)	(3.2)	(2.0)	-25%	25%
Mineral Soils	(1.1)	(1.9)	(0.4)	-66%	66%
Settlements Converted to Forest Land	**(34.1)**	**(40.6)**	**(27.6)**	**-19%**	**19%**
Aboveground Biomass	(20.8)	(27.0)	(14.6)	-30%	30%
Belowground Biomass	(4.0)	(5.3)	(2.7)	-33%	33%
Dead Wood	(3.9)	(5.0)	(2.7)	-30%	30%
Litter	(5.3)	(6.2)	(4.4)	-17%	17%
Mineral Soil	(0.1)	(0.1)	+	-44%	44%
Wetlands Converted to Forest Land	**(3.2)**	**(3.4)**	**(3.0)**	**-5%**	**5%**
Aboveground Biomass	(1.4)	(1.5)	(1.2)	-10%	10%
Belowground Biomass	(0.3)	(0.3)	(0.2)	-12%	12%
Dead Wood	(0.4)	(0.4)	(0.3)	-11%	11%
Litter	(1.2)	(1.3)	(1.1)	-5%	5%
Mineral Soils	0.0	0.0	0.0	NA	NA
Total: Aboveground Biomass	**(56.1)**	**(66.9)**	**(45.4)**	**-19%**	**19%**
Total: Belowground Biomass	**(10.5)**	**(12.3)**	**(8.8)**	**-17%**	**17%**
Total: Dead Wood	**(11.8)**	**(13.6)**	**(10.0)**	**-15%**	**15%**
Total: Litter	**(19.9)**	**(21.6)**	**(18.4)**	**-8%**	**8%**
Total: Mineral Soils	**(1.1)**	**(1.7)**	**(0.6)**	**-50%**	**50%**
Total: Lands Converted to Forest Lands	**(99.5)**	**(110.7)**	**(88.3)**	**-11%**	**11%**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

NA (Not Applicable)

[a] Range of flux estimate for 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net uptake. It is not possible to separate emissions from drained organic soils between *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* so estimates for organic soils are included in Table 6-8 and Table 6-9 of the *Forest Land Remaining Forest Land* section of the Inventory.

QA/QC and Verification

See QA/QC and Verification sections under *Forest Land Remaining Forest Land* and for mineral soil estimates *Cropland Remaining Cropland.*

Recalculations Discussion

The approach for estimating carbon stock changes in *Land Converted to Forest Land* is consistent with the methods used for *Forest Land Remaining Forest Land* and is described in Annex 3.13. The *Land Converted to Forest Land* estimates in this Inventory are based on the land use change information in the annual NFI. All conversions are based on empirical estimates compiled using plot remeasurements from the NFI, IPCC (2006) default biomass C stocks removed from Croplands and Grasslands in the year of conversion on individual plots and the Tier 2 method for estimating mineral soil C stock changes (Ogle et al. 2003, 2006; IPCC 2006). All annual NFI plots available through August 2020 were used in this Inventory. This is the third year that remeasurement data from the annual NFI were available throughout the CONUS (with the exception of Wyoming and western Oklahoma) to estimate land use conversion. The availability of remeasurement data from the annual NFI allowed for consistent plot-level estimation of C stocks and stock changes for *Forest Land Remaining Forest Land* and the *Land Converted to Forest Land* categories. Estimates in the previous Inventory were based on state-level carbon density estimates and a combination of NRI data and NFI data in the eastern United States. The refined analysis in this Inventory resulted in changes in the *Land Converted to Forest Land* categories. Overall, the *Land Converted to Forest Land* C stock changes decreased by less than 1 percent in 2019 between the previous Inventory and the current Inventory (Table 6-27). This decrease is directly attributed to the incorporation of annual NFI data into the compilation system. In the previous Inventory, *Grasslands Converted to Forest* Land represented the largest transfer and uptake of C across the land use conversion categories. In this Inventory, *Cropland Converted to Forest Land* represented the largest transfer and uptake of C across the land use change categories followed by *Settlements Converted to Forest Land* (Table 6-27).

Table 6-27: Recalculations of the Net C Flux from Forest C Pools in Land Converted to Forest Land by Land Use Change Category (MMT C)

Conversion category and Carbon pool (MMT C)	2019 Estimate, Previous Inventory	2019 Estimate, Current Inventory	2020 Estimate, Current Inventory
Cropland Converted to Forest Land	**(10.9)**	**(10.8)**	**(10.8)**
Aboveground Biomass	(6.3)	(6.3)	(6.3)
Belowground Biomass	(1.2)	(1.2)	(1.2)
Dead Wood	(1.4)	(1.4)	(1.4)
Litter	(1.9)	(1.9)	(1.9)
Mineral soil	(0.1)	(0.1)	(0.1)
Grassland Converted to Forest Land	**(2.9)**	**(3.2)**	**(3.2)**
Aboveground Biomass	(1.3)	(1.7)	(1.7)
Belowground Biomass	(0.3)	(0.3)	(0.3)
Dead Wood	(0.3)	(0.3)	(0.3)
Litter	(1.1)	(1.1)	(1.1)
Mineral soil	0.1	0.1	0.1
Other Land Converted to Forest Land	**(3.0)**	**(3.0)**	**(3.0)**
Aboveground Biomass	(1.3)	(1.3)	(1.3)
Belowground Biomass	(0.2)	(0.2)	(0.2)
Dead Wood	(0.4)	(0.4)	(0.4)
Litter	(0.7)	(0.7)	(0.7)
Mineral soil	(0.3)	(0.3)	(0.3)
Settlements Converted to Forest Land	**(9.4)**	**(9.3)**	**(9.3)**
Aboveground Biomass	(5.7)	(5.7)	(5.7)
Belowground Biomass	(1.1)	(1.1)	(1.1)
Dead Wood	(1.1)	(1.1)	(1.1)
Litter	(1.5)	(1.5)	(1.5)
Mineral soil	(0.0)	(0.0)	(0.0)
Wetlands Converted to Forest Land	**(0.9)**	**(0.9)**	**(0.9)**
Aboveground Biomass	(0.4)	(0.4)	(0.4)
Belowground Biomass	(0.1)	(0.1)	(0.1)
Dead Wood	(0.1)	(0.1)	(0.1)
Litter	(0.3)	(0.3)	(0.3)

Mineral soil	0.0	0.0	0.0
Total Aboveground Biomass Flux	**(15.0)**	**(15.3)**	**(15.3)**
Total Belowground Biomass Flux	**(2.9)**	**(2.9)**	**(2.9)**
Total Dead Wood Flux	**(3.2)**	**(3.2)**	**(3.2)**
Total Litter Flux	**(5.6)**	**(5.4)**	**(5.4)**
Total SOC (mineral) Flux	**(0.3)**	**(0.3)**	**(0.3)**
Total Flux	**(27.0)**	**(27.1)**	**(27.1)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Planned Improvements

There are many improvements necessary to improve the estimation of carbon stock changes associated with land use conversion to forest land over the entire time series. First, soil C has historically been reported to a depth of 100 cm in the *Forest Land Remaining Forest Land* category (Domke et al. 2017) while other land-use categories (e.g., Grasslands and Croplands) report soil carbon to a depth of 30 cm. To ensure greater consistency in the *Land Converted to Forest Land* category where C stock transfers occur between land-use categories, all mineral soil estimates in the *Land Converted to Forest Land* category in this Inventory are based on methods from Ogle et al. (2003, 2006) and IPCC (2006). Methods have recently been developed (Domke et al. 2017) to estimate soil C to depths of 20, 30, and 100 cm in the Forest Land category using in situ measurements from the Forest Inventory and Analysis program within the USDA Forest Service and the International Soil Carbon Network. In subsequent Inventories, a common reporting depth will be defined for all land use conversion categories and Domke et al. (2017) will be used in the *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* categories to ensure consistent reporting across all forest land. Third, due to the 5 to 10-year remeasurement periods within the FIA program and limited land use change information available over the entire time series, estimates presented in this section may not reflect the entire 20-year conversion history. Work is underway to integrate the dense time series of remotely sensed data into a new estimation system, which will facilitate land conversion estimation over the entire time series.

6.4 Cropland Remaining Cropland (CRF Category 4B1)

Carbon (C) in cropland ecosystems occurs in biomass, dead organic matter, and soils. However, C storage in cropland biomass and dead organic matter is relatively ephemeral and does not need to be reported according to the IPCC (2006), with the exception of C stored in perennial woody crop biomass, such as citrus groves and apple orchards, in addition to the biomass, downed wood and dead organic matter in agroforestry systems. Within soils, C is found in organic and inorganic forms of C, but soil organic C is the main source and sink for atmospheric CO_2 in most soils. IPCC (2006) recommends reporting changes in soil organic C stocks due to agricultural land-use and management activities for mineral and organic soils.[38]

Well-drained mineral soils typically contain from 1 to 6 percent organic C by weight, whereas mineral soils with high water tables for substantial periods of a year may contain significantly more C (NRCS 1999). Conversion of mineral soils from their native state to agricultural land uses can cause up to half of the soil organic C to be lost to the atmosphere due to enhanced microbial decomposition. The rate and ultimate magnitude of C loss depends on subsequent management practices, climate and soil type (Ogle et al. 2005). Agricultural practices, such as clearing, drainage, tillage, planting, grazing, crop residue management, fertilization, application of biosolids (i.e., treated sewage sludge) and flooding, can modify both organic matter inputs and decomposition, and thereby result in a

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[38] Carbon dioxide emissions associated with liming and urea application are also estimated but are included in the Liming and Urea Fertilization sections of the Agriculture chapter of the Inventory.

net C stock change (Paustian et al. 1997a; Lal 1998; Conant et al. 2001; Ogle et al. 2005; Griscom et al. 2017; Ogle et al. 2019). Eventually, the soil can reach a new equilibrium that reflects a balance between C inputs (e.g., decayed plant matter, roots, and organic amendments such as manure and crop residues) and C loss through microbial decomposition of organic matter (Paustian et al. 1997b).

Organic soils, also referred to as *Histosols*, include all soils with more than 12 to 20 percent organic C by weight, depending on clay content (NRCS 1999; Brady and Weil 1999). The organic layer of these soils can be very deep (i.e., several meters), and form under inundated conditions that results in minimal decomposition of plant residues. When organic soils are prepared for crop production, they are drained and tilled, leading to aeration of the soil that accelerates both the decomposition rate and CO_2 emissions.[39] Due to the depth and richness of the organic layers, C loss from drained organic soils can continue over long periods of time, which varies depending on climate and composition (i.e., decomposability) of the organic matter (Armentano and Menges 1986). Due to deeper drainage and more intensive management practices, the use of organic soils for annual crop production leads to higher C loss rates than drainage of organic soils in grassland or forests (IPCC 2006).

Cropland Remaining Cropland includes all cropland in an Inventory year that has been cropland for a continuous time period of at least 20 years. This determination is based on the United States Department of Agriculture (USDA) National Resources Inventory (NRI) for non-federal lands (USDA-NRCS 2018a) and the National Land Cover Dataset for federal lands (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015). Cropland includes all land that is used to produce food and fiber, forage that is harvested and used as feed (e.g., hay and silage), in addition to cropland that has been enrolled in the Conservation Reserve Program (CRP)[40] (i.e., considered set-aside cropland).

Cropland in Alaska is not included in the Inventory, but is a relatively small amount of U.S. cropland area (approximately 28,700 hectares). Some miscellaneous croplands are also not included in the Inventory due to limited understanding of greenhouse gas emissions from these management systems (e.g., aquaculture). This leads to a small discrepancy between the managed area in *Cropland Remaining Cropland* (see Table 6-31 in Planned Improvements for more details on the land area discrepancies) and the cropland area included in the Inventory analysis. Improvements are underway to include croplands in Alaska as part of future C inventories.

Land-use and land management of mineral soils are the largest contributor to total net C stock change, especially in the early part of the time series (see Table 6-28 and Table 6-29). In 2020, mineral soils are estimated to sequester 56.2 MMT CO_2 Eq. from the atmosphere (15.3 MMT C). This rate of C storage in mineral soils represents about a 3 percent decrease in the rate since the initial reporting year of 1990. Carbon dioxide emissions from organic soils are 32.9 MMT CO_2 Eq. (9.0 MMT C) in 2020, which is a 6 percent decrease compared to 1990. In total, United States agricultural soils in *Cropland Remaining Cropland* sequestered approximately 23.3 MMT CO_2 Eq. (6.4 MMT C) in 2020.

Table 6-28: Net CO_2 Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (MMT CO_2 Eq.)

Soil Type	1990		2005		2016	2017	2018	2019	2020
Mineral Soils	(58.2)		(62.4)		(54.3)	(55.1)	(49.4)	(47.4)	(56.2)
Organic Soils	35.0		33.4		31.6	32.8	32.8	32.9	32.9
Total Net Flux	**(23.2)**		**(29.0)**		**(22.7)**	**(22.3)**	**(16.6)**	**(14.5)**	**(23.3)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

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[39] N_2O emissions from drained organic soils are included in the Agricultural Soil Management section of the Agriculture chapter of the Inventory.

[40] The Conservation Reserve Program (CRP) is a land conservation program administered by the Farm Service Agency (FSA). In exchange for a yearly rental payment, farmers enrolled in the program agree to remove environmentally sensitive land from agricultural production and plant species that will improve environmental health and quality. Contracts for land enrolled in CRP are 10 to 15 years in length. The long-term goal of the program is to re-establish valuable land cover to help improve water quality, prevent soil erosion, and reduce loss of wildlife habitat.

Table 6-29: Net CO_2 Flux from Soil C Stock Changes in *Cropland Remaining Cropland* (MMT C)

Soil Type	**1990**	**2005**	**2016**	**2017**	**2018**	**2019**	**2020**
Mineral Soils	(15.9)	(17.0)	(14.8)	(15.0)	(13.5)	(12.9)	(15.3)
Organic Soils	9.5	9.1	8.6	8.9	8.9	9.0	9.0
Total Net Flux	**(6.3)**	**(7.9)**	**(6.2)**	**(6.1)**	**(4.5)**	**(4.0)**	**(6.4)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Soil organic C stocks increase in *Cropland Remaining Cropland* largely due to conservation tillage (i.e., reduced- and no-till practices), land set-aside from production in the Conservation Reserve Program, annual crop production with hay or pasture in rotations, and manure amendments. However, there is a decline in the net amount of C sequestration (i.e., 2020 is 0.7 percent less than 1990 for mineral and organic soils), and this decline is due to lower sequestration rates in set-aside lands, less impact of manure amendments and annual crop production with hay and pasture in rotation. Soil organic C losses from drainage of organic soils are relatively stable across the time series with a small decline associated with the land base declining for *Cropland Remaining Cropland* on organic soils since 1990.

The spatial variability in the 2015 annual soil organic C stock changes[41] are displayed in Figure 6-6 and Figure 6-7 for mineral and organic soils, respectively. Isolated areas with high rates of C accumulation occur throughout the agricultural land base in the United States, but there are more concentrated areas. In particular, higher rates of net C accumulation in mineral soils occur in the Corn Belt region, which is the region with the largest amounts of conservation tillage, along with moderate rates of CRP enrollment. The regions with the highest rates of emissions from drainage of organic soils occur in the Southeastern Coastal Region (particularly Florida), upper Midwest and Northeast surrounding the Great Lakes, and isolated areas along the Pacific Coast (particularly California), which coincides with the largest concentrations of organic soils in the United States that are used for agricultural production.

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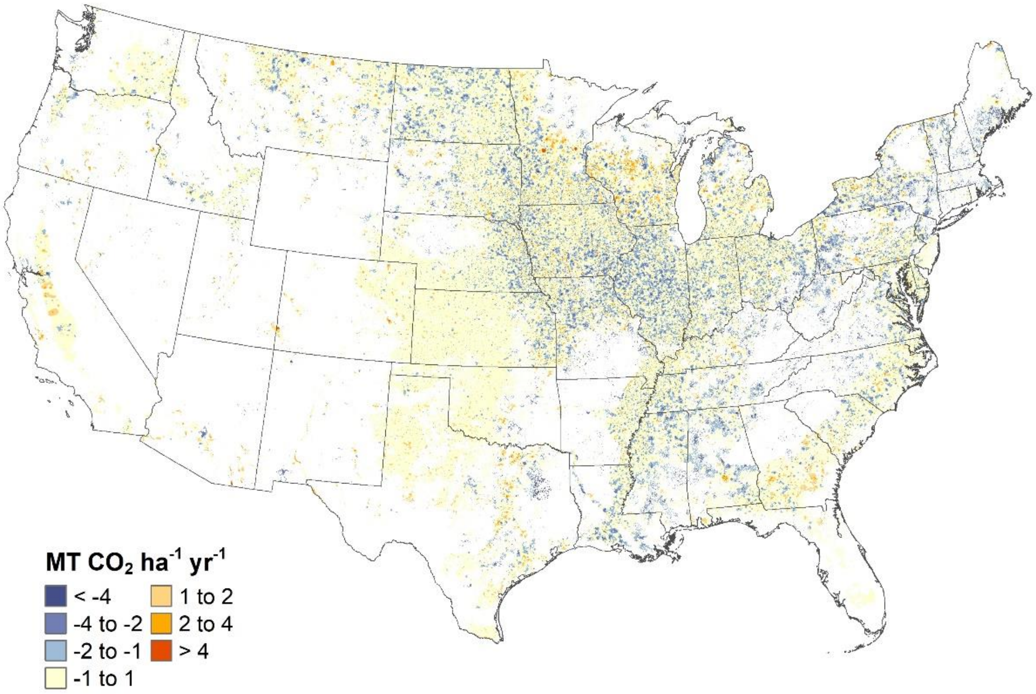
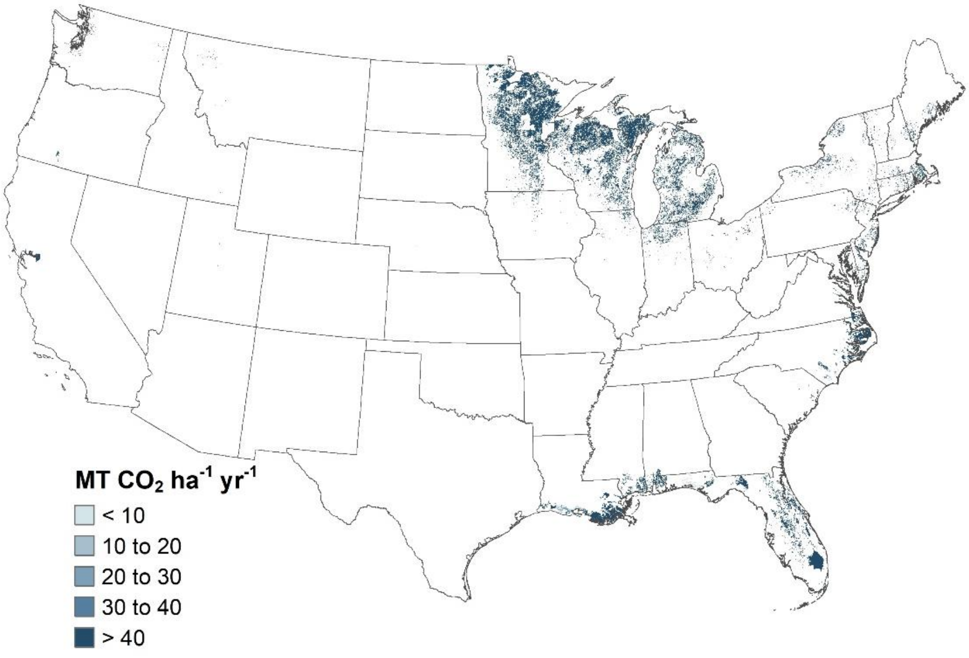
[41] Only national-scale emissions are estimated for 2016 to 2020 in this Inventory using the surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2015.

Figure 6-6: Total Net Annual Soil C Stock Changes for Mineral Soils under Agricultural Management within States, 2015, *Cropland Remaining Cropland*



Note: Only national-scale soil organic C stock changes are estimated for 2016 to 2020 in the current Inventory using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2015. Negative values represent a net increase in soil organic C stocks, and positive values represent a net decrease in soil organic C stocks.

Figure 6-7: Total Net Annual Soil C Stock Changes for Organic Soils under Agricultural Management within States, 2015, *Cropland Remaining Cropland*



Note: Only national-scale soil organic C stock changes are estimated for 2016 to 2019 in the current Inventory using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2015.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate changes in soil organic C stocks for *Cropland Remaining Cropland*, including (1) agricultural land-use and management activities on mineral soils; and (2) agricultural land-use and management activities on organic soils. Carbon dioxide emissions and removals[42] due to changes in mineral soil organic C stocks are estimated using a Tier 3 method for the majority of annual crops (Ogle et al. 2010). A Tier 2 IPCC method is used for the remaining crops not included in the Tier 3 method (see list of crops in the Mineral Soil Carbon Stock Changes section below) (Ogle et al. 2003, 2006). In addition, a Tier 2 method is used for very gravelly, cobbly, or shaley soils (i.e., classified as soils that have greater than 35 percent of soil volume comprised of gravel, cobbles, or shale, regardless of crop). Emissions from organic soils are estimated using a Tier 2 IPCC method. While a combination of Tier 2 and 3 methods are used to estimate C stock changes across most of the time series, a surrogate data method has been applied to estimate stock changes in the last few years of the Inventory. Stock change estimates based on surrogate data will be recalculated in a future Inventory report using the Tier 2 and 3 methods when data become available.

Soil organic C stock changes on non-federal lands are estimated for *Cropland Remaining Cropland* (as well as agricultural land falling into the IPCC categories Land Converted to Cropland, Grassland Remaining Grassland, and *Land Converted to Grassland*) according to land-use histories recorded in the USDA NRI survey (USDA-NRCS 2018a). The NRI is a statistically-based sample of all non-federal land, and includes approximately 489,178 survey locations in agricultural land for the conterminous United States and Hawaii. Each survey location is associated with an "expansion factor" that allows scaling of C stock changes from NRI survey locations to the entire country

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[42] Removals occur through uptake of CO_2 into crop and forage biomass that is later incorporated into soil C pools.

(i.e., each expansion factor represents the amount of area that is expected to have the same land-use/management history as the sample point). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) are collected for each NRI point on a 5-year cycle beginning from 1982 through 1997. For cropland, data has been collected for 4 out of 5 years during each survey cycle (i.e., 1979 through 1982, 1984 through 1987, 1989 through 1992, and 1994 through 1997). In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2015 (USDA-NRCS 2018a). NRI survey locations are classified as *Cropland Remaining Cropland* in a given year between 1990 and 2015 if the land use has been cropland for a continuous time period of at least 20 years. NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an overestimation of *Cropland Remaining Cropland* in the early part of the time series to the extent that some areas are converted to cropland between 1971 and 1978.

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate organic C stock changes for mineral soils on the majority of land that is used to produce annual crops and forage crops that are harvested and used as feed (e.g., hay and silage) in the United States. These crops include alfalfa hay, barley, corn, cotton, grass hay, grass-clover hay, oats, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco and wheat, but is not applied to estimate organic C stock changes from other crops or rotations with other crops. The model-based approach uses the DayCent biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001, 2011) to estimate soil organic C stock changes, soil nitrous oxide (N_2O) emissions from agricultural soil management, and methane (CH_4) emissions from rice cultivation. Carbon and N dynamics are linked in plant-soil systems through the biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Coupling the two source categories (i.e., agricultural soil C and N_2O) in a single inventory analysis ensures that there is a consistent treatment of the processes and interactions between C and N cycling in soils.

The remaining crops on mineral soils are estimated using an IPCC Tier 2 method (Ogle et al. 2003), including some vegetables, perennial/horticultural crops, and crops that are rotated with these crops. The Tier 2 method is also used for very gravelly, cobbly, or shaley soils (greater than 35 percent by volume), and soil organic C stock changes on federal croplands. Mineral soil organic C stocks are estimated using a Tier 2 method for these areas because the DayCent model, which is used for the Tier 3 method, has not been fully tested for estimating C stock changes associated with these crops and rotations, as well as cobbly, gravelly, or shaley soils. In addition, there is insufficient information to simulate croplands on federal lands using DayCent.

A surrogate data method is used to estimate soil organic C stock changes from 2016 to 2020 at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2015 stock change data that are derived using the Tier 2 and 3 methods. Surrogate data for these regression models include corn and soybean yields from USDA-NASS statistics,[43] and weather data from the PRISM Climate Group (PRISM 2018). See Box 6-4 for more information about the surrogate data method. Stock change estimates for 2016 to 2020 will be recalculated in future Inventories with an updated time series of activity data.

Box 6-4: Surrogate Data Method

Time series extension is needed because there are typically gaps at the end of the time series. This is mainly because the NRI, which provides critical data for estimating greenhouse gas emissions and removals, does not release new activity data every year.

A surrogate data method has been used to impute missing emissions at the end of the time series for soil organic C stock changes in Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland, and Land Converted to Grassland. A linear regression model with autoregressive moving-average

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[43] See https://quickstats.nass.usda.gov/.

(ARMA) errors (Brockwell and Davis 2016) is used to estimate the relationship between the surrogate data and the modeled 1990 to 2015 emissions data that has been compiled using the inventory methods described in this section. The model to extend the time series is given by

$$Y = X\beta + \varepsilon,$$

where Y is the response variable (e.g., soil organic carbon), Xβ contains specific surrogate data depending on the response variable, and ε is the remaining unexplained error. Models with a variety of surrogate data were tested, including commodity statistics, weather data, or other relevant information. Parameters are estimated from the emissions data for 1990 to 2015 using standard statistical techniques, and these estimates are used to predict the missing emissions data for 2016 to 2020.

A critical issue with application of splicing methods is to adequately account for the additional uncertainty introduced by predicting emissions rather than compiling the full inventory. Consequently, uncertainty will increase for years with imputed estimates based on the splicing methods, compared to those years in which the full inventory is compiled. This added uncertainty is quantified within the model framework using a Monte Carlo approach. The approach requires estimating parameters for results in each iteration of the Monte Carlo analysis for the full inventory (i.e., the surrogate data model is refit with the emissions estimated in each Monte Carlo iteration from the full inventory analysis with data from 1990 to 2015), estimating emissions from each model and deriving confidence intervals combining uncertainty across all iterations. This approach propagates uncertainties through the calculations from the original inventory and the surrogate data method. Furthermore, the 95 percent confidence intervals are estimated using the 3 sigma rules assuming a unimodal density (Pukelsheim 1994).

Tier 3 Approach. Mineral soil organic C stocks and stock changes are estimated to a 30 cm depth using the DayCent biogeochemical[44] model (Parton et al. 1998; Del Grosso et al. 2001, 2011), which simulates cycling of C, N, and other nutrients in cropland, grassland, forest, and savanna ecosystems. The DayCent model utilizes the soil C modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Input data on land use and management are specified at a daily resolution and include land-use type, crop/forage type, and management activities (e.g., planting, harvesting, fertilization, manure amendments, tillage, irrigation, cover crops, and grazing; more information is provided below). The model simulates net primary productivity (NPP) using the NASA-CASA production algorithm MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1, for most croplands[45] (Potter et al. 1993, 2007). The model simulates soil temperature and water dynamics, using daily weather data from a 4-kilometer gridded product developed by the PRISM Climate Group (2018), and soil attributes from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2019). This method is more accurate than the Tier 1 and 2 approaches provided by the IPCC (2006) because the simulation model treats changes as continuous over time as opposed to the simplified discrete changes represented in the default method (see Box 6-5 for additional information).

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[44] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

[45] NPP is estimated with the NASA-CASA algorithm for most of the cropland that is used to produce major commodity crops in the central United States from 2000 to 2015. Other regions and years prior to 2000 are simulated with a method that incorporates water, temperature and moisture stress on crop production (see Metherell et al. 1993), but does not incorporate the additional information about crop condition provided with remote sensing data.

Box 6-5: Tier 3 Approach for Soil C Stocks Compared to Tier 1 or 2 Approaches

A Tier 3 model-based approach is used to estimate soil organic C stock changes for the majority of agricultural land with mineral soils. This approach results in a more complete and accurate estimation of soil organic C stock changes and entails several fundamental differences from the IPCC Tier 1 or 2 methods, as described below.

1) The IPCC Tier 1 and 2 methods are simplified approaches for estimating soil organic C stock changes and classify land areas into discrete categories based on highly aggregated information about climate (six regions), soil (seven types), and management (eleven management systems) in the United States. In contrast, the Tier 3 model incorporates the same variables (i.e., climate, soils, and management systems) with considerably more detail both temporally and spatially, and captures multi-dimensional interactions through the more complex model structure.
2) The IPCC Tier 1 and 2 methods have a coarser spatial resolution in which data are aggregated to soil types in climate regions, of which there about 30 combinations in the United States. In contrast, the Tier 3 model simulates soil C dynamics at about 350,000 individual NRI survey locations in crop fields and grazing lands.

The IPCC Tier 1 and 2 methods use a simplified approach for estimating changes in C stocks that assumes a step-change from one equilibrium level of the C stock to another equilibrium level. In contrast, the Tier 3 approach simulates a continuum of C stock changes that may reach a new equilibrium over an extended period of time depending on the environmental conditions (i.e., a new equilibrium often requires hundreds to thousands of years to reach). More specifically, the DayCent model, which is used in the United States Inventory, simulates soil C dynamics (and CO_2 emissions and uptake) on a daily time step based on C emissions and removals from plant production and decomposition processes. These changes in soil organic C stocks are influenced by multiple factors that affect primary production and decomposition, including changes in land use and management, weather variability and secondary feedbacks between management activities, climate, and soils.

Historical land-use patterns and irrigation histories are simulated with DayCent based on the 2015 USDA NRI survey (USDA-NRCS 2018a). Additional sources of activity data are used to supplement the activity data from the NRI. The USDA-NRCS Conservation Effects and Assessment Project (CEAP) provides data on a variety of cropland management activities, and is used to inform the inventory analysis about tillage practices, mineral fertilization, manure amendments, cover cropping management, as well as planting and harvest dates (USDA-NRCS 2018b; USDA-NRCS 2012). CEAP data are collected at a subset of NRI survey locations, and currently provide management information from approximately 2002 to 2006. These data are combined with other datasets in an imputation analysis that extend the time series from 1990 to 2015. This imputation analysis is comprised of three steps: a) determine the trends in management activity across the time series by combining information across several datasets (discussed below), b) use an artificial neural network to determine the likely management practice at a given NRI survey location (Cheng and Titterington 1994), and c) assign management practices from the CEAP survey to the specific NRI locations using predictive mean matching methods that is adapted to reflect the trending information (Little 1988, van Buuren 2012). The artificial neural network is a machine learning method that approximates nonlinear functions of inputs and searches through a very large class of models to impute an initial value for management practices at specific NRI survey locations. The predictive mean matching method identifies the most similar management activity recorded in the CEAP survey that matches the prediction from the artificial neural network. Predictive mean matching ensures that imputed management activities are realistic for each NRI survey location, and not odd or physically unrealizable results that could be generated by the artificial neural network. There are six complete imputations of the management activity data using these methods.

To determine trends in mineral fertilization and manure amendments from 1979 to 2015, CEAP data are combined with information on fertilizer use and rates by crop type for different regions of the United States from the USDA Economic Research Service. The data collection program was known as the Cropping Practices Surveys through 1995 (USDA-ERS 1997), and is now part of a data collection program known as the Agricultural Resource Management Surveys (ARMS) (USDA-ERS 2018). Additional data on fertilization practices are compiled through other sources particularly the National Agricultural Statistics Service (USDA-NASS 1992, 1999, 2004). The donor survey data from CEAP contain both mineral fertilizer rates and manure amendment rates, so that the selection of a donor via predictive mean matching yields the joint imputation of both rates. This approach captures the relationship between mineral fertilization and manure amendment practices for U.S. croplands based directly on the observed patterns in the CEAP survey data.

To determine the trends in tillage management from 1979 to 2015, CEAP data are combined with Conservation Technology Information Center data between 1989 and 2004 (CTIC 2004) and USDA-ERS Agriculture Resource Management Surveys (ARMS) data from 2002 to 2015 (Claasen et al. 2018). CTIC data are adjusted for long-term adoption of no-till agriculture (Towery 2001). It is assumed that the majority of agricultural lands are managed with full tillage prior to 1985. For cover crops, CEAP data are combined with information from 2011 to 2016 in the USDA Census of Agriculture (USDA-NASS 2012, 2017). It is assumed that cover cropping was minimal prior to 1990 and the rates increased linearly over the decade to the levels of cover crop management derived from the CEAP survey.

Uncertainty in the C stock estimates from DayCent associated with management activity includes input uncertainty due to missing management data in the NRI survey, which is imputed from other sources as discussed above; model uncertainty due to incomplete specification of C and N dynamics in the DayCent model algorithms and associated parameterization; and sampling uncertainty associated with the statistical design of the NRI survey. To assess input uncertainty, the C and N dynamics at each NRI survey location are simulated six times using the imputation product and other model driver data. Uncertainty in parameterization and model algorithms are determined using a structural uncertainty estimator as described in Ogle et al. (2007, 2010). Sampling uncertainty is assessed using the NRI replicate sampling weights.

Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2015 using the DayCent model. However, note that the areas have been modified in the original NRI survey through the process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (Homer et al. 2007; Fry et al. 2011; Homer et al. 2015) are harmonized with the NRI data. This process ensures that the areas of *Forest Land Remaining Forest Land* and *Land Converted to Forest Land* are consistent with other land use categories while maintaining a consistent time series for the total land area of the United States. For example, if the FIA estimate less *Cropland Converted to Forest Land* than the NRI, then the amount of area for this land use conversion is reduced in the NRI dataset and re-classified as *Cropland Remaining Cropland* (See Section 6.1, Representation of the U.S. Land Base for more information). Further elaboration on the methodology and data used to estimate stock changes from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the Tier 3 method is applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes from 2016 to 2020 are approximated with a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (See Box 6-4). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). Time series of activity data will be updated in a future inventory, and emissions from 2016 to 2020 will be recalculated.

Tier 2 Approach. In the IPCC Tier 2 method, data on climate, soil types, land-use, and land management activity are used to classify land area and apply appropriate factors to estimate soil organic C stock changes to a 30 cm depth (Ogle et al. 2003, 2006). The primary source of activity data for land use, crop and irrigation histories is the 2015 NRI survey (USDA-NRCS 2018a). Each NRI survey location is classified by soil type, climate region, and management condition using data from other sources. Survey locations on federal lands are included in the NRI, but land use and cropping history are not compiled for these locations in the survey program (i.e., NRI is restricted to data collection on non-federal lands). Therefore, land-use patterns for the NRI survey locations on federal lands are based on the National Land Cover Database (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007; Homer et al. 2015).

Additional management activities needed for the Tier 2 method are based on the imputation product described for the Tier 3 approach, including tillage practices, mineral fertilization, and manure amendments that are assigned to NRI survey locations. The one exception are activity data on wetland restoration of Conservation Reserve Program land that are obtained from Euliss and Gleason (2002). Climate zones in the United States are classified using mean precipitation and temperature (1950 to 2000) variables from the WorldClim data set (Hijmans et al. 2005) and potential evapotranspiration data from the Consortium for Spatial Information (CGIAR-CSI) (Zomer et al. 2008, 2007) (Figure A-9). IPCC climate zones are then assigned to NRI survey locations.

Reference C stocks are estimated using the National Soil Survey Characterization Database (NRCS 1997) with cultivated cropland as the reference condition, rather than native vegetation as used in IPCC (2006). Soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (NRCS 1997) than are soils under a native condition, and therefore cultivated cropland provides a more robust sample for estimating the reference condition. Country-specific C stock change factors are derived from published literature to determine the impact of management practices on soil organic C storage (Ogle et al. 2003, 2006). The factors represent changes in tillage, cropping rotations, intensification, and land-use change between cultivated and uncultivated conditions. However, country-specific factors associated with organic matter amendments are not estimated due to an insufficient number of studies in the United States to analyze the impacts. Instead, factors from IPCC (2006) are used to estimate the effect of those activities.

Changes in soil organic C stocks for mineral soils are estimated 1,000 times for 1990 through 2015, using a Monte Carlo stochastic simulation approach and probability distribution functions for the country-specific stock change factors, reference C stocks, and land-use activity data (Ogle et al. 2003; Ogle et al. 2006). Further elaboration on the methodology and data used to estimate stock changes from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes for the remainder of the time series are approximated with a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (See Box 6-4). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). As with the Tier 3 method, time series of activity data will be updated in a future inventory, and emissions from 2016 to 2020 will be recalculated (see Planned Improvements section).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Cropland Remaining Cropland* are estimated using the Tier 2 method provided in IPCC (2006), with country-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. The final estimates include a measure of uncertainty as determined from a Monte Carlo Simulation with 1,000 iterations. Emissions are based on the land area data for drained organic soils from 1990 to 2015 for *Cropland Remaining Cropland* in the 2015 NRI (USDA-NRCS 2018a). Further elaboration on the methodology and data used to estimate stock changes from organic soils are described in Annex 3.12.

In order to ensure time-series consistency, the same Tier 2 method is applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes for the remainder of the time series are approximated with a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (See Box 6-4). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). Estimates for 2016 to 2020 will be recalculated in a future inventory when new activity data are incorporated into the analysis.

Uncertainty

Uncertainty is quantified for changes in soil organic C stocks associated with *Cropland Remaining Cropland* (including both mineral and organic soils). Uncertainty estimates are presented in Table 6-30 for each subsource (mineral and organic soil C stocks) and the methods that are used in the Inventory analyses (i.e., Tier 2 and Tier 3). Uncertainty for the Tier 2 and 3 approaches is derived using a Monte Carlo approach (see Annex 3.12 for further discussion). For 2016 to 2020, additional uncertainty is propagated through the Monte Carlo Analysis that is associated with the surrogate data method. Soil organic C stock changes from the Tier 2 and 3 approaches are combined using the simple error propagation method provided by the IPCC (2006). The combined uncertainty is calculated by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities.

The combined uncertainty for soil organic C stocks in *Cropland Remaining Cropland* ranges from 317 percent below to 317 percent above the 2020 stock change estimate of -23.3 MMT CO_2 Eq. The large relative uncertainty around the 2020 stock change estimate is mostly due to variation in soil organic C stock changes that is not explained by the surrogate data method, leading to high prediction error with this splicing method.

Table 6-30: Approach 2 Quantitative Uncertainty Estimates for Soil C Stock Changes occurring within *Cropland Remaining Cropland* (MMT CO_2 Eq. and Percent)

Source	2020 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Flux Estimate[a] (%)	
		Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 3 Inventory Methodology	(51.4)	(122.4)	19.7	-138%	+138%
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	(4.9)	(11.9)	2.1	-144%	+144%
Organic Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	32.9	13.9	51.9	-58%	+58%
Combined Uncertainty for Flux associated with Agricultural Soil Carbon Stock Change in Cropland Remaining Cropland	**(23.3)**	**(97.2)**	**50.5**	**-317%**	**+317%**

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation with a 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Uncertainty is also associated with lack of reporting of agricultural woody biomass and dead organic matter C stock changes. However, woody biomass C stock changes are likely minor in perennial crops, such as orchards and nut plantations. There will be removal and replanting of tree crops each year, but the net effect on biomass C stock changes is probably minor because the overall area and tree density is relatively constant across time series. In contrast, agroforestry practices, such as shelterbelts, riparian forests and intercropping with trees, may have more significant changes over the Inventory time series, compared to perennial woody crops, at least in some regions of the United States, but there are currently no datasets to evaluate the trends. Changes in litter C stocks are also assumed to be negligible in croplands over annual time frames, although there are certainly significant changes at sub-annual time scales across seasons. This trend may change in the future, particularly if crop residue becomes a viable feedstock for bioenergy production.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. Results from the DayCent model are compared to field measurements and soil monitoring sites associated with the NRI (Spencer et al. 2011), and a statistical relationship has been developed to assess uncertainties in the predictive capability of the model (Ogle et al. 2007). The comparisons include 72 long-term experiment sites and 142 NRI soil monitoring network sites, with 948 observations across all of the sites (see Annex 3.12 for more information).

Recalculations Discussion

There are no recalculations in the time series from the previous Inventory.

Planned Improvements

A key improvement for a future Inventory will be to incorporate additional management activity data from the USDA-NRCS Conservation Effects Assessment Project survey. This survey has compiled new data in recent years that will be available for the Inventory analysis by next year. The latest land use data will also be incorporated from the USDA National Resources Inventory and related management data from USDA-ERS ARMS surveys.

There are several other planned improvements underway related to the plant production module. Crop parameters associated with temperature effects on plant production will be further improved in DayCent with additional model calibration. Senescence events following grain filling in crops, such as wheat, are being modified based on recent model algorithm development, and will be incorporated. There will also be further testing and parameterization of the DayCent model to reduce the bias in model predictions for grasslands, which was discovered through model evaluation by comparing output to measurement data from 72 experimental sites and 142 NRI soil monitoring network sites (See QA/QC and Verification section).

Improvements are underway to simulate crop residue burning in the DayCent model based on the amount of crop residues burned according to the data that are used in the Field Burning of Agricultural Residues source category (see Section 5.7). This improvement will more accurately represent the C inputs to the soil that are associated with residue burning.

A review of available data on biosolids (i.e., treated sewage sludge) application will be undertaken to improve the distribution of biosolids application on croplands, grasslands and settlements.

In the future, the Inventory will include an analysis of C stock changes in Alaska for cropland, using the Tier 2 method for mineral and organic soils that is described earlier in this section. This analysis will initially focus on land use change, which typically has a larger impact on soil organic C stock changes than management practices, but will be further refined over time to incorporate management data. See Table 6-31 for the amount of managed area in *Cropland Remaining Cropland* that is not included in the Inventory, which is less than one thousand hectares per year. This includes the area in Alaska and also other miscellaneous cropland areas, such as aquaculture.

Many of these improvements are expected to be completed for the 1990 through 2021 Inventory (i.e., 2023 submission to the UNFCCC). However, the timeline may be extended if there are insufficient resources to fund all or part of these planned improvements.

Table 6-31: Area of Managed Land in *Cropland Remaining Cropland* that is not included in the current Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	Managed Land	Inventory	Not Included in Inventory
1990	162,163	162,134	29
1991	161,721	161,692	29
1992	161,252	161,223	29
1993	159,449	159,420	29
1994	157,732	157,703	29
1995	157,054	157,025	29
1996	156,409	156,380	29
1997	155,767	155,738	29
1998	152,016	151,987	29
1999	151,135	151,105	29
2000	150,981	150,952	29
2001	150,471	150,442	29
2002	150,175	150,146	29
2003	150,843	150,814	29
2004	150,645	150,616	29

2005	150,304	150,275	29
2006	149,791	149,762	29
2007	150,032	150,003	29
2008	149,723	149,694	29
2009	149,743	149,714	29
2010	149,343	149,314	29
2011	148,844	148,815	29
2012	148,524	148,495	29
2013	149,018	148,989	29
2014	149,492	149,463	29
2015	148,880	148,851	29
2016	ND	ND	ND
2017	ND	ND	ND
2018	ND	ND	ND
2019	ND	ND	ND
2020	ND	ND	ND

Note: NRI data are not available after 2015, and so these years are designated as ND (No data).

6.5 Land Converted to Cropland (CRF Category 4B2)

Land Converted to Cropland includes all cropland in an inventory year that had been in another land use(s) during the previous 20 years (USDA-NRCS 2018), and used to produce food or fiber, or forage that is harvested and used as feed (e.g., hay and silage). For example, grassland or forest land converted to cropland during the past 20 years would be reported in this category. Recently converted lands are retained in this category for 20 years as recommended by IPCC (2006). This Inventory includes all croplands in the conterminous United States and Hawaii, but does not include a minor amount of Land Converted to Cropland in Alaska. Some miscellaneous croplands are also not included in the Inventory due to limited understanding of greenhouse gas dynamics in management systems (e.g., aquaculture). Consequently, there is a discrepancy between the total amount of managed area in Land Converted to Cropland (see Section 6.1 Representation of the U.S. Land Base) and the cropland area included in the Inventory. Improvements are underway to include croplands in Alaska and miscellaneous croplands in future C inventories (see Table 6-35 in the Planned Improvements section for more details on the land area discrepancies).

Land-use change can lead to large losses of C to the atmosphere, particularly conversions from forest land (Houghton et al. 1983; Houghton and Nassikas 2017). Moreover, conversion of forest to another land use (i.e., deforestation) is one of the largest anthropogenic sources of emissions to the atmosphere globally, although this source may be declining according to a recent assessment (Tubiello et al. 2015).

The *2006 IPCC Guidelines* recommend reporting changes in biomass, dead organic matter and soil organic C stocks with land use change. All soil organic C stock changes are estimated and reported for Land Converted to Cropland, but reporting of C stock changes for aboveground and belowground biomass, dead wood, and litter pools is limited to *Forest* Land Converted to Cropland.[46]

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[46] Changes in biomass C stocks are not currently reported land use conversions to cropland except for Forest Land Converted to Cropland, but this is a planned improvement for a future Inventory. Note: changes in dead organic matter are assumed to negligible for other land use conversions to cropland, except Forest Land.

Forest Land Converted to Cropland is the largest source of emissions from 1990 to 2020, accounting for approximately 87 percent of the average total loss of C among all of the land use conversions in Land Converted to Cropland. The pattern is due to the large losses of biomass and dead organic matter C for *Forest* Land Converted to Cropland. The next largest source of emissions is Grassland Converted to Cropland accounting for approximately 17 percent of the total emissions (Table 6-32 and Table 6-33).

The net change in total C stocks for 2020 led to CO_2 emissions to the atmosphere of 54.4 MMT CO_2 Eq. (14.8 MMT C), including 28.2 MMT CO_2 Eq. (7.7 MMT C) from aboveground biomass C losses, 5.5 MMT CO_2 Eq. (1.5 MMT C) from belowground biomass C losses, 5.5 MMT CO_2 Eq. (1.5 MMT C) from dead wood C losses, 8.0 MMT CO_2 Eq. (2.2 MMT C) from litter C losses, 3.5 MMT CO_2 Eq. (0.9 MMT C) from mineral soils and 3.8 MMT CO_2 Eq. (1.0 MMT C) from drainage and cultivation of organic soils. Emissions in 2020 are 5 percent higher than emissions in the initial reporting year, i.e., 1990.

Table 6-32: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes in Land Converted to Cropland by Land Use Change Category (MMT CO_2 Eq.)

	1990	2005	2016	2017	2018	2019	2020
Grassland Converted to Cropland	**6.9**	**7.5**	**8.5**	**8.7**	**8.5**	**8.4**	**8.8**
Mineral Soils	4.1	4.0	5.2	5.4	5.1	5.1	5.5
Organic Soils	2.7	3.5	3.3	3.3	3.3	3.3	3.3
Forest Land Converted to Cropland	**46.3**	**46.6**	**47.3**	**47.3**	**47.3**	**47.3**	**47.3**
Aboveground Live Biomass	27.4	27.7	28.2	28.2	28.2	28.2	28.2
Belowground Live Biomass	5.3	5.4	5.5	5.5	5.5	5.5	5.5
Dead Wood	5.4	5.4	5.5	5.5	5.5	5.5	5.5
Litter	7.7	7.8	8.0	8.0	8.0	8.0	8.0
Mineral Soils	0.4	0.2	0.1	0.1	0.1	0.1	0.2
Organic Soils	0.1	0.1	+	+	+	+	+
Other Lands Converted to Cropland	**(2.2)**	**(2.9)**	**(2.1)**	**(2.2)**	**(2.2)**	**(2.3)**	**(2.3)**
Mineral Soils	(2.3)	(2.9)	(2.1)	(2.2)	(2.2)	(2.3)	(2.3)
Organic Soils	0.2	0.1	0.0	0.0	0.0	0.0	0.0
Settlements Converted to Cropland	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**
Mineral Soils	(0.1)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Cropland	**0.8**	**0.9**	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**
Mineral Soils	0.3	0.3	0.2	0.2	0.2	0.2	0.2
Organic Soils	0.6	0.6	0.3	0.3	0.4	0.4	0.4
Aboveground Live Biomass	**27.4**	**27.7**	**28.2**	**28.2**	**28.2**	**28.2**	**28.2**
Belowground Live Biomass	**5.3**	**5.4**	**5.5**	**5.5**	**5.5**	**5.5**	**5.5**
Dead Wood	**5.4**	**5.4**	**5.5**	**5.5**	**5.5**	**5.5**	**5.5**
Litter	**7.7**	**7.8**	**8.0**	**8.0**	**8.0**	**8.0**	**8.0**
Total Mineral Soil Flux	**2.3**	**1.3**	**3.3**	**3.4**	**3.1**	**3.0**	**3.5**
Total Organic Soil Flux	**3.7**	**4.3**	**3.7**	**3.7**	**3.7**	**3.7**	**3.8**
Total Net Flux	**51.8**	**52.0**	**54.1**	**54.3**	**54.0**	**53.9**	**54.4**

+ Does not exceed 0.05 MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Table 6-33: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes in Land Converted to Cropland (MMT C)

	1990	2005	2016	2017	2018	2019	2020
Grassland Converted to Cropland	**1.9**	**2.0**	**2.3**	**2.4**	**2.3**	**2.3**	**2.4**
Mineral Soils	1.1	1.1	1.4	1.5	1.4	1.4	1.5
Organic Soils	0.7	1.0	0.9	0.9	0.9	0.9	0.9
Forest Land Converted to Cropland	**12.6**	**12.7**	**12.9**	**12.9**	**12.9**	**12.9**	**12.9**
Aboveground Live Biomass	7.5	7.6	7.7	7.7	7.7	7.7	7.7
Belowground Live Biomass	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Dead Wood	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Litter	2.1	2.1	2.2	2.2	2.2	2.2	2.2

Mineral Soils	0.1	+	+	+	+	+	+
Organic Soils	+	+	+	+	+	+	+
Other Lands Converted to Cropland	**(0.6)**	**(0.8)**	**(0.6)**	**(0.6)**	**(0.6)**	**(0.6)**	**(0.6)**
Mineral Soils	(0.6)	(0.8)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)
Organic Soils	+	+	0.0	0.0	0.0	0.0	0.0
Settlements Converted to Cropland	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Cropland	**0.2**	**0.3**	**0.1**	**0.2**	**0.2**	**0.2**	**0.2**
Mineral Soils	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Organic Soils	0.2	0.2	0.1	0.1	0.1	0.1	0.1
Aboveground Live Biomass	**7.5**	**7.6**	**7.7**	**7.7**	**7.7**	**7.7**	**7.7**
Belowground Live Biomass	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**
Dead Wood	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**
Litter	**2.1**	**2.1**	**2.2**	**2.2**	**2.2**	**2.2**	**2.2**
Total Mineral Soil Flux	**0.6**	**0.4**	**0.9**	**0.9**	**0.8**	**0.8**	**0.9**
Total Organic Soil Flux	**1.0**	**1.2**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
Total Net Flux	**14.1**	**14.2**	**14.8**	**14.8**	**14.7**	**14.7**	**14.8**

+ Does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate C stock changes for Land Converted to Cropland, including (1) loss of aboveground and belowground biomass, dead wood and litter C with conversion of forest lands to croplands, as well as (2) the impact from all land use conversions to cropland on mineral and soil organic C stocks.

Biomass, Dead Wood and Litter Carbon Stock Changes

A Tier 2 method is applied to estimate biomass, dead wood, and litter C stock changes for Forest Land Converted to Cropland. Estimates are calculated in the same way as those in the *Forest Land Remaining Forest Land* category using data from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (USDA Forest Service 2020). However, there are no country-specific data for cropland biomass, so default biomass values (IPCC 2006) were used to estimate the carbon stocks for the new cropland (litter and dead wood carbon stocks were assumed to be zero since no reference C density estimates exist for croplands). The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. If FIA plots include data on individual trees, aboveground and belowground C density estimates are based on Woodall et al. (2011). Aboveground and belowground biomass estimates also include live understory which is a minor component of biomass defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this Inventory, it was assumed that 10 percent of total understory C mass is belowground (Smith et al. 2006). Estimates of C density are based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003).

For dead organic matter, if FIA plots include data on standing dead trees, standing dead tree C density is estimated following the basic method applied to live trees (Woodall et al. 2011) with additional modifications to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). If FIA plots include data on downed dead wood, downed dead wood C density is estimated based on measurements of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood C estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter C is the pool of organic C (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots are measured for litter C. If FIA plots include litter material, a modeling approach using litter C measurements from FIA plots is used to estimate litter C density (Domke et al. 2016). In order to ensure time-series consistency, the same methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. See Annex 3.13 for more information about reference C density estimates for forest land and the compilation system used to estimate carbon stock changes from forest land.

Soil Carbon Stock Changes

Soil organic stock changes are estimated for Land Converted to Cropland according to land-use histories recorded in the 2015 USDA NRI survey for non-federal lands (USDA-NRCS 2018). Land-use and some management information (e.g., crop type, soil attributes, and irrigation) had been collected for each NRI point on a 5-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, which are currently available through 2015 (USDA-NRCS 2018). NRI survey locations are classified as Land Converted to Cropland in a given year between 1990 and 2015 if the land use is cropland but had been another use during the previous 20 years. NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998, which may have led to an underestimation of Land Converted to Cropland in the early part of the time series to the extent that some areas are converted to cropland from 1971 to 1978. For federal lands, the land use history is derived from land cover changes in the National Land Cover Dataset (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate C stock changes from 1990 to 2015 for mineral soils on the majority of land that is used to produce annual crops and forage crops that are harvested and used as feed (e.g., hay and silage) in the United States. These crops include alfalfa hay, barley, corn, cotton, grass hay, grass-clover hay, oats, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco, and wheat. Soil organic C stock changes on the remaining mineral soils are estimated with the IPCC Tier 2 method (Ogle et al. 2003), including land used to produce some vegetables and perennial/horticultural crops and crops rotated with these crops; land on very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted from another land use or federal ownership.[47]

For the years 2016 to 2020, a surrogate data method is used to estimate soil organic C stock changes at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2015 stock change data from the Tier 2 and 3 methods. Surrogate data for these regression models include corn and soybean yields from USDA-NASS statistics,[48] and weather data from the PRISM Climate Group (PRISM 2018). See Box 6-4 in the Methodology section of *Cropland Remaining Cropland* for more information about the surrogate data method. Stock change estimates for 2016 to 2020 will be recalculated in future Inventories when the time series of activity data are updated.

Tier 3 Approach. For the Tier 3 method, mineral soil organic C stocks and stock changes are estimated using the DayCent biogeochemical model (Parton et al. 1998; Del Grosso et al. 2001, 2011). The DayCent model utilizes the soil C modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. National estimates are obtained by using the model to simulate historical land-use change patterns as recorded in the USDA NRI survey (USDA-NRCS 2018). Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2015. See the *Cropland Remaining Cropland* section and Annex 3.12 for additional discussion of the Tier 3 methodology for mineral soils.

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[47] Federal land is not a land use, but rather an ownership designation that is treated as grassland for purposes of these calculations. The specific land use on federal lands is not identified in the NRI survey (USDA-NRCS 2015).

[48] See https://quickstats.nass.usda.gov/.

In order to ensure time-series consistency, the Tier 3 method is applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. Soil organic C stock changes from 2016 to 2020 are approximated using a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (described in Box 6-4 of the Methodology section in *Cropland Remaining Cropland*). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). Time series of activity data will be updated in a future Inventory, and emissions from 2016 to 2020 will be recalculated.

Tier 2 Approach. For the mineral soils not included in the Tier 3 analysis, soil organic C stock changes are estimated using a Tier 2 Approach, as described in the Tier 2 Approach for mineral soils in *Cropland Remaining Cropland*. In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes are approximated for the remainder of the 2016 to 2020 time series with a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) (See Box 6-4 of the Methodology section in *Cropland Remaining Cropland*). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). As with the Tier 3 method, time series of activity data will be updated in a future Inventory, and emissions from 2016 to 2020 will be recalculated.

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in Land Converted to Cropland are estimated using the Tier 2 method provided in IPCC (2006), with country-specific C loss rates (Ogle et al. 2003) as described in the *Cropland Remaining Cropland* section for organic soils. Further elaboration on the methodology is also provided in Annex 3.12.

In order to ensure time-series consistency, the Tier 2 methods are applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes for the remainder of the time series (i.e., 2016 to 2020) are approximated with a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (See Box 6-4 of the Methodology section in *Cropland Remaining Cropland*). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). Estimates will be recalculated in future Inventories when new NRI data are available.

Uncertainty

The uncertainty analysis for biomass, dead wood and litter C losses with Forest Land Converted to Cropland is conducted in the same way as the uncertainty assessment for forest ecosystem C flux associated with *Forest Land Remaining Forest Land*. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006) by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details, see the Uncertainty Analysis in Annex 3.13.

The uncertainty analyses for mineral soil organic C stock changes using the Tier 3 and Tier 2 methodologies are based on a Monte Carlo approach that is described in *Cropland Remaining Cropland* (Also see Annex 3.12 for further discussion). The uncertainty for annual C emission estimates from drained organic soils in Land Converted to Cropland is estimated using a Monte Carlo approach, which is also described in the *Cropland Remaining Cropland* section. For 2016 to 2020, there is additional uncertainty propagated through the Monte Carlo Analysis associated with the surrogate data method, which is also described in *Cropland Remaining Cropland*.

Uncertainty estimates are presented in Table 6-34 for each subsource (i.e., biomass C stocks, dead wood C stocks, litter C stocks, soil organic C stocks for mineral and organic soils) and the method applied in the Inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates for the total C stock changes for biomass, dead organic matter and soils are combined using the simple error propagation methods provided by the IPCC (2006), as discussed in the previous paragraph. The combined uncertainty for total C stocks in Land Converted to Cropland ranged from 95 percent below to 95 percent above the 2020 stock change estimate of 54.4 MMT CO_2 Eq. The large relative uncertainty in the 2020 estimate is mostly due to variation in soil organic C stock changes that is not explained by the surrogate data method, leading to high prediction error with this splicing method.

Table 6-34: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass C Stock Changes occurring within Land Converted to Cropland (MMT CO_2 Eq. and Percent)

Source	2020 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a]			
		(MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Grassland Converted to Cropland	**8.8**	**(25.5)**	**43.1**	**-390%**	**390%**
Mineral Soil C Stocks: Tier 3	1.1	(33.0)	35.2	-3006%	3,006%
Mineral Soil C Stocks: Tier 2	4.4	1.3	7.4	-70%	70%
Organic Soil C Stocks: Tier 2	3.3	0.8	5.8	-75%	75%
Forest Land Converted to Cropland	**47.3**	**8.8**	**85.8**	**-81%**	**81%**
Aboveground Live Biomass	28.2	(7.6)	64.0	-127%	127%
Belowground Live Biomass	5.5	(1.5)	12.5	-127%	127%
Dead Wood	5.5	(1.5)	12.5	-127%	127%
Litter	8.0	(2.2)	18.2	-127%	143%
Mineral Soil C Stocks: Tier 2	0.2	(0.1)	0.4	-134%	134%
Organic Soil C Stocks: Tier 2	+	(0.1)	0.1	-1852%	1852%
Other Lands Converted to Cropland	**(2.3)**	**(3.7)**	**(0.8)**	**-64%**	**64%**
Mineral Soil C Stocks: Tier 2	(2.3)	(3.7)	(0.8)	-64%	64%
Organic Soil C Stocks: Tier 2	+	+	+	+	+
Settlements Converted to Cropland	**(0.1)**	**(0.3)**	**+**	**-117%**	**117%**
Mineral Soil C Stocks: Tier 2	(0.2)	(0.3)	+	-90%	90%
Organic Soil C Stocks: Tier 2	+	+	0.1	-85%	85%
Wetlands Converted to Croplands	**0.6**	**+**	**1.3**	**-97%**	**97%**
Mineral Soil C Stocks: Tier 2	0.2	+	0.5	-107%	107%
Organic Soil C Stocks: Tier 2	0.4	(0.2)	1.0	-142%	142%
Total: Land Converted to Cropland	**54.4**	**2.8**	**106.0**	**-95%**	**95%**
Aboveground Live Biomass	**28.2**	**(7.6)**	**64.0**	**-127%**	**127%**
Belowground Live Biomass	**5.5**	**(1.5)**	**12.5**	**-127%**	**127%**
Dead Wood	**5.5**	**(1.5)**	**12.5**	**-127%**	**127%**
Litter	**8.0**	**(2.2)**	**18.2**	**-127%**	**127%**
Mineral Soil C Stocks: Tier 3	**1.1**	**(33.0)**	**35.2**	**-3006%**	**3,006%**
Mineral Soil C Stocks: Tier 2	**2.3**	**(1.1)**	**5.7**	**-147%**	**147%**
Organic Soil C Stocks: Tier 2	**3.8**	**1.2**	**6.3**	**-68%**	**68%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Uncertainty is also associated with lack of reporting of agricultural biomass and dead organic matter C stock changes. Biomass C stock changes are likely minor in perennial crops, such as orchards and nut plantations, given the small amount of change in land that is used to produce these commodities in the United States. In contrast, agroforestry practices, such as shelterbelts, riparian forests and intercropping with trees, may have led to larger changes in biomass C stocks at least in some regions of the United States. However, there are currently no datasets to evaluate the trends. Changes in dead organic matter C stocks are assumed to be negligible with conversion of land to croplands with the exception of forest lands, which are included in this analysis. This assumption will be further explored in a future Inventory.

QA/QC and Verification

See the QA/QC and Verification section in *Cropland Remaining Cropland* for information on QA/QC steps.

Recalculations Discussion

Recalculations are associated with new FIA data from 1990 to 2020 on biomass, dead wood and litter C stocks in Forest Land Converted to Cropland, and updated estimates for mineral soils from 2016 to 2020 using the linear extrapolation method. As a result, Land Converted to Cropland has an estimated smaller C loss of 0.13 MMT CO_2 Eq. on average over the time series. This represents a 1 percent decrease in C stock changes for *Land Converted to Grassland* compared to the previous Inventory.

Planned Improvements

Planned improvements are underway to include an analysis of C stock changes in Alaska for cropland, using the Tier 2 method for mineral and organic soils that is described earlier in this section. This analysis will initially focus on land use change, which typically has a larger impact on soil organic C stock changes than management practices, but will be further refined over time to incorporate management data that drive C stock changes on long-term cropland. See Table 6-35 for the amount of managed area in Land Converted to Cropland that is not included in the Inventory, which is less than one thousand hectares per year. This includes the area in Alaska and other miscellaneous cropland areas, such as aquaculture. Additional planned improvements are discussed in the Planned Improvements section of *Cropland Remaining Cropland*.

Table 6-35: Area of Managed Land in Land Converted to Cropland that is not included in the current Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	Managed Land	Inventory	Not Included in Inventory
1990	12,308	12,308	<1
1991	12,654	12,654	<1
1992	12,943	12,943	<1
1993	14,218	14,218	<1
1994	15,400	15,400	<1
1995	15,581	15,581	<1
1996	15,888	15,888	<1
1997	16,073	16,073	<1
1998	17,440	17,440	<1
1999	17,819	17,819	<1
2000	17,693	17,693	<1
2001	17,600	17,600	<1
2002	17,487	17,487	<1
2003	16,257	16,257	<1
2004	15,317	15,317	<1
2005	15,424	15,424	<1
2006	15,410	15,410	<1
2007	14,923	14,923	<1
2008	14,399	14,399	<1
2009	13,814	13,814	<1
2010	13,905	13,905	<1
2011	14,186	14,186	<1
2012	14,429	14,429	<1
2013	13,752	13,752	<1
2014	13,050	13,050	<1
2015	13,049	13,049	<1

2016	ND	ND	ND
2017	ND	ND	ND
2018	ND	ND	ND
2019	ND	ND	ND
2020	ND	ND	ND

Note: NRI data are not available after 2015 so these years are designated as ND (No data).

6.6 Grassland Remaining Grassland (CRF Category 4C1)

Carbon (C) in grassland ecosystems occurs in biomass, dead organic matter, and soils. Soils are the largest pool of C in grasslands, and have the greatest potential for longer-term storage or release of C. Biomass and dead organic matter C pools are relatively ephemeral compared to the soil C pool, with the exception of C stored in tree and shrub biomass that occurs in grasslands. The *2006 IPCC Guidelines* recommend reporting changes in biomass, dead organic matter and soil organic C stocks with land use and management. C stock changes for aboveground and belowground biomass, dead wood and litter pools are reported for woodlands (i.e., a subcategory of grasslands), and may be extended to include agroforestry management associated with grasslands in the future. For soil organic C, the *2006 IPCC Guidelines* (IPCC 2006) recommend reporting changes due to (1) agricultural land-use and management activities on mineral soils, and (2) agricultural land-use and management activities on organic soils.[49]

Grassland Remaining Grassland includes all grassland in an Inventory year that had been grassland for a continuous time period of at least 20 years (USDA-NRCS 2018). Grassland includes pasture and rangeland that are primarily, but not exclusively used for livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are typically seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation or interseeding of legumes. Woodlands are also considered grassland and are areas of continuous tree cover that do not meet the definition of forest land (See Land Representation section for more information about the criteria for forest land). The current Inventory includes all grasslands in the conterminous United States and Hawaii, but does not include approximately 50 million hectares of Grassland Remaining Grassland in Alaska. This leads to a discrepancy with the total amount of managed area in Grassland Remaining Grassland (see Table 6-39 in Planned Improvements for more details on the land area discrepancies) and the grassland area included in the Inventory analysis.

In Grassland Remaining Grassland, there has been considerable variation in C stocks between 1990 and 2020. These changes are driven by variability in weather patterns and associated interaction with land management activity. Moreover, changes are small on a per hectare rate basis across the time series even in the years with a larger total change in stocks. The net change in total C stocks for 2020 led to net CO_2 emissions to the atmosphere of 4.5 MMT CO_2 Eq. (1.2 MMT C), including 0.2 MMT CO_2 Eq. (0.1 MMT C) from net losses of aboveground biomass C, 0.1 MMT CO_2 Eq. (<0.05 MMT C) from net losses in belowground biomass C, 2.3 MMT CO_2 Eq. (0.6 MMT C) from net losses in dead wood C, 0.2 MMT CO_2 Eq. (0.1 MMT C) from net gains in litter C, 3.3 MMT CO_2 Eq. (0.9 MMT C) from net gains in mineral soil organic C, and 5.4 MMT CO_2 Eq. (1.5 MMT C) from losses of C due to drainage and cultivation of organic soils (Table 6-36 and Table 6-37). Losses of carbon are 35 percent lower in 2020 compared to 1990, but as noted previously, stock changes are highly variable from 1990 to 2020, with an average annual change of 7.2 MMT CO_2 Eq. (2.0 MMT C).

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[49] CO_2 emissions associated with liming and urea fertilization are also estimated but included in the Agriculture chapter of the report.

Table 6-36: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes in Grassland Remaining Grassland (MMT CO_2 Eq.)

Soil Type	1990	2005	2016	2017	2018	2019	2020
Aboveground Live Biomass	0.1	0.1	0.2	0.2	0.2	0.2	0.2
Belowground Live Biomass	+	0.1	0.1	0.1	0.1	0.1	0.1
Dead Wood	2.8	2.7	2.4	2.4	2.4	2.3	2.3
Litter	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Mineral Soils	(2.2)	0.8	0.1	1.4	1.8	4.6	(3.3)
Organic Soils	6.3	5.2	5.4	5.4	5.4	5.4	5.4
Total Net Flux	**6.9**	**8.7**	**8.0**	**9.3**	**9.7**	**12.4**	**4.5**

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Table 6-37: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes in Grassland Remaining Grassland (MMT C)

Soil Type	1990	2005	2016	2017	2018	2019	2020
Aboveground Live Biomass	+	+	0.1	0.1	0.1	0.1	0.1
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	0.8	0.7	0.7	0.7	0.6	0.6	0.6
Litter	+	+	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Mineral Soils	(0.6)	0.2	+	0.4	0.5	1.2	(0.9)
Organic Soils	1.7	1.4	1.5	1.5	1.5	1.5	1.5
Total Net Flux	**1.9**	**2.4**	**2.2**	**2.5**	**2.6**	**3.4**	**1.2**

+ Does not exceed 0.05 MMT C

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

The spatial variability in soil organic C stock changes for 2015[50] is displayed in Figure 6-8 for mineral soils and in Figure 6-9 for organic soils. Although relatively small on a per-hectare basis, grassland soils gained C in isolated areas that mostly occurred in pastures of the eastern United States. For organic soils, the regions with the highest rates of emissions coincide with the largest concentrations of organic soils used for managed grassland, including the Southeastern Coastal Region (particularly Florida), upper Midwest and Northeast, and a few isolated areas along the Pacific Coast.

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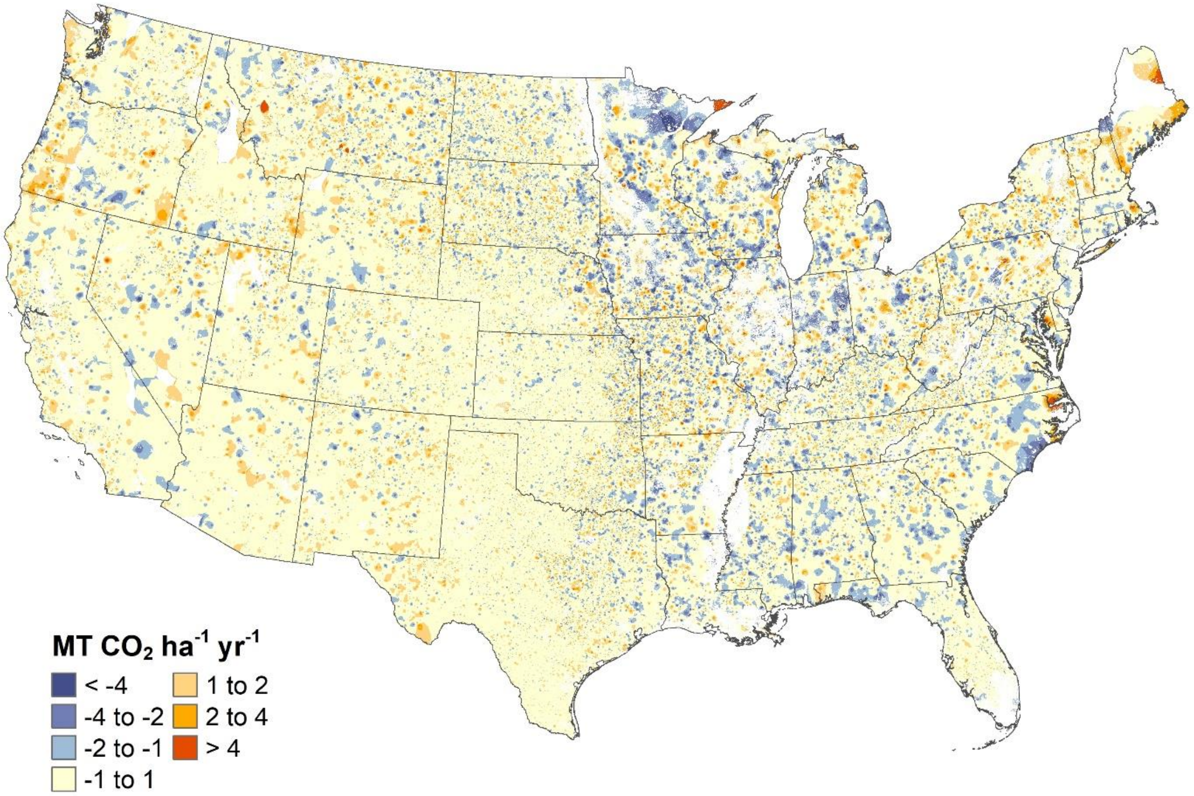
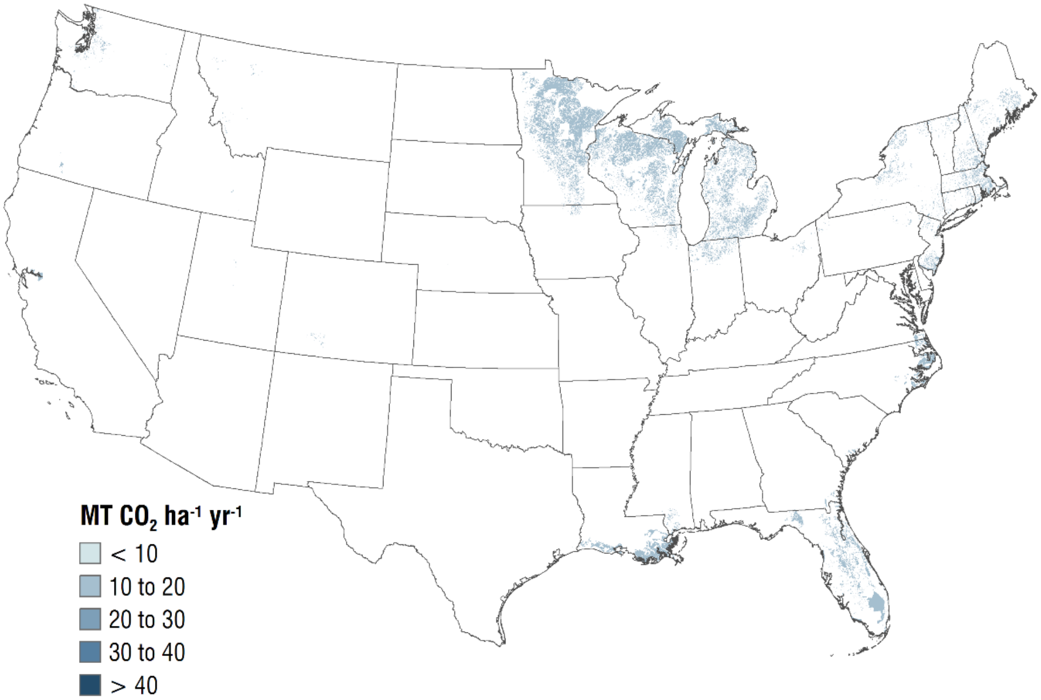
[50] Only national-scale emissions are estimated for 2016 to 2020 in the current Inventory using the surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2015.

Figure 6-8: Total Net Annual Soil C Stock Changes for Mineral Soils under Agricultural Management within States, 2015, *Grassland Remaining Grassland*



Note: Only national-scale soil organic C stock changes are estimated for 2016 to 2020 in the current Inventory using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2015. Negative values represent a net increase in soil organic C stocks, and positive values represent a net decrease in soil organic C stocks.

Figure 6-9: Total Net Annual Soil C Stock Changes for Organic Soils under Agricultural Management within States, 2015, *Grassland Remaining Grassland*



Note: Only national-scale soil organic carbon stock changes are estimated for 2016 to 2020 in the current Inventory using a surrogate data method, and therefore the fine-scale emission patterns in this map are based on inventory data from 2015.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate C stock changes for *Grassland Remaining Grassland*, including (1) aboveground and belowground biomass, dead wood and litter C for woodlands, as well as (2) soil organic C stocks for mineral and organic soils.

Biomass, Dead Wood and Litter Carbon Stock Changes

The methodology is consistent with IPCC (2006). Woodlands are lands that do not meet the definition of forest land or agroforestry (see Section 6.1 Representation of the U.S. Land Base), but include woody vegetation with C storage in aboveground and belowground biomass, dead wood and litter C (IPCC 2006) as described in the *Forest Land Remaining Forest Land* section. Carbon stocks and net annual C stock change were determined according to the stock-difference method for the CONUS, which involved applying C estimation factors to annual forest inventories across time to obtain C stocks and then subtracting the values between years to estimate the stock changes. The methods for estimating carbon stocks and stock changes for woodlands in *Grassland Land Remaining Grassland* are consistent with those in the *Forest Land Remaining Forest Land* section and are described in Annex 3.13. All annual National Forest Inventory (NFI) plots available in the public FIA database (USDA Forest Service 2020) were used in the current Inventory. While the NFI is an all-lands inventory, only those plots that meet the definition of forest land are typically measured. However, in some cases, particularly in the Central Plains and Southwest United States, woodlands have been measured as part of the survey. This analysis is limited to those plots and is not considered a comprehensive assessment of trees outside of forest land that meet the definition of grassland. The same methods are applied from 1990 to 2020 in order to ensure time-series consistency.

Soil Carbon Stock Changes

The following section includes a brief description of the methodology used to estimate changes in soil organic C stocks for *Grassland Remaining Grassland*, including: (1) agricultural land-use and management activities on mineral soils; and (2) agricultural land-use and management activities on organic soils. Further elaboration on the methodologies and data used to estimate stock changes from mineral and organic soils are provided in the *Cropland Remaining Cropland* section and Annex 3.12.

Soil organic C stock changes are estimated for *Grassland Remaining Grassland* on non-federal lands according to land use histories recorded in the 2015 USDA NRI survey (USDA-NRCS 2018). Land-use and some management information (e.g., grass type, soil attributes, and irrigation) were originally collected for each NRI survey location on a 5-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2015 (USDA-NRCS 2015). NRI survey locations are classified as *Grassland Remaining Grassland* in a given year between 1990 and 2015 if the land use had been grassland for 20 years. NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an overestimation of *Grassland Remaining Grassland* in the early part of the time series to the extent that some areas are converted to grassland between 1971 and 1978. For federal lands, the land use history is derived from land cover changes in the National Land Cover Dataset (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate C stock changes from 1990 to 2015 for most mineral soils in *Grassland Remaining Grassland*. The C stock changes for the remaining soils are estimated with an IPCC Tier 2 method (Ogle et al. 2003), including gravelly, cobbly, or shaley soils (greater than 35 percent by volume), the additional stock changes associated with biosolids (i.e., treated sewage sludge) amendments, and federal land.[51]

A surrogate data method is used to estimate soil organic C stock changes from 2016 to 2020 at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2015 emissions data from the Tier 2 and 3 methods. Surrogate data for these regression models are based on weather data from the PRISM Climate Group (PRISM Climate Group 2018). See Box 6-4 in the Methodology section of *Cropland Remaining Cropland* for more information about the surrogate data method. Stock change estimates for 2016 to 2020 will be recalculated in future Inventories when the activity data time series is updated.

Tier 3 Approach. Mineral soil organic C stocks and stock changes for *Grassland Remaining Grassland* are estimated using the DayCent biogeochemical[52] model (Parton et al. 1998; Del Grosso et al. 2001, 2011), as described in *Cropland Remaining Cropland*. The DayCent model utilizes the soil C modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Historical land-use patterns and irrigation histories are simulated with DayCent based on the 2015 USDA NRI survey (USDA-NRCS 2018).

The amount of manure produced by each livestock type is calculated for managed and unmanaged waste management systems based on methods described in Section 5.2 Manure Management and Annex 3.11. Manure N deposition from grazing animals (i.e., PRP manure) is an input to the DayCent model to estimate the influence of PRP manure on C stock changes for lands included in the Tier 3 method. Carbon stocks and 95 percent confidence

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[51] Federal land is not a land use, but rather an ownership designation that is treated as grassland for purposes of these calculations. The specific land use on federal lands is not identified in the NRI survey (USDA-NRCS 2015).

[52] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

intervals are estimated for each year between 1990 and 2015 using the NRI survey data. Further elaboration on the Tier 3 methodology and data used to estimate C stock changes from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes from 2016 to 2020 are approximated using a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) errors, described in Box 6-4 of the Methodology section in *Cropland Remaining Cropland.* Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). Future Inventories will be updated with new activity data, and the time series will be recalculated for 2016 to 2020 (see the Planned Improvements section in *Cropland Remaining Cropland*).

Tier 2 Approach. The Tier 2 approach is based on the same methods described in the Tier 2 portion of *Cropland Remaining Cropland* section for mineral soils, with the exception of the manure N deposition from grazing animals (i.e., PRP manure), and the land use and management data that are used in the Inventory for federal grasslands. First, the PRP N manure is included in the Tier 2 method that is not deposited on lands included in the Tier 3 method. Second, the NRI (USDA-NRCS 2018) provides land use and management histories for all non-federal lands, and is the basis for the Tier 2 analysis for these areas. However, NRI does not provide land use information on federal lands. The land use data for federal lands is based on the National Land Cover Database (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007; Homer et al. 2015). In addition, the Bureau of Land Management (BLM) manages some of the federal grasslands, and compiles information on grassland condition through the BLM Rangeland Inventory (BLM 2014). To estimate soil organic C stock changes from federal grasslands, rangeland conditions in the BLM data are aligned with IPCC grassland management categories of nominal, moderately degraded, and severely degraded in order to apply the appropriate emission factors. Further elaboration on the Tier 2 methodology and data used to estimate C stock changes from mineral soils are described in Annex 3.12.

In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes are approximated for the remainder of the time series with a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) (See Box 6-4 of the Methodology section in *Cropland Remaining Cropland*). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). As with the Tier 3 method, time series of activity data will be updated in a future Inventory, and emissions from 2016 to 2020 will be recalculated.

*Additional Mineral C Stock Change Calculation*s

A Tier 2 method is used to adjust annual C stock change estimates for mineral soils between 1990 and 2020 to account for additional C stock changes associated with biosolids (i.e., treated sewage sludge) amendments. Estimates of the amounts of biosolids N applied to agricultural land are derived from national data on biosolids generation, disposition, and N content (see Section 7.2, Wastewater Treatment for a detailed discussion of the methodology for estimating treated sewage sludge available for land application application). Although biosolids can be added to land managed for other land uses, it is assumed that agricultural amendments only occur in *Grassland Remaining Grassland*. Total biosolids generation data for 1988, 1996, and 1998, in dry mass units, are obtained from EPA (1999) and estimates for 2004 are obtained from an independent national biosolids survey (NEBRA 2007). These values are linearly interpolated to estimate values for the intervening years, and linearly extrapolated to estimate values for years since 2004. Nitrogen application rates from Kellogg et al. (2000) are used to determine the amount of area receiving biosolids amendments. The soil organic C storage rate is estimated at 0.38 metric tons C per hectare per year for biosolids amendments to grassland as described above. The stock change rate is based on country-specific factors and the IPCC default method (see Annex 3.12 for further discussion).

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Grassland Remaining Grassland* are estimated using the Tier 2 method in IPCC (2006), which utilizes country-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. For more information, see the *Cropland Remaining Cropland* section for organic soils and Annex 3.12.

In order to ensure time-series consistency, the Tier 2 methods are applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes for the remainder of the time series (i.e., 2016 to 2020) are approximated with a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) errors (See Box 6-4 of the Methodology section in *Cropland Remaining Cropland*). Linear extrapolation is a standard data splicing method for approximating emissions at the end of a time series (IPCC 2006). Estimates will be recalculated in future Inventories when new NRI data are available.

Uncertainty

The uncertainty analysis for biomass, dead wood and litter C losses with *Forest Land Converted to Grassland* is conducted in the same way as the uncertainty assessment for forest ecosystem C flux associated with *Forest Land Remaining Forest Land*. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006) by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details, see the Uncertainty Analysis in Annex 3.13.

Uncertainty analysis for mineral soil organic C stock changes using the Tier 3 and Tier 2 methodologies are based on a Monte Carlo approach that is described in the *Cropland Remaining Cropland* section and Annex 3.12. The uncertainty for annual C emission estimates from drained organic soils in *Grassland Remaining Grassland* is estimated using a Monte Carlo approach, which is also described in the *Cropland Remaining Cropland* section. For 2016 to 2020, there is additional uncertainty propagated through the Monte Carlo Analysis associated with the surrogate data method.

Uncertainty estimates are presented in Table 6-38 for each subsource (i.e., soil organic C stocks for mineral and organic soils) and the method applied in the Inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates from the Tier 2 and 3 approaches are combined using the simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities.

The combined uncertainty for soil organic C stocks in *Grassland Remaining Grassland* ranges from more than 3,256 percent below and above the 2020 stock change estimate of 4.5 MMT CO_2 Eq. The large relative uncertainty is mostly due to large uncertainty in the Tier 3 method and variation in soil organic C stock changes that is not explained by the surrogate data method, leading to high prediction error.

Table 6-38: Approach 2 Quantitative Uncertainty Estimates for C Stock Changes Occurring Within *Grassland Remaining Grassland* (MMT CO_2 Eq. and Percent)

Source	2020 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Woodland Biomass:					
Aboveground live biomass	0.2	0.2	0.2	-31%	31%

Belowground live biomass	0.1	0.1	0.1	-16%	16%
Dead wood	2.3	1.8	2.8	-22%	22%
Litter	(0.2)	(0.4)	+	-104%	104%
Mineral Soil C Stocks Grassland Remaining Grassland, Tier 3 Methodology	(2.3)	(148.4)	143.9	-6,479%	6,479%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	(0.9)	(9.9)	8.1	-986%	986%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology (Change in Soil C due to Biosolids [i.e., Treated Sewage Sludge] Amendments)	(0.2)	(0.3)	(0.1)	-50%	50%
Organic Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	5.4	1.2	9.6	-77%	77%
Combined Uncertainty for Flux Associated with Carbon Stock Changes Occurring in Grassland Remaining Grassland	**4.5**	**(142.0)**	**150.9**	**-3,256%**	**3,256%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Uncertainty is also associated with a lack of reporting on biomass, dead wood and litter C stock changes for agroforestry systems. Changes in biomass and dead organic matter C stocks are assumed to be negligible in other grasslands, largely comprised of herbaceous biomass, although there are certainly significant changes at sub-annual time scales across seasons.

QA/QC and Verification

See the QA/QC and Verification section in *Cropland Remaining Cropland*.

Recalculations Discussion

Recalculations are associated with updated estimates for mineral soils from 2016 to 2020 using the linear extrapolation method, in addition to a correction in the estimation of biomass C. The correction is associated with foliage estimates for woodlands that had been based on values for non-woodland foliage in the previous Inventory. As a result of these new data, *Grassland Remaining Grassland* has a smaller loss of C compared to the previous Inventory, estimated at a reduction in C loss of 1.3 MMT CO_2 Eq., or 32 percent decrease in C loss, on average over the time series for *Grassland Remaining Grassland* compared to the previous Inventory.

Planned Improvements

Grasslands in Alaska are not currently included in the Inventory. This is a significant planned improvement and estimates are expected to be available in a future Inventory contingent on funding availability. Table 6-39 provides information on the amount of managed area in Alaska that is *Grassland Remaining Grassland*, which includes about 50 million hectares per year. For information about other improvements, see the Planned Improvements section in *Cropland Remaining Cropland*.

Table 6-39: Area of Managed Land in *Grassland Remaining Grassland* in Alaska that is not included in the current Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	Managed Land	Inventory	Not Included in Inventory
1990	327,446	277,406	50,040
1991	326,959	276,918	50,040
1992	326,462	276,422	50,040
1993	324,524	274,484	50,040
1994	322,853	272,813	50,040
1995	322,015	271,975	50,040
1996	321,164	271,123	50,040
1997	320,299	270,259	50,040
1998	318,214	268,174	50,040
1999	317,341	267,301	50,040
2000	316,242	266,202	50,040
2001	315,689	265,649	50,040
2002	315,232	265,192	50,040
2003	315,442	265,403	50,039
2004	315,459	265,421	50,038
2005	315,161	265,123	50,038
2006	314,841	264,804	50,037
2007	314,786	264,749	50,036
2008	314,915	264,878	50,037
2009	315,137	265,099	50,037
2010	314,976	264,942	50,035
2011	314,662	264,627	50,035
2012	314,466	264,413	50,053
2013	315,301	265,239	50,062
2014	316,242	266,180	50,062
2015	316,287	266,234	50,053
2016	ND	ND	ND
2017	ND	ND	ND
2018	ND	ND	ND
2019	ND	ND	ND
2020	ND	ND	ND

Note: NRI data are not available after 2015, and these years are designated as ND (No data).

Additionally, a review of available data on biosolids (i.e., treated sewage sludge) application will be undertaken to improve the distribution of biosolids application on croplands, grasslands and settlements.

Non-CO_2 Emissions from Grassland Fires (CRF Source Category 4C1)

Fires are common in grasslands, and are thought to have been a key feature shaping the evolution of the grassland vegetation in North America (Daubenmire 1968; Anderson 2004). Fires can occur naturally through lightning strikes, but are also an important management practice to remove standing dead vegetation and improve forage for grazing livestock. Woody and herbaceous biomass will be oxidized in a fire, although in this section the current focus is primarily on herbaceous biomass.[53] Biomass burning emits a variety of trace gases including non-CO_2 greenhouse gases such as CH_4 and N_2O, as well as CO and NO_x that can become greenhouse gases when they react with other gases in the atmosphere (Andreae and Merlet 2001). IPCC (2006) recommends reporting non-CO_2 greenhouse gas emissions from all wildfires and prescribed burning occurring in managed grasslands.

Biomass burning in grassland of the United States (Including burning emissions in *Grassland Remaining Grassland* and *Land Converted to Grassland*) is a relatively small source of emissions, but it has increased by nearly 300 percent since 1990. In 2020, CH_4 and N_2O emissions from biomass burning in grasslands were 0.3 MMT CO_2 Eq. (12 kt) and 0.3 MMT CO_2 Eq. (1 kt), respectively. Annual emissions from 1990 to 2020 have averaged approximately 0.3 MMT CO_2 Eq. (12 kt) of CH_4 and 0.3 MMT CO_2 Eq. (1 kt) of N_2O (see Table 6-40 and Table 6-41).

Table 6-40: CH_4 and N_2O Emissions from Biomass Burning in Grassland (MMT CO_2 Eq.)

	1990	2005	2016	2017	2018	2019	2020
CH_4	0.1	0.3	0.3	0.3	0.3	0.3	0.3
N_2O	0.1	0.3	0.3	0.3	0.3	0.3	0.3
Total Net Flux	**0.2**	**0.7**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**

Table 6-41: CH_4, N_2O, CO, and NO_x Emissions from Biomass Burning in Grassland (kt)

	1990	2005	2016	2017	2018	2019	2020
CH_4	3	13	11	12	12	12	12
N_2O	+	1	1	1	1	1	1
CO	84	358	324	345	331	341	334
NO_x	5	21	19	21	20	20	20

+ Does not exceed 0.5 kt.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate non-CO_2 greenhouse gas emissions from biomass burning in grassland, including (1) determination of the land base that is classified as managed grassland; (2) assessment of managed grassland area that is burned each year, and (3) estimation of emissions resulting from the fires. For this Inventory, the IPCC Tier 1 method is applied to estimate non-CO_2 greenhouse gas emissions from biomass burning in grassland from 1990 to 2014 (IPCC 2006). A data splicing method is used to estimate the emissions from 2015 to 2020, which is discussed later in this section.

The land area designated as managed grassland is based primarily on the National Resources Inventory (NRI) (Nusser and Goebel 1997; USDA-NRCS 2015). NRI has survey locations across the entire United States, but does not classify land use on federally-owned areas, and so survey locations on federal lands are designated as grassland using land cover data from the National Land Cover Dataset (NLCD) (Fry et al. 2011; Homer et al. 2007; Homer et al. 2015) (see Section 6.1 Representation of the U.S. Land Base).

The area of biomass burning in grasslands (*Grassland Remaining Grassland* and *Land Converted to Grassland*) is determined using 30-m fire data from the Monitoring Trends in Burn Severity (MTBS) program for 1990 through 2014.[54] NRI survey locations on grasslands are designated as burned in a year if there is a fire within 500 m of the survey point according to the MTBS fire data. The area of biomass burning is estimated from the NRI spatial weights and aggregated to the country (Table 6-42).

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[53] A planned improvement is underway to incorporate woodland tree biomass into the Inventory.

[54] See http://www.mtbs.gov.

Table 6-42: Thousands of Grassland Hectares Burned Annually

Year	Thousand Hectares
1990	317
2005	1,343
2016	NE
2017	NE
2018	NE
2019	NE
2020	NE

Notes: Burned area was not estimated (NE) for 2015 to 2020 but will be updated in a future Inventory. Burned area for the year 2014 is estimated to be 1,659 thousand hectares.

For 1990 to 2014, the total area of grassland burned is multiplied by the IPCC default factor for grassland biomass (4.1 tonnes dry matter per ha) (IPCC 2006) to estimate the amount of combusted biomass. A combustion factor of 1 is assumed in this Inventory, and the resulting biomass estimate is multiplied by the IPCC default grassland emission factors for CH_4 (2.3 g CH_4 per kg dry matter), N_2O (0.21 g N_2O per kg dry matter), CO (65 g CO per kg dry matter) and NO_x (3.9 g NO_x per kg dry matter) (IPCC 2006). The Tier 1 analysis is implemented in the Agriculture and Land Use National Greenhouse Gas Inventory (ALU) software (Ogle et al. 2016).[55]

A linear extrapolation of the trend in the time series is applied to estimate emissions for 2015 to 2020 because new activity data have not been compiled for these years. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to estimate the trend in emissions over time from 1990 to 2014, and the trend is used to approximate the 2015 to 2020 emissions. The Tier 1 method described previously will be applied to recalculate the 2015 to 2020 emissions in a future Inventory.

The same methods are applied from 1990 to 2014, and a data splicing method is used to extend the time series from 2015 to 2020 ensuring a consistent time series of emissions data. The trend extrapolation is a standard data splicing method for estimating emissions at the end of a time series if activity data are not available (IPCC 2006).

Uncertainty

Emissions are estimated using a linear regression model with ARMA errors for 2015 to 2020. The linear regression ARMA model produced estimates of the upper and lower bounds of the emission estimate and the results are summarized in Table 6-43. Methane emissions from Biomass Burning in Grassland for 2020 are estimated to be between approximately 0.0 and 0.7 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 100 percent below and 145 percent above the 2020 emission estimate of 0.3 MMT CO_2 Eq. Nitrous oxide emissions are estimated to be between approximately 0.0 and 0.8 MMT CO_2 Eq., or approximately 100 percent below and 145 percent above the 2020 emission estimate of 0.3 MMT CO_2 Eq.

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[55] See http://www.nrel.colostate.edu/projects/ALUsoftware/.

Table 6-43: Uncertainty Estimates for Non-CO_2 Greenhouse Gas Emissions from Biomass Burning in Grassland (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Grassland Burning	CH_4	0.3	+	0.7	-100%	145%
Grassland Burning	N_2O	0.3	+	0.8	-100%	145%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by linear regression time-series model for a 95 percent confidence interval.

Uncertainty is also associated with lack of reporting of emissions from biomass burning in grassland of Alaska. Grassland burning emissions could be relatively large in this region of the United States, and therefore extending this analysis to include Alaska is a planned improvement for the Inventory. There is also uncertainty due to lack of reporting combustion of woody biomass, and this is another planned improvement.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. Quality control identified problems with input data for common reporting format tables in the spreadsheets, which have been corrected.

Recalculations Discussion

There are no recalculations in the time series from the previous Inventory.

Planned Improvements

A data splicing method is applied to estimate emissions in the latter part of the time series, which introduces additional uncertainty in the emissions data. Therefore, a key improvement for the next Inventory will be to update the time series with new activity data from the Monitoring Trends in Burn Severity program and recalculate the emissions. Two other planned improvements have been identified for this source category, including a) incorporation of country-specific grassland biomass factors, and b) extending the analysis to include Alaska. In the current Inventory, biomass factors are based on a global default for grasslands that is provided by the IPCC (2006). There is considerable variation in grassland biomass, however, which would affect the amount of fuel available for combustion in a fire. Alaska has an extensive area of grassland and includes tundra vegetation, although some of the areas are not managed. There has been an increase in fire frequency in boreal forest of the region (Chapin et al. 2008), and this may have led to an increase in burning of neighboring grassland areas. There is also an effort under development to incorporate grassland fires into DayCent model simulations. Both improvements are expected to reduce uncertainty and produce more accurate estimates of non-CO_2 greenhouse gas emissions from grassland burning.

6.7 Land Converted to Grassland (CRF Category 4C2)

Land Converted to Grassland includes all grassland in an Inventory year that had been in another land use(s) during the previous 20 years (USDA-NRCS 2018).[56] For example, cropland or forest land converted to grassland during the past 20 years would be reported in this category. Recently converted lands are retained in this category for 20 years as recommended by IPCC (2006). Grassland includes pasture and rangeland that are used primarily but not exclusively for livestock grazing. Rangelands are typically extensive areas of native grassland that are not intensively managed, while pastures are typically seeded grassland (possibly following tree removal) that may also have additional management, such as irrigation or interseeding of legumes. This Inventory includes all grasslands in the conterminous United States and Hawaii, but does not include *Land Converted to Grassland* in Alaska. Consequently, there is a discrepancy between the total amount of managed area for *Land Converted to Grassland* (see Table 6-47 in Planned Improvements) and the grassland area included in the inventory analysis.

Land use change can lead to large losses of C to the atmosphere, particularly conversions from forest land (Houghton et al. 1983, Houghton and Nassikas 2017). Moreover, conversion of forest to another land use (i.e., deforestation) is one of the largest anthropogenic sources of emissions to the atmosphere globally, although this source may be declining according to a recent assessment (Tubiello et al. 2015).

IPCC (2006) recommends reporting changes in biomass, dead organic matter, and soil organic C stocks due to land use change. All soil organic C stock changes are estimated and reported for *Land Converted to Grassland*, but there is limited reporting of other pools in this Inventory. Losses of aboveground and belowground biomass, dead wood and litter C from *Forest Land Converted to Grassland* are reported, but these C stock changes are not estimated for other land use conversions to grassland.[57]

The largest C losses with *Land Converted to Grassland* are associated with aboveground biomass, belowground biomass, and litter C losses from *Forest Land Converted to Grassland* (see Table 6-44 and Table 6-45). These three pools led to net emissions in 2020 of 11.6, 2.1, and 4.6 MMT CO_2 Eq. (3.2, 0.6, and 1.3 MMT C), respectively. Land use and management of mineral soils in *Land Converted to Grassland* led to an increase in soil organic C stocks, estimated at 43.9 MMT CO_2 Eq. (12.0 MMT C) in 2020. The gains are primarily associated with conversion of Other Land, which have relatively low soil organic C stocks, to Grassland that tend to have conditions suitable for storing larger amounts of C in soils, and also due to conversion of Cropland to Grassland that leads to less intensive management of the soil. Drainage of organic soils for grassland management led to CO_2 emissions to the atmosphere of 1.8 MMT CO_2 Eq. (0.5 MMT C). The total net C stock change in 2020 for *Land Converted to Grassland* is estimated as a gain of 24.1 MMT CO_2 Eq. (6.6 MMT C), which represents an increase in C stock change of 584 percent compared to the initial reporting year of 1990.

Table 6-44: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes for *Land Converted to Grassland* (MMT CO_2 Eq.)

	1990	2005	2016	2017	2018	2019	2020
Cropland Converted to Grassland	**(18.3)**	**(23.5)**	**(17.8)**	**(18.0)**	**(18.0)**	**(17.4)**	**(19.7)**
Mineral Soils	(18.9)	(25.0)	(19.1)	(19.4)	(19.3)	(18.7)	(21.0)

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[56] NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 2001. This may have led to an underestimation of *Land Converted to Grassland* in the early part of the time series to the extent that some areas are converted to grassland between 1971 and 1978.

[57] Changes in biomass C stocks are not currently reported for other conversions to grassland (other than forest land), but this is a planned improvement for a future Inventory. Note: changes in dead organic matter are assumed to negligible for other land use conversions (i.e., other than forest land) to grassland based on the Tier 1 method in IPCC (2006).

Organic Soils	0.6	1.5	1.4	1.4	1.3	1.3	1.3
Forest Land Converted to Grassland	**19.4**	**19.4**	**18.1**	**18.1**	**18.1**	**18.1**	**18.1**
Aboveground Live Biomass	12.8	12.6	11.6	11.6	11.6	11.6	11.6
Belowground Live Biomass	2.3	2.2	2.1	2.1	2.1	2.1	2.1
Dead Wood	(0.4)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Litter	4.7	4.8	4.6	4.6	4.6	4.6	4.6
Mineral Soils	(0.1)	(0.1)	(0.1)	+	+	(0.1)	+
Organic Soils	+	0.2	0.2	0.2	0.2	0.2	0.2
Other Lands Converted to Grassland	**(4.2)**	**(31.7)**	**(22.2)**	**(22.1)**	**(21.9)**	**(21.5)**	**(21.8)**
Mineral Soils	(4.2)	(31.7)	(22.3)	(22.2)	(21.9)	(21.6)	(21.9)
Organic Soils	+	+	0.1	0.1	0.1	0.1	0.1
Settlements Converted to Grassland	**(0.2)**	**(1.4)**	**(0.9)**	**(1.0)**	**(0.9)**	**(0.9)**	**(1.0)**
Mineral Soils	(0.2)	(1.4)	(0.9)	(1.0)	(0.9)	(0.9)	(1.0)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Grassland	**0.1**	**0.2**	**0.3**	**0.3**	**0.3**	**0.3**	**0.2**
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	0.1	0.2	0.3	0.2	0.2	0.2	0.2
Aboveground Live Biomass	**12.8**	**12.6**	**11.6**	**11.6**	**11.6**	**11.6**	**11.6**
Belowground Live Biomass	**2.3**	**2.2**	**2.1**	**2.1**	**2.1**	**2.1**	**2.1**
Dead Wood	**(0.4)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**
Litter	**4.7**	**4.8**	**4.6**	**4.6**	**4.6**	**4.6**	**4.6**
Total Mineral Soil Flux	**(23.4)**	**(58.2)**	**(42.4)**	**(42.5)**	**(42.2)**	**(41.3)**	**(43.9)**
Total Organic Soil Flux	**0.8**	**1.9**	**1.9**	**1.9**	**1.9**	**1.8**	**1.8**
Total Net Flux	**(3.1)**	**(37.0)**	**(22.6)**	**(22.7)**	**(22.4)**	**(21.5)**	**(24.1)**

+ Does not exceed 0.05 MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Table 6-45: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes for *Land Converted to Grassland* (MMT C)

	1990	2005	2016	2017	2018	2019	2020
Cropland Converted to Grassland	**(5.0)**	**(6.4)**	**(4.8)**	**(4.9)**	**(4.9)**	**(4.7)**	**(5.4)**
Mineral Soils	(5.2)	(6.8)	(5.2)	(5.3)	(5.3)	(5.1)	(5.7)
Organic Soils	0.2	0.4	0.4	0.4	0.4	0.4	0.4
Forest Land Converted to Grassland	**5.3**	**5.3**	**4.9**	**4.9**	**4.9**	**4.9**	**4.9**
Aboveground Live Biomass	3.5	3.4	3.2	3.2	3.2	3.2	3.2
Belowground Live Biomass	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Dead Wood	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Litter	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	+	0.1	0.1	0.1	0.1	0.1
Other Lands Converted to Grassland	**(1.1)**	**(8.6)**	**(6.1)**	**(6.0)**	**(6.0)**	**(5.9)**	**(5.9)**
Mineral Soils	(1.2)	(8.6)	(6.1)	(6.1)	(6.0)	(5.9)	(6.0)
Organic Soils	+	+	+	+	+	+	+
Settlements Converted to Grassland	**+**	**(0.4)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.2)**	**(0.3)**
Mineral Soils	+	(0.4)	(0.3)	(0.3)	(0.3)	(0.2)	(0.3)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Grassland	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1

Aboveground Live Biomass	**3.5**		**3.4**		**3.2**	**3.2**	**3.2**	**3.2**	**3.2**
Belowground Live Biomass	**0.6**		**0.6**		**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Dead Wood	**(0.1)**		**(0.1)**		**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**
Litter	**1.3**		**1.3**		**1.3**	**1.3**	**1.3**	**1.3**	**1.3**
Total Mineral Soil Flux	**(6.4)**		**(15.9)**		**(11.6)**	**(11.6)**	**(11.5)**	**(11.3)**	**(12.0)**
Total Organic Soil Flux	**0.2**		**0.5**		**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
Total Net Flux	**(0.9)**		**(10.1)**		**(6.2)**	**(6.2)**	**(6.1)**	**(5.9)**	**(6.6)**

+ Does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate C stock changes for *Land Converted to Grassland*, including (1) loss of aboveground and belowground biomass, dead wood and litter C with conversion of *Forest Land Converted to Grassland*, as well as (2) the impact from all land use conversions to grassland on mineral and organic soil organic C stocks.

Biomass, Dead Wood, and Litter Carbon Stock Changes

A Tier 3 method is applied to estimate biomass, dead wood and litter C stock changes for *Forest Land Converted to Grassland*. Estimates are calculated in the same way as those in the *Forest Land Remaining Forest Land* category using data from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (USDA Forest Service 2020). There are limited data on the herbaceous grassland C stocks following conversion so default biomass estimates (IPCC 2006) for grasslands are used to estimate C stock changes (Note: litter and dead wood C stocks are assumed to be zero following conversion because no reference C density estimates exist for grasslands). The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion.

The amount of biomass C that is lost abruptly with *Forest Land Converted to Grasslands* is estimated based on the amount of C before conversion and the amount of C following conversion according to remeasurements in the FIA program. This approach is consistent with IPCC (2006) that assumes there is an abrupt change during the first year, but does not necessarily capture the slower change over the years following conversion until a new steady is reached. It was determined that using an IPCC Tier I approach that assumes all C is lost in the year of conversion for *Forest Land Converted to Grasslands* in the West and Great Plains states does not accurately characterize the transfer of C in woody biomass during abrupt or gradual land use change. To estimate this transfer of C in woody biomass, state-specific C densities for woody biomass remaining on these former forest lands following conversion to grasslands were developed and included in the estimation of C stock changes from *Forest Land Converted to Grasslands* in the West and Great Plains states. A review of the literature in grassland and rangeland ecosystems (Asner et al. 2003; Huang et al. 2009; Tarhouni et al. 2016), as well as an analysis of FIA data, suggests that a conservative estimate of 50 percent of the woody biomass C density was lost during conversion from Forest Land to Grasslands. This estimate was used to develop state-specific C density estimates for biomass, dead wood, and litter for Grasslands in the West and Great Plains states and these state-specific C densities were applied in the compilation system to estimate the C losses associated with conversion from forest land to grassland in the West and Great Plains states. Further, losses from forest land to what are characterized as woodlands are included in this category using FIA plot re-measurements and the methods and models described hereafter.

If FIA plots include data on individual trees, aboveground and belowground C density estimates are based on Woodall et al. (2011). Aboveground and belowground biomass estimates also include live understory which is a minor component of biomass defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this Inventory, it was assumed that 10 percent of total understory C mass is belowground (Smith et al. 2006). Estimates of C density are based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003).

If FIA plots include data on standing dead trees, standing dead tree C density is estimated following the basic method applied to live trees (Woodall et al. 2011) with additional modifications to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). If FIA plots include data on downed dead wood, downed dead wood C density is estimated based on measurements of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter that are not attached to live or standing dead trees at transect intersection. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood C estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter C is the pool of organic C (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots is measured for litter C. If FIA plots include litter material, a modeling approach using litter C measurements from FIA plots is used to estimate litter C density (Domke et al. 2016). The same methods are applied from 1990 to 2020 in order to ensure time-series consistency. See Annex 3.13 for more information about reference C density estimates for forest land.

Soil Carbon Stock Changes

Soil organic C stock changes are estimated for *Land Converted to Grassland* according to land use histories recorded in the 2015 USDA NRI survey for non-federal lands (USDA-NRCS 2018). Land use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI survey locations on a 5-year cycle beginning in 1982. In 1998, the NRI Program began collecting annual data, and the annual data are currently available through 2015 (USDA-NRCS 2018). NRI survey locations are classified as *Land Converted to Grassland* in a given year between 1990 and 2015 if the land use is grassland but had been classified as another use during the previous 20 years. NRI survey locations are classified according to land use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an underestimation of *Land Converted to Grassland* in the early part of the time series to the extent that some areas are converted to grassland between 1971 and 1978. For federal lands, the land use history is derived from land cover changes in the National Land Cover Dataset (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Mineral Soil Carbon Stock Changes

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate C stock changes in mineral soils for most of the area in *Land Converted to Grassland*. C stock changes on the remaining area are estimated with an IPCC Tier 2 approach (Ogle et al. 2003), including prior cropland used to produce vegetables, tobacco, and perennial/horticultural crops; land areas with very gravelly, cobbly, or shaley soils (greater than 35 percent by volume); and land converted to grassland from another land use other than cropland.

A surrogate data method is used to estimate soil organic C stock changes from 2016 to 2020 at the national scale for land areas included in the Tier 2 and Tier 3 methods. Specifically, linear regression models with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) are used to estimate the relationship between surrogate data and the 1990 to 2015 emissions data that are derived using the Tier 2 and 3 methods. Surrogate data for these regression models includes weather data from the PRISM Climate Group (PRISM Climate Group 2018). See Box 6-4 in the Methodology section of *Cropland Remaining Cropland* for more information about the surrogate data method. Stock change estimates for 2016 to 2020 will be recalculated in future Inventories when the times series of activity data is updated.

Tier 3 Approach*.* Mineral soil organic C stocks and stock changes are estimated using the DayCent biogeochemical[58] model (Parton et al. 1998; Del Grosso et al. 2001, 2011). The DayCent model utilizes the soil C modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Historical land use patterns and irrigation histories are simulated with DayCent based on the 2015 USDA NRI survey (USDA-NRCS 2018). Carbon stocks and 95 percent

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[58] Biogeochemical cycles are the flow of chemical elements and compounds between living organisms and the physical environment.

confidence intervals are estimated for each year between 1990 and 2015. See the *Cropland Remaining Cropland* section and Annex 3.12 for additional discussion of the Tier 3 methodology for mineral soils.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes from 2016 to 2020 are approximated using a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) errors, described in Box 6-4 of the Methodology section in *Cropland Remaining Cropland.* Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). Future Inventories will be updated with new activity data, and the time series will be recalculated for 2016 to 2020 (see the Planned Improvements section in *Cropland Remaining Cropland*)

Tier 2 Approach*.* For the mineral soils not included in the Tier 3 analysis, soil organic C stock changes are estimated using a Tier 2 Approach, as described in the Tier 2 Approach for mineral soils in *Grassland Remaining Grassland* and Annex 3.12. In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes are approximated for the remainder of the time series with a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) (See Box 6-4 of the Methodology section in *Cropland Remaining Cropland*). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). As with the Tier 3 method, time series of activity data will be updated in a future Inventory, and emissions from 2016 to 2020 will be recalculated.

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in *Land Converted to Grassland* are estimated using the Tier 2 method provided in IPCC (2006), with country-specific C loss rates (Ogle et al. 2003) as described in the *Cropland Remaining Cropland* section. Further elaboration on the methodology is also provided in Annex 3.12 for organic soils.

In order to ensure time-series consistency, the Tier 2 method is applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic C stock changes are approximated for the remainder of the time series with a linear extrapolation of emission patterns from 1990 to 2015. The extrapolation is based on a linear regression model with moving-average (ARMA) (See Box 6-4 of the Methodology section in *Cropland Remaining Cropland*). Linear extrapolation is a standard data splicing method for estimating emissions at the end of a time series (IPCC 2006). As with the Tier 3 method, time series of activity data will be updated in a future Inventory, and emissions from 2016 to 2020 will be recalculated.

Uncertainty

The uncertainty analysis for biomass, dead wood and litter C losses with *Forest Land Converted to Grassland* is conducted in the same way as the uncertainty assessment for forest ecosystem C flux in the *Forest Land Remaining Forest Land* category. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006), by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details see the Uncertainty Analysis in Annex 3.13.

The uncertainty analyses for mineral soil organic C stock changes using the Tier 3 and Tier 2 methodologies are based on a Monte Carlo approach that is described in the *Cropland Remaining Cropland* section and Annex 3.12. The uncertainty for annual C emission estimates from drained organic soils in *Land Converted to Grassland* is estimated using a Monte Carlo approach, which is also described in the *Cropland Remaining Cropland* section. For 2016 to 2020, there is additional uncertainty propagated through the Monte Carlo Analysis associated with a surrogate data method, which is also described in *Cropland Remaining Cropland*.

Uncertainty estimates are presented in Table 6-46 for each subsource (i.e., biomass C stocks, mineral and organic C stocks in soils) and the method applied in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates from the Tier 2 and 3 approaches are combined using the simple error propagation methods provided by the IPCC

(2006), as discussed in the previous paragraph. The combined uncertainty for total C stocks in *Land Converted to Grassland* ranges from 153 percent below to 153 percent above the 2020 stock change estimate of 24.1 MMT CO_2 Eq. The large relative uncertainty around the 2020 stock change estimate is partly due to large uncertainties in biomass and dead organic matter C losses with *Forest Land Conversion to Grassland*. The large relative uncertainty is also partly due to variation in soil organic C stock changes that is not explained by the surrogate data method, leading to high prediction error with the splicing method.

Table 6-46: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass C Stock Changes occurring within *Land Converted to Grassland* (MMT CO_2 Eq. and Percent)

Source	2020 Flux Estimate[a] (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Grassland	**(19.7)**	**(50.3)**	**10.9**	**-155%**	**155%**
Mineral Soil C Stocks: Tier 3	(17.3)	(47.7)	13.2	-176%	176%
Mineral Soil C Stocks: Tier 2	(3.8)	(7.0)	(0.6)	-85%	85%
Organic Soil C Stocks: Tier 2	1.3	+	2.7	-103%	103%
Forest Land Converted to Grassland	**18.1**	**4.9**	**31.3**	**-73%**	**73%**
Aboveground Live Biomass	11.6	(0.5)	23.7	-104%	104%
Belowground Live Biomass	2.1	(0.1)	4.2	-103%	104%
Dead Wood	(0.3)	(0.1)	+	-78%	100%
Litter	4.6	(0.2)	9.4	-104%	104%
Mineral Soil C Stocks: Tier 2	+	(0.2)	0.1	-348%	348%
Organic Soil C Stocks: Tier 2	0.2	+	0.4	-114%	114%
Other Lands Converted to Grassland	**(21.8)**	**(37.3)**	**(6.3)**	**-71%**	**71%**
Mineral Soil C Stocks: Tier 2	(21.9)	(37.4)	(6.3)	-71%	71%
Organic Soil C Stocks: Tier 2	0.1	+	0.2	-155%	155%
Settlements Converted to Grassland	**(1.0)**	**(1.7)**	**(0.2)**	**-76%**	**76%**
Mineral Soil C Stocks: Tier 2	(1.0)	(1.7)	(0.2)	-75%	75%
Organic Soil C Stocks: Tier 2	+	+	+	-292%	292%
Wetlands Converted to Grasslands	**0.2**	**+**	**0.5**	**-116%**	**116%**
Mineral Soil C Stocks: Tier 2	+	(0.1)	0.1	-882%	882%
Organic Soil C Stocks: Tier 2	0.2	+	0.5	-116%	116%
Total: Land Converted to Grassland	**(24.1)**	**(60.9)**	**12.7**	**-153%**	**153%**
Aboveground Live Biomass	**11.6**	**(0.5)**	**23.7**	**-104%**	**104%**
Belowground Live Biomass	**2.1**	**(0.1)**	**4.2**	**-103%**	**104%**
Dead Wood	**(0.3)**	**(0.1)**	**+**	**-78%**	**100%**
Litter	**4.6**	**(0.2)**	**9.4**	**-104%**	**104%**
Mineral Soil C Stocks: Tier 3	**(17.3)**	**(47.7)**	**13.2**	**-176%**	**176%**
Mineral Soil C Stocks: Tier 2	**(26.6)**	**(42.5)**	**(10.8)**	**-60%**	**60%**
Organic Soil C Stocks: Tier 2	**1.8**	**0.4**	**3.2**	**-77%**	**77%**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Uncertainty is also associated with a lack of reporting on biomass, dead wood and litter C stock changes for agroforestry systems. However, there are currently no datasets to evaluate the trends. Changes in biomass and dead organic matter C stocks are assumed to be negligible with the exception of forest lands, which are included in this analysis in other grasslands. This assumption will be further explored in a future Inventory.

QA/QC and Verification

See the QA/QC and Verification section in *Cropland Remaining Cropland* and *Grassland Remaining Grassland* for information on QA/QC steps.

Recalculations Discussion

Recalculations are associated with new FIA data from 1990 to 2020 on biomass, dead wood and litter C stocks in *Forest Land Converted to Grassland,* and updated estimates for mineral soils from 2016 to 2020 using the linear extrapolation method. As a result, *Land Converted to Grassland* has an estimated smaller gain in C of 2.93 MMT CO_2 Eq. on average over the time series. This represents a 15 percent decrease in C stock changes for *Land Converted to Grassland* compared to the previous Inventory.

Planned Improvements

The amount of biomass C that is lost abruptly or the slower changes that continue to occur over a decade or longer with *Forest Land Converted to Grasslands* will be further refined in a future Inventory. The current values are estimated based on the amount of C before conversion and an estimated level of C left after conversion based on limited plot data from the FIA and published literature for the Western United States and Great Plains Regions. The amount of C left after conversion will be further investigated with additional data collection, particularly in the Western United States and Great Plains, including tree biomass, understory biomass, dead wood and litter C pools. In addition, biomass C stock changes will be estimated for *Cropland Converted to Grassland*, and other land use conversions to grassland, to the extent that data are available.

An additional planned improvement for the *Land Converted to Grassland* category is to develop an inventory of C stock changes for grasslands in Alaska. Table 6-47 provides information on the amount of managed area in Alaska that is *Land Converted to Grassland*, which is as high as 54 thousand hectares in 2011.[59] Note that areas of *Land Converted to Grassland* in Alaska for 1990 to 2001 are classified as *Grassland Remaining Grassland* because land use change data are not available until 2002. For information about other improvements, see the Planned Improvements section in *Cropland Remaining Cropland* and *Grassland Remaining Grassland*.

Table 6-47: Area of Managed Land in *Land Converted to Grassland* in Alaska that is not included in the current Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	Managed Land	Inventory	Not Included in Inventory
1990	9,394	9,394	0
1991	9,485	9,485	0
1992	9,691	9,691	0
1993	11,566	11,566	0
1994	13,378	13,378	0
1995	13,994	13,994	0
1996	14,622	14,622	0
1997	15,162	15,162	0
1998	19,052	19,052	0
1999	19,931	19,931	0
2000	20,859	20,859	0
2001	21,968	21,968	0
2002	22,395	22,392	3

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[59] All of the *Land Converted to Grassland* according to the land representation is included in the inventory from 1990 through 2001 for the conterminous United States. However, there are no data to evaluate land use change in Alaska for this time period, and so the balance of the managed area that may be converted to grassland in these years is included in Grassland Remaining Grassland section. This gap in land use change data for Alaska will be addressed in a future Inventory.

2003	22,015	22,008	7
2004	22,557	22,547	10
2005	22,460	22,447	13
2006	22,718	22,702	16
2007	22,450	22,428	21
2008	22,685	22,661	24
2009	22,608	22,581	26
2010	22,664	22,634	29
2011	22,805	22,750	54
2012	22,643	22,596	47
2013	21,472	21,439	33
2014	20,195	20,163	33
2015	20,242	20,210	33
2016	ND	ND	ND
2017	ND	ND	ND
2018	ND	ND	ND
2019	ND	ND	ND
2020	ND	ND	ND

Note: NRI data are not available after 2015, and these years are designated as ND (No data).

6.8 Wetlands Remaining Wetlands (CRF Category 4D1)

Wetlands Remaining Wetlands includes all wetland in an Inventory year that had been classified as wetland for the previous 20 years, and in this Inventory the flux estimates include Peatlands, Coastal Wetlands, and Flooded Land.

Peatlands Remaining Peatlands

Emissions from Managed Peatlands

Managed peatlands are peatlands that have been cleared and drained for the production of peat. The production cycle of a managed peatland has three phases: land conversion in preparation for peat extraction (e.g., clearing surface biomass, draining), extraction (which results in the emissions reported under Peatlands Remaining Peatlands), and abandonment, restoration, rewetting, or conversion of the land to another use.

Carbon dioxide emissions from the removal of biomass and the decay of drained peat constitute the major greenhouse gas flux from managed peatlands. Managed peatlands may also emit CH_4 and N_2O. The natural production of CH_4 is largely reduced but not entirely shut down when peatlands are drained in preparation for peat extraction (Strack et al. 2004 as cited in the *2006 IPCC Guidelines*). Drained land surface and ditch networks contribute to the CH_4 flux in peatlands managed for peat extraction. Methane emissions were considered insignificant under the IPCC Tier 1 methodology (IPCC 2006), but are included in the emissions estimates for Peatlands Remaining Peatlands consistent with the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2013). Nitrous oxide emissions from managed peatlands depend on site fertility. In addition, abandoned and restored peatlands continue to release greenhouse gas emissions. Although methodologies are provided for rewetted organic soils (which includes rewetted/restored peatlands) in IPCC (2013) guidelines, information on the areal extent of rewetted/restored peatlands in the United States is currently unavailable. The current Inventory estimates CO_2, CH_4 and N_2O emissions from peatlands managed for peat extraction in accordance with IPCC (2006 and 2013) guidelines.

CO_2, N_2O, and CH_4 Emissions from Peatlands Remaining Peatlands

IPCC (2013) recommends reporting CO_2, N_2O, and CH_4 emissions from lands undergoing active peat extraction (i.e., Peatlands Remaining Peatlands) as part of the estimate for emissions from managed wetlands. Peatlands occur where plant biomass has sunk to the bottom of water bodies and water-logged areas and exhausted the oxygen supply below the water surface during the course of decay. Due to these anaerobic conditions, much of the plant matter does not decompose but instead forms layers of peat over decades and centuries. In the United States, peat is extracted for horticulture and landscaping growing media, and for a wide variety of industrial, personal care, and other products. It has not been used for fuel in the United States for many decades. Peat is harvested from two types of peat deposits in the United States: *Sphagnum* bogs in northern states (e.g., Minnesota) and wetlands in states further south (e.g., Florida). The peat from *Sphagnum* bogs in northern states, which is nutrient-poor, is generally corrected for acidity and mixed with fertilizer. Production from more southerly states is relatively coarse (i.e., fibrous) but nutrient-rich.

IPCC (2006 and 2013) recommend considering both on-site and off-site emissions when estimating CO_2 emissions from Peatlands Remaining Peatlands using the Tier 1 approach. Current methodologies estimate only on-site N_2O and CH_4 emissions, since off-site N_2O estimates are complicated by the risk of double-counting emissions from nitrogen fertilizers added to horticultural peat, and off-site CH_4 emissions are not relevant given the non-energy uses of peat, so methodologies are not provided in IPCC (2013) guidelines.

On-site emissions from managed peatlands occur as the land is cleared of vegetation and the underlying peat is exposed to sun and weather. As this occurs, some peat deposit is lost and CO_2 is emitted from the oxidation of the peat. Since N_2O emissions from saturated ecosystems tend to be low unless there is an exogenous source of nitrogen, N_2O emissions from drained peatlands are dependent on nitrogen mineralization and therefore on soil fertility. Peatlands located on highly fertile soils contain significant amounts of organic nitrogen in inactive form. Draining land in preparation for peat extraction allows bacteria to convert the nitrogen into nitrates which leach to the surface where they are reduced to N_2O, and contributes to the activity of methanogens and methanotrophs that result in CH_4 emissions (Blodau 2002; Treat et al. 2007 as cited in IPCC 2013). Drainage ditches, which are constructed to drain the land in preparation for peat extraction, also contribute to the flux of CH_4 through *in situ* production and lateral transfer of CH_4 from the organic soil matrix (IPCC 2013).

Off-site CO_2 emissions from managed peatlands occur from waterborne carbon losses and the horticultural and landscaping use of peat. Dissolved organic carbon from water drained off peatlands reacts within aquatic ecosystems and is converted to CO_2, which is then emitted to the atmosphere (Billet et al. 2004 as cited in IPCC 2013). During the horticultural and landscaping use of peat, nutrient-poor (but fertilizer-enriched) peat tends to be used in bedding plants and in greenhouse and plant nursery production, whereas nutrient-rich (but relatively coarse) peat is used directly in landscaping, athletic fields, golf courses, and plant nurseries. Most (nearly 94 percent) of the CO_2 emissions from peat occur off-site, as the peat is processed and sold to firms which, in the United States, use it predominantly for the aforementioned horticultural and landscaping purposes.

Total emissions from Peatlands Remaining Peatlands were estimated to be 0.7 MMT CO_2 Eq. in 2020 (see Table 6-48 and Table 6-49) comprising 0.7 MMT CO_2 Eq. (708 kt) of CO_2, 0.004 MMT CO_2 Eq. (0.15 kt) of CH_4 and 0.0006 MMT CO_2 Eq. (0.002 kt) of N_2O. Total emissions in 2020 were 6.2 percent less than total emissions in 2019.

Total emissions from Peatlands Remaining Peatlands have fluctuated between 0.7 and 1.3 MMT CO_2 Eq. across the time series with a decreasing trend from 1990 until 1993, followed by an increasing trend until reaching peak emissions in 2000. After 2000, emissions generally decreased until 2006 and then increased until 2009. The trend reversed in 2009 and total emissions have generally decreased between 2009 and 2020. Carbon dioxide emissions from Peatlands Remaining Peatlands have fluctuated between 0.7 and 1.3 MMT CO_2 across the time series, and these emissions drive the trends in total emissions. Methane and N_2O emissions remained close to zero across the time series. Nitrous oxide emissions showed a decreasing trend from 1990 until 1995, followed by an increasing trend through 2001. Nitrous oxide emissions decreased between 2001 and 2006, followed by a leveling off between 2008 and 2010, and a general decline between 2011 and 2020. Methane emissions decreased from 1990 until 1995, followed by an increasing trend through 2000, a period of fluctuation through 2010, and a general decline between 2010 and 2020 (emissions rose slightly from 2016 to 2017 but resumed the downward trend since).

Table 6-48: Emissions from Peatlands Remaining Peatlands (MMT CO_2 Eq.)

Gas	1990	2005	2016	2017	2018	2019	2020
CO_2	**1.1**	**1.1**	**0.7**	**0.8**	**0.8**	**0.8**	**0.7**
Off-site	1.0	1.0	0.7	0.8	0.7	0.7	0.7
On-site	0.1	0.1	+	0.1	0.1	+	+
CH_4 (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**
N_2O (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Total	**1.1**	**1.1**	**0.7**	**0.8**	**0.8**	**0.8**	**0.7**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: These numbers are based on U.S. production data in accordance with Tier 1 guidelines, which does not take into account imports, exports, and stockpiles (i.e., apparent consumption). Off-site N_2O emissions are not estimated to avoid double-counting N_2O emitted from the fertilizer that the peat is mixed with prior to horticultural use (see IPCC 2006). Totals may not sum due to independent rounding.

Table 6-49: Emissions from Peatlands Remaining Peatlands (kt)

Gas	1990	2005	2016	2017	2018	2019	2020
CO_2	**1,055**	**1,101**	**733**	**829**	**792**	**755**	**708**
Off-site	985	1,030	686	774	741	706	662
On-site	70	71	47	55	51	49	46
CH_4 (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**
N_2O (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**

+ Does not exceed 0.5 kt

Note: These numbers are based on U.S. production data in accordance with Tier 1 guidelines, which does not take into account imports, exports, and stockpiles (i.e., apparent consumption). Off-site N_2O emissions are not estimated to avoid double-counting N_2O emitted from the fertilizer that the peat is mixed with prior to horticultural use (see IPCC 2006). Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

Off-Site CO_2 Emissions

Carbon dioxide emissions from domestic peat production were estimated using a Tier 1 methodology consistent with IPCC (2006). Off-site CO_2 emissions from Peatlands Remaining Peatlands were calculated by apportioning the annual weight of peat produced in the United States (Table 6-50) into peat extracted from nutrient-rich deposits and peat extracted from nutrient-poor deposits using annual percentage-by-weight figures. These nutrient-rich and nutrient-poor production values were then multiplied by the appropriate default C fraction conversion factor taken from IPCC (2006) in order to obtain off-site emission estimates. For the lower 48 states, both annual percentages of peat type by weight and domestic peat production data were sourced from estimates and industry statistics provided in the *Minerals Yearbook* and *Mineral Commodity Summaries* from the U.S. Geological Survey (USGS 1995 through 2017; USGS 2021a; USGS 2021b). To develop these data, the U.S. Geological Survey (USGS; U.S. Bureau of Mines prior to 1997) obtained production and use information by surveying domestic peat producers. On average, about 75 percent of the peat operations respond to the survey; and USGS estimates data for non-respondents on the basis of prior-year production levels (Apodaca 2011).

The Alaska estimates rely on reported peat production from the annual *Alaska's Mineral Industry* reports (DGGS 1993 through 2015). Similar to the U.S. Geological Survey, the Alaska Department of Natural Resources, Division of Geological & Geophysical Surveys (DGGS) solicits voluntary reporting of peat production from producers for the

Alaska's Mineral Industry report. However, the report does not estimate production for the non-reporting producers, resulting in larger inter-annual variation in reported peat production from Alaska depending on the number of producers who report in a given year (Szumigala 2011). In addition, in both the lower 48 states and Alaska, large variations in peat production can also result from variations in precipitation and the subsequent changes in moisture conditions, since unusually wet years can hamper peat production. The methodology estimates Alaska emissions separately from lower 48 emissions because the state conducts its own mineral survey and reports peat production by volume, rather than by weight (Table 6-51). However, volume production data were used to calculate off-site CO_2 emissions from Alaska applying the same methodology but with volume-specific C fraction conversion factors from IPCC (2006).[60] Peat production was not reported for 2015 in *Alaska's Mineral Industry 2014* report (DGGS 2015); and reliable data are not available beyond 2012, so Alaska's peat production in 2013 through 2019 (reported in cubic yards) was assumed to be equal to the 2012 value.

Consistent with IPCC (2013) guidelines, off-site CO_2 emissions from dissolved organic carbon were estimated based on the total area of peatlands managed for peat extraction, which is calculated from production data using the methodology described in the On-Site CO_2 Emissions section below. Carbon dioxide emissions from dissolved organic C were estimated by multiplying the area of peatlands by the default emission factor for dissolved organic C provided in IPCC (2013).

The *apparent consumption* of peat, which includes production plus imports minus exports plus the decrease in stockpiles, in the United States is over time the amount of domestic peat production. However, consistent with the Tier 1 method whereby only domestic peat production is accounted for when estimating off-site emissions, off-site CO_2 emissions from the use of peat not produced within the United States are not included in the Inventory. The United States has largely imported peat from Canada for horticultural purposes; in 2018, imports of *Sphagnum* moss (nutrient-poor) peat from Canada represented 96 percent of total U.S. peat imports (USGS 2021a). Most peat produced in the United States is reed-sedge peat, generally from southern states, which is classified as nutrient-rich by IPCC (2006). Higher-tier calculations of CO_2 emissions from apparent consumption would involve consideration of the percentages of peat types stockpiled (nutrient-rich versus nutrient-poor) as well as the percentages of peat types imported and exported.

Table 6-50: Peat Production of Lower 48 States (kt)

Type of Deposit	**1990**	**2005**	**2016**	**2017**	**2018**	**2019**	**2020**
Nutrient-Rich	595.1	657.6	388.1	423.3	415.0	410.4	417.1
Nutrient-Poor	55.4	27.4	52.9	74.7	62.0	45.6	12.9
Total Production	**692.0**	**685.0**	**441.0**	**498.0**	**477.0**	**456.0**	**430.0**

Sources: United States Geological Survey (USGS) (1991–2017) *Minerals Yearbook: Peat (1994–2016);* United States Geological Survey (USGS) (2018) *Minerals Yearbook: Peat – Tables-only release (2018);* United States Geological Survey (USGS) (2021) *Mineral Commodity Summaries: Peat (2021).*

Table 6-51: Peat Production of Alaska (Thousand Cubic Meters)

	1990	**2005**	**2016**	**2017**	**2018**	**2019**	**2020**
Total Production	49.7	47.8	93.1	93.1	93.1	93.1	93.1

Sources: Division of Geological & Geophysical Surveys (DGGS), Alaska Department of Natural Resources (1997–2015) *Alaska's Mineral Industry Report (1997–2014)*.

On-site CO_2 Emissions

IPCC (2006) suggests basing the calculation of on-site emission estimates on the area of peatlands managed for peat extraction differentiated by the nutrient type of the deposit (rich versus poor). Information on the area of

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[60] Peat produced from Alaska was assumed to be nutrient poor; as is the case in Canada, "where deposits of high-quality [but nutrient poor] *Sphagnum* moss are extensive" (USGS 2008).

land managed for peat extraction is currently not available for the United States, but consistent with IPCC (2006), an average production rate for the industry was applied to derive an area estimate. In a mature industrialized peat industry, such as exists in the United States and Canada, the vacuum method can extract up to 100 metric tons per hectare per year (Cleary et al. 2005 as cited in IPCC 2006).[61] The area of land managed for peat extraction in the lower 48 states of the United States was estimated using nutrient-rich and nutrient-poor production data and the assumption that 100 metric tons of peat are extracted from a single hectare in a single year, see Table 6-52. The annual land area estimates were then multiplied by the IPCC (2013) default emission factor in order to calculate on-site CO_2 emission estimates.

Production data are not available by weight for Alaska. In order to calculate on-site emissions resulting from Peatlands Remaining Peatlands in Alaska, the production data by volume were converted to weight using annual average bulk peat density values, and then converted to land area estimates using the assumption that a single hectare yields 100 metric tons, see Table 6-53. The IPCC (2006) on-site emissions equation also includes a term that accounts for emissions resulting from the change in C stocks that occurs during the clearing of vegetation prior to peat extraction. Area data on land undergoing conversion to peatlands for peat extraction is also unavailable for the United States. However, USGS records show that the number of active operations in the United States has been declining since 1990; therefore, it seems reasonable to assume that no new areas are being cleared of vegetation for managed peat extraction. Other changes in C stocks in living biomass on managed peatlands are also assumed to be zero under the Tier 1 methodology (IPCC 2006 and 2013).

Table 6-52: Peat Production Area of Lower 48 States (Hectares)

	1990[a]	2005	2016	2017	2018	2019	2020
Nutrient-Rich	5,951	6,576	3,881	4,233	4,150	4,104	4,171
Nutrient-Poor	554	274	529	747	620	456	129
Total Production	**6,920**	**6,850**	**4,410**	**4,980**	**4,770**	**4,560**	**4,300**

[a] A portion of the production in 1990 is of unknown nutrient type, resulting in a total production value greater than the sum of nutrient-rich and nutrient-poor.

Notes: Calculated using peat production values in Table 6-50, an assumed yield of 100 metric tons per hectare per year.

Table 6-53: Peat Production Area of Alaska (Hectares)

	1990	2005	2016	2017	2018	2019	2020
Nutrient-Rich	0	0	0	0	0	0	0
Nutrient-Poor	286	104	201	333	212	212	212
Total Production	**286**	**104**	**201**	**333**	**212**	**212**	**212**

Sources: Calculated using peat production values in Table 6-51, an assumed yield of 100 metric tons per hectare per year.

On-site N_2O Emissions

IPCC (2006) suggests basing the calculation of on-site N_2O emission estimates on the area of nutrient-rich peatlands managed for peat extraction. These area data are not available directly for the United States, but the on-site CO_2 emissions methodology above details the calculation of area data from production data. In order to estimate N_2O emissions, the area of nutrient-rich Peatlands Remaining Peatlands was multiplied by the appropriate default emission factor taken from IPCC (2013).

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[61] The vacuum method is one type of extraction that annually "mills" or breaks up the surface of the peat into particles, which then dry during the summer months. The air-dried peat particles are then collected by vacuum harvesters and transported from the area to stockpiles (IPCC 2006).

On-site CH_4 Emissions

IPCC (2013) also suggests basing the calculation of on-site CH_4 emission estimates on the total area of peatlands managed for peat extraction. Area data is derived using the calculation from production data described in the On-site CO_2 Emissions section above. In order to estimate CH_4 emissions from drained land surface, the area of Peatlands Remaining Peatlands was multiplied by the emission factor for direct CH_4 emissions taken from IPCC (2013). In order to estimate CH_4 emissions from drainage ditches, the total area of peatland was multiplied by the default fraction of peatland area that contains drainage ditches, and the appropriate emission factor taken from IPCC (2013). See Table 6-54 for the calculated area of ditches and drained land.

Table 6-54: Peat Production (Hectares)

	1990		2005		2016	2017	2018	2019	2020
Lower 48 States									
Area of Drained Land	6,574		6,508		4,190	4,731	4,532	4,332	4,085
Area of Ditches	346		343		221	249	239	228	215
Total Production	**6,920**		**6,850**		**4,410**	**4,980**	**4,770**	**4,560**	**4,300**
Alaska									
Area of Drained Land	272		99		191	317	202	202	202
Area of Ditches	14		5		10	17	11	11	11
Total Production	**286**		**104**		**201**	**333**	**212**	**212**	**212**

Sources: Calculated using peat production values in Tables Table 6-50 and Table 6-51, an assumed yield of 100 metric tons per hectare per year, and an assumed value of 5 percent ditch area.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020. The same data sources were used throughout the time series, when available. When data were unavailable or the available data were outliers, missing values were estimates based on the past available data.

Uncertainty

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the uncertainty of CO_2, CH_4, and N_2O emissions from Peatlands Remaining Peatlands for 2020, using the following assumptions:

- The uncertainty associated with peat production data was estimated to be ± 25 percent (Apodaca 2008) and assumed to be normally distributed.
- The uncertainty associated with peat production data stems from the fact that the USGS receives data from the smaller peat producers but estimates production from some larger peat distributors. The peat type production percentages were assumed to have the same uncertainty values and distribution as the peat production data (i.e., ± 25 percent with a normal distribution).
- The uncertainty associated with the reported production data for Alaska was assumed to be the same as for the lower 48 states, or ± 25 percent with a normal distribution. It should be noted that the DGGS estimates that around half of producers do not respond to their survey with peat production data; therefore, the production numbers reported are likely to underestimate Alaska peat production (Szumigala 2008).
- The uncertainty associated with the average bulk density values was estimated to be ± 25 percent with a normal distribution (Apodaca 2008).
- IPCC (2006 and 2013) gives uncertainty values for the emissions factors for the area of peat deposits managed for peat extraction based on the range of underlying data used to determine the emission factors. The uncertainty associated with the emission factors was assumed to be triangularly distributed.
- The uncertainty values surrounding the C fractions were based on IPCC (2006) and the uncertainty was assumed to be uniformly distributed.

- The uncertainty values associated with the fraction of peatland covered by ditches was assumed to be ± 100 percent with a normal distribution based on the assumption that greater than 10 percent coverage, the upper uncertainty bound, is not typical of drained organic soils outside of The Netherlands (IPCC 2013).

The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-55. Carbon dioxide emissions from Peatlands Remaining Peatlands in 2020 were estimated to be between 0.6 and 0.8 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 17 percent below to 17 percent above the 2020 emission estimate of 0.71 MMT CO_2 Eq. Methane emissions from Peatlands Remaining Peatlands in 2020 were estimated to be between 0.002 and 0.007 MMT CO_2 Eq. This indicates a range of 58 percent below to 77 percent above the 2020 emission estimate of 0.004 MMT CO_2 Eq. Nitrous oxide emissions from Peatlands Remaining Peatlands in 2020 were estimated to be between 0.0003 and 0.0009 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 53 percent below to 53 percent above the 2020 emission estimate of 0.0006 MMT CO_2 Eq.

Table 6-55: Approach 2 Quantitative Uncertainty Estimates for CO_2, CH_4, and N_2O Emissions from Peatlands Remaining Peatlands (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Peatlands Remaining Peatlands	CO_2	0.7	0.6	0.8	-17%	17%
Peatlands Remaining Peatlands	CH_4	+	+	+	-58%	77%
Peatlands Remaining Peatlands	N_2O	+	+	+	-53%	53%

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

A QA/QC analysis was performed to review input data and calculations, and no issues were identified. In addition, the emission trends were analyzed to ensure they reflected activity data trends.

Recalculations Discussion

The lower 48 states peat production estimates for Peatlands Remaining Peatlands were updated using the Peat section of the *Mineral Commodity Summaries 2021*. The 2021 edition updated 2018 and 2019 peat production data and provided peat type production estimates for 2020. The updated data lowered previously estimated emissions for 2018 and 2019 by 0.4 percent and 2.9 percent versus estimated emissions for 2018 and 2019 in the previous (i.e., 1990 through 2019) Inventory for Peatlands Remaining Peatlands.

Although Alaska peat production data for 2015 through 2020 were unavailable, 2014 data are available in the *Alaska's Mineral Industry 2014* report. However, the reported values represented an apparent 98 percent decrease in production since 2012. Due to the uncertainty of the most recent data, 2013, 2014, 2015, 2016, 2017, 2018, 2019, and 2020 values were assumed to be equal to the 2012 value, seen in the *Alaska's Mineral Industry 2013* report. If updated Alaska data are available for the next Inventory cycle, this will result in a recalculation in the next (i.e., 1990 through 2021) Inventory report.

Planned Improvements

In order to further improve estimates of CO_2, N_2O, and CH_4 emissions from Peatlands Remaining Peatlands, future efforts will investigate if improved data sources exist for determining the quantity of peat harvested per hectare and the total area undergoing peat extraction.

During the next Inventory cycle, efforts are planned to identify a new source for Alaska peat production. The current source has not been reliably updated since 2012 and Alaska Department of Natural Resources indicated future publication of data has been discontinued. In addition, edits to the trends and methodology sections are planned based on expert review comments.

The USGS has not published a *Minerals Yearbook* since the 2018 Advance Release. If more recent versions of the Minerals Yearbook are made available, these updated data will be included in the next inventory cycle. Correspondence with USGS indicated the Minerals Yearbook publications undergo a lengthy editing process and may delay the release of the publications (Brioche 2021).

The implied emission factors will be calculated and included in this chapter for future Inventories. Currently, the N_2O emissions calculation uses different land areas than the CO_2 and CH_4 emission calculations, so estimating the implied emission factor per total land area is not appropriate and are not generated in the CRF tables. The inclusion of implied emission factors in this chapter will provide another method of QA/QC and verification.

Coastal Wetlands Remaining Coastal Wetlands

This Inventory recognizes Wetlands as a "land-use that includes land covered or saturated for all or part of the year, in addition to areas of lakes, reservoirs, and rivers." Consistent with ecological definitions of wetlands,[62] the United States has historically included under the category of Wetlands those coastal shallow water areas of estuaries and bays that lie within the extent of the Land Representation.

Guidance on quantifying greenhouse gas emissions and removals on Coastal Wetlands is provided in the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (*Wetlands Supplement*), which recognizes the particular importance of vascular plants in sequestering CO_2 from the atmosphere within biomass, dead organic material (DOM; including litter and dead wood stocks) and soils. Thus, the *Wetlands Supplement* provides specific guidance on quantifying emissions and removals on organic and mineral soils that are covered or saturated for part of the year by tidal fresh, brackish or saline water and are vegetated by vascular plants and may extend seaward to the maximum depth of vascular plant vegetation. The United States calculates emissions and removals based upon the stock change method for soil carbon and the gain-loss method for biomass and DOM. Presently, this Inventory does not calculate the lateral flux of carbon to or from any land use. Lateral transfer of organic carbon to coastal wetlands and to marine sediments within U.S. waters is the subject of ongoing scientific investigation.

The United States recognizes both Vegetated Wetlands and Unvegetated Open Water as Coastal Wetlands. Per guidance provided by the *Wetlands Supplement*, sequestration of carbon into biomass, DOM and soil carbon pools is recognized only in Vegetated Coastal Wetlands and does not occur in Unvegetated Open Water Coastal Wetlands. The United States takes the additional step of recognizing that stock losses occur when Vegetated Coastal Wetlands are converted to Unvegetated Open Water Coastal Wetlands.

This Inventory includes all privately-owned and publicly-owned coastal wetlands (i.e., mangroves and tidal marsh) along the oceanic shores on the conterminous United States, but does not include *Coastal Wetlands Remaining Coastal Wetlands* in Alaska or Hawaii. Seagrasses are not currently included within the Inventory due to insufficient data on distribution, change through time and carbon (C) stocks or C stock changes as a result of anthropogenic influence.

Under the *Coastal Wetlands Remaining Coastal Wetlands* category, the following emissions and removals are quantified in this chapter:

1) Carbon stock changes and CH_4 emissions on *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*,
2) Carbon stock changes on *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands*,

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[62] See https://water.usgs.gov/nwsum/WSP2425/definitions.html; accessed August 2021.

3) Carbon stock changes on *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands*, and

4) *Nitrous Oxide Emissions from Aquaculture in Coastal Wetlands*.

Vegetated coastal wetlands hold C in all five C pools (i.e., aboveground, belowground, dead organic matter [DOM; dead wood and litter], and soil) though typically soil C and, to a lesser extent, aboveground and belowground biomass are the dominant pools, depending on wetland type (i.e., forested vs. marsh). Vegetated Coastal Wetlands are net accumulators of C over centuries to millennia as soils accumulate C under anaerobic soil conditions and in plant biomass. Large emissions from soil C and biomass stocks occur when Vegetated Coastal Wetlands are converted to Unvegetated Open Water Coastal Wetlands (e.g., when Vegetated Coastal Wetlands are lost due to subsidence, channel cutting through Vegetated Coastal Wetlands), but are still recognized as Coastal Wetlands in this Inventory. These C stock losses resulting from conversion to Unvegetated Open Water Coastal Wetlands can cause the release of decades to centuries of accumulated soil C, as well as the standing stock of biomass C. Conversion of Unvegetated Open Water Coastal Wetlands to Vegetated Coastal Wetlands, either through restoration efforts or naturally, initiates the building of C stocks within soils and biomass. In applying the *Wetlands Supplement* methodologies for CH_4 emissions, coastal wetlands in salinity conditions greater than 18 parts per thousand have little to no CH_4 emissions compared to those experiencing lower salinity brackish and freshwater conditions. Conversion of Vegetated Coastal Wetlands to or from Unvegetated Open Water Coastal Wetlands are conservatively assumed to not result in a change in salinity condition and are assumed to have no impact on CH_4 emissions. The *Wetlands Supplement* provides methodologies to estimate N_2O emissions from coastal wetlands that occur due to aquaculture. The N_2O emissions from aquaculture result from the N derived from consumption of the applied food stock that is then excreted as N load available for conversion to N_2O. While N_2O emissions can also occur due to anthropogenic N loading from the watershed and atmospheric deposition, these emissions are not reported here to avoid double-counting of indirect N_2O emissions with the Agricultural Soils Management, Forest Land and Settlements categories.

The *Wetlands Supplement* provides methodologies for estimating C stock changes and CH_4 emissions from mangroves, tidal marshes and seagrasses. Depending upon their height and area, C stock changes from mangroves may be reported under the Forest Land category or under Coastal Wetlands. If mangrove stature is 5 m or greater or if there is evidence that trees can obtain that height, mangroves are reported under the Forest Land category. Mangrove forests that are less than 5 m are reported under Coastal Wetlands. All other non-drained, intact coastal marshes are intended to be reported under Coastal Wetlands.

Because of human activities and level of regulatory oversight, all coastal wetlands within the conterminous United States are included within the managed land area described in Section 6.1, and as such estimates of C stock changes, emissions of CH_4, and emissions of N_2O from aquaculture are included in this Inventory. At the present stage of inventory development, Coastal Wetlands are not explicitly shown in the Land Representation analysis while work continues to harmonize data from NOAA's Coastal Change Analysis Program (C-CAP)[63] with NRI, FIA and NLDC data used to compile the Land Representation. However, a check was undertaken to confirm that Coastal Wetlands recognized by C-CAP represented a subset of Wetlands recognized by the NRI for marine coastal states.

The greenhouse gas fluxes for all four wetland categories described above are summarized in Table 6-56. *Coastal Wetlands Remaining Coastal Wetlands* are generally a net C sink, with the fluxes ranging from -3.7 to -4.8 MMT CO_2 Eq. across the majority of the time series, however, between 2006 and 2010 they were a net source of emissions (ranging from of 5.2 to 5.5 MMT CO_2 Eq.), resulting from large loss of vegetated coastal wetlands to open water due to hurricanes (Table 6-56). Recognizing removals of CO_2 to soil of 10.2 MMT CO_2 Eq. and CH_4 emissions of 3.8 MMT CO_2 Eq. in 2020, *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* are a net sink of 6.4 MMT CO_2 Eq. Loss of coastal wetlands, primarily in the Mississippi Delta as a result of hurricane impacts and sediment diversion and other human impacts, recognized as Veg*etated Coastal Wetlands Converted to Unvegetated Coastal* Wetlands, drive an emission of 1.5 MMT CO_2 Eq. over the past five years, primarily from

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[63] See https://coast.noaa.gov/digitalcoast/tools/lca.html; accessed August 2021.

soils. Building of new wetlands from open water, recognized as *Unvegetated Coastal Wetlands Converted to Vegetated Coastal*, results each year in removal of 0.03 MMT CO_2 Eq. Aquaculture is a minor industry in the United States, resulting in an emission of N_2O across the time series of between 0.1 to 0.2 MMT CO_2 Eq. In all, *Coastal Wetlands* are a net sink of 4.8 MMT CO_2 Eq. in 2020.

Table 6-56: Emissions and Removals from Coastal Wetlands Remaining Coastal Wetlands (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2016	2017	2018	2019	2020
Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands	**(6.5)**	**(6.4)**	**(6.4)**	**(6.4)**	**(6.4)**	**(6.4)**	**(6.4)**
Biomass C Flux	(+)	0.1	(+)	(+)	(+)	(+)	(+)
Soil C Flux	(10.2)	(10.2)	(10.2)	(10.2)	(10.2)	(10.2)	(10.2)
Net CH_4 Flux	3.7	3.8	3.8	3.8	3.8	3.8	3.8
Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands	**1.8**	**2.6**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**
Biomass C Flux	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Dead Organic Matter C Flux	+	+	+	+	+	+	+
Soil C Flux	1.7	2.5	1.5	1.5	1.5	1.5	1.5
Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands	**(+)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**
Biomass C Flux	(+)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Organic Matter C Flux	(+)	(+)	0	0	0	0	0
Soil C Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Net N_2O Flux from Aquaculture in Coastal Wetlands	**0.1**	**0.2**	**0.1**	**0.1**	**0.2**	**0.2**	**0.2**
Total Biomass C Flux	**+**	**0.1**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**
Total Dead Organic Matter C Flux	**(+)**	**(+)**	**+**	**+**	**+**	**+**	**+**
Total Soil C Flux	**(8.5)**	**(7.7)**	**(8.7)**	**(8.7)**	**(8.7)**	**(8.7)**	**(8.7)**
Total CH_4 Flux	**3.7**	**3.8**	**3.8**	**3.8**	**3.8**	**3.8**	**3.8**
Total N_2O Flux	**0.1**	**0.2**	**0.1**	**0.1**	**0.2**	**0.2**	**0.2**
Total Flux	**(4.6)**	**(3.7)**	**(4.8)**	**(4.8)**	**(4.8)**	**(4.8)**	**(4.8)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Emissions and Removals from Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands

The conterminous United States currently has 2.98 million hectares of intertidal *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* comprised of tidally influenced palustrine emergent marsh (660,448 ha), palustrine scrub shrub (133,148 ha) and estuarine emergent marsh (1,894,045 ha), estuarine scrub shrub (94,110 ha) and estuarine forested wetlands (195,619 ha). Mangroves fall under both estuarine forest and estuarine scrub shrub categories depending upon height. Dwarf mangroves, found in subtropical states along the Gulf of Mexico, do not attain the height status to be recognized as Forest Land, and are therefore always classified within Vegetated Coastal Wetlands. *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* are found in cold temperate (53,973 ha), warm temperate (896,253 ha), subtropical (1,964,383 ha) and Mediterranean (62,762 ha) climate zones.

Soils are the largest C pool in *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*, reflecting long-term removal of atmospheric CO_2 by vegetation and transfer into the soil pool in the form of both autochthonous and allochthonous decaying organic matter. Soil C emissions are not assumed to occur in coastal wetlands that remain vegetated. This Inventory includes changes in biomass C stocks along with soils. Methane emissions from decomposition of organic matter in anaerobic conditions are present at salinity less than half that of sea water. Mineral and organic soils are not differentiated in terms of C stock changes or CH_4 emissions.

Table 6-57 through Table 6-59 below summarize nationally aggregated biomass and soil C stock changes and CH_4 emissions on *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*. Intact *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* hold a total biomass C stock of 88.8 MMT C. Removals from biomass C stocks in 2020 were 0.05 MMT CO_2 Eq. (0.01 MMT C), which has increased over the time series (Table 6-57 and Table 6-58). Carbon dioxide emissions from biomass in *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* between 2002 and 2011 are not inherently typical and are a result of coastal wetland loss over time. Most of the coastal wetland loss has occurred in palustrine and estuarine emergent wetlands. Vegetated coastal wetlands maintain a large C stock within the top 1 meter of soil (estimated to be 804 MMT C) to which C accumulated at a rate of 10.2 MMT CO_2 Eq. (2.8 MMT C) in 2020, a value that has remained relatively constant across the reporting period. For *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*, methane emissions of 3.8 of MMT CO_2 Eq. (154 kt CH_4) in 2020 (Table 6-59) offset C removals resulting in a net removal of 6.4 MMT CO_2 Eq. in 2020; this rate has been relatively consistent across the reporting period. Dead organic matter stock changes are not calculated in *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* since this stock is considered to be in a steady state when using Tier 1 methods (IPCC 2014). Due to federal regulatory protection, loss of Vegetated Coastal Wetlands through human activities slowed considerably in the 1970s and the current annual rates of C stock change and CH_4 emissions are relatively constant over time.

Table 6-57: Net CO_2 Flux from C Stock Changes in *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* (MMT CO_2 Eq.)

Year	1990	2005	2016	2017	2018	2019	2020
Biomass Flux	(+)	0.1	(+)	(+)	(+)	(+)	(+)
Soil Flux	(10.2)	(10.2)	(10.2)	(10.2)	(10.2)	(10.2)	(10.2)
Total C Stock Change	**(10.2)**	**(10.2)**	**(10.2)**	**(10.2)**	**(10.2)**	**(10.2)**	**(10.2)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Table 6-58: Net CO_2 Flux from C Stock Changes in *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* (MMT C)

Year	1990	2005	2016	2017	2018	2019	2020
Biomass Flux	(+)	+	(+)	(+)	(+)	(+)	(+)
Soil Flux	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)	(2.8)
Total C Stock Change	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**	**(2.8)**

+ Absolute value does not exceed 0.05 MMT C.

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Table 6-59: CH_4 Emissions from *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* (MMT CO_2 Eq. and kt CH_4)

Year	1990	2005	2016	2017	2018	2019	2020
Methane Emissions (MMT CO_2 Eq.)	3.7	3.8	3.8	3.8	3.8	3.8	3.8
Methane Emissions (kt CH_4)	149	151	153	153	153	153	154

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate changes in biomass C stocks, soil C stocks and emissions of CH_4 for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*. Dead organic matter is not calculated for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* since it is assumed to be in steady state (IPCC 2014).

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020.

Biomass Carbon Stock Changes

Above- and below ground biomass C Stocks for palustrine (freshwater) and estuarine (saline) marshes are estimated for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* on land below the elevation of high tides (taken to be mean high water spring tide elevation) and as far seawards as the extent of intertidal vascular plants according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2006, 2010, and 2016 NOAA C-CAP surveys (NOAA OCM 2020). C-CAP areas are calculated at the state/territory level and summed according to climate zone to national values. Federal and non-federal lands are represented. Trends in land cover change are extrapolated to 1990 and 2020 from these datasets. Based upon NOAA C-CAP, coastal wetlands are subdivided into palustrine and estuarine classes and further subdivided into emergent marsh, scrub shrub and forest classes (Table 6-60). Biomass is not sensitive to soil organic content but is differentiated based on climate zone. Aboveground biomass carbon stocks for non-forested wetlands data are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). The aboveground biomass carbon stock for estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017). Root to shoot ratios from the *Wetlands Supplement* (Table 6-62; IPCC 2014) were used to account for belowground biomass, which were multiplied by the aboveground carbon stock. Above- and belowground values were summed to obtain total biomass carbon stocks. Biomass C stock changes per year for *Wetlands Remaining Wetlands* were determined by calculating the difference in area between that year and the previous year to calculate gain/loss of area for each climate type, which was multiplied by the mean biomass for that climate type.

Table 6-60: Area of *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*, *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands*, and *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* (ha)

Year	1990	2005	2016	2017	2018	2019	2020
Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands	2,985,512	2,988,258	2,972,368	2,972,634	2,974,900	2,976,166	2,977,432
Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands	1,720	2,515	1,488	1,488	1,488	1,488	1,488
Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands	953	1,775	2,406	2,406	2,406	2,406	2,406

Table 6-61: Aboveground Biomass Carbon Stocks for *Vegetated Coastal Wetlands* (t C ha^{-1})

	Climate Zone			
Wetland Type	**Cold Temperate**	**Warm Temperate**	**Subtropical**	**Mediterranean**
Palustrine Scrub/Shrub Wetland	3.25	3.17	2.24	4.69
Palustrine Emergent Wetland	3.25	3.17	2.24	4.69
Estuarine Forested Wetland	3.05	3.10	17.83	3.44
Estuarine Scrub/Shrub Wetland	3.05	3.05	2.43	3.44
Estuarine Emergent Wetland	3.05	3.10	2.43	3.44

Source: All data from Byrd et al. (2017, 2018 and 2020) except for subtropical estuarine forested wetlands, which is from Lu and Megonigal (2017).

Table 6-62: Root to Shoot Ratios for *Vegetated Coastal Wetlands*

	Climate Zone			
Wetland Type	**Cold Temperate**	**Warm Temperate**	**Subtropical**	**Mediterranean**
Palustrine Scrub/Shrub Wetland	1.15	1.15	3.65	3.63

Palustrine Emergent Wetland	1.15	1.15	3.65	3.63
Estuarine Forested Wetland	1.15	1.15	0.96	3.63
Estuarine Scrub/Shrub Wetland	2.11	2.11	3.65	3.63
Estuarine Emergent Wetland	2.11	2.11	3.65	3.63

Source: All values from IPCC (2014).

Soil Carbon Stock Changes

Soil C stock changes are estimated for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* for both mineral and organic soils. Soil C stock changes, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature (Table 6-63; Lynch 1989; Orson et al. 1990; Kearny & Stevenson 1991; Roman et al. 1997; Craft et al. 1998; Orson et al. 1998; Merrill 1999; Hussein et al. 2004; Church et al. 2006; Köster et al. 2007; Callaway et al. 2012a&b; Bianchi et al. 2013; Crooks et al. 2014; Weston et al. 2014; Villa & Mitsch 2015; Marchio et al. 2016; Noe et al. 2016).

Tier 2 level estimates of soil C removals associated with annual soil C accumulation on managed *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* were developed with country-specific soil C removal factors multiplied by activity data of land area for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*. The methodology follows Eq. 4.7, Chapter 4 of the *Wetlands Supplement*, and is applied to the area of *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* on an annual basis. To estimate soil C stock changes, no differentiation is made between organic and mineral soils since currently no statistical evidence supports disaggregation (Holmquist et al. 2018).

Table 6-63: Annual Soil Carbon Accumulation Rates for *Vegetated Coastal Wetlands* (t C ha^{-1} yr^{-1})

Climate Zone	Cold Temperate	Warm Temperate	Subtropical	Mediterranean
Palustrine Scrub/Shrub Wetland	1.01	1.54	0.45	0.85
Palustrine Emergent Wetland	1.01	1.54	0.45	0.85
Estuarine Forested Wetland	1.01	0.82	0.87	0.85
Estuarine Scrub/Shrub Wetland	1.01	0.82	1.09	0.85
Estuarine Emergent Wetland	2.17	0.82	1.09	0.85

Source: All data from Lu and Megonigal (2017)[64]

Soil Methane Emissions

Tier 1 estimates of CH_4 emissions for *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* are derived from the same wetland map used in the analysis of wetland soil C fluxes, produced from C-CAP, LiDAR and tidal data, in combination with default CH_4 emission factors provided in Table 4.14 of the *Wetlands Supplement.* The methodology follows Equation 4.9, Chapter 4 of the *Wetlands Supplement*; Tier 1 emissions factors are multiplied by the area of freshwater (palustrine) coastal wetlands. The CH_4 fluxes applied are determined based on salinity; only palustrine wetlands are assumed to emit CH_4. Estuarine coastal wetlands in the C-CAP classification include wetlands with salinity less than 18 ppt, a threshold at which methanogenesis begins to occur (Poffenbarger et al. 2011), but the dataset currently does not differentiate estuarine wetlands based on their salinities and as a result CH_4 emissions from estuarine wetlands are not included at this time.

Uncertainty

Underlying uncertainties in the estimates of soil and biomass C stock changes and CH_4 emissions include uncertainties associated with Tier 2 literature values of soil C stocks, biomass C stocks and CH_4 flux, assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing

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[64] See https://github.com/Smithsonian/Coastal-Wetland-NGGI-Data-Public; accessed August 2021.

data. Uncertainty specific to *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* include differentiation of palustrine and estuarine community classes, which determines the soil C stock and CH_4 flux applied. Uncertainties for soil and biomass C stock data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment of a C stock to a disaggregation of a community class. Because mean soil and biomass C stocks for each available community class are in a fairly narrow range, the same overall uncertainty was assigned to each, respectively (i.e., applying approach for asymmetrical errors, where the largest uncertainty for any one soil C stock referenced using published literature values for a community class; uncertainty approaches provide that if multiple values are available for a single parameter, the highest uncertainty value should be applied to the propagation of errors; IPCC 2000). Uncertainty for root to shoot ratios, which are used for quantifying belowground biomass, are derived from the *2013 Wetlands Supplement*. Uncertainties for CH_4 flux are the Tier 1 default values reported in the *2013 IPCC Wetlands Supplement*. Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10 to 15 percent; IPCC 2003). However, there is significant uncertainty in salinity ranges for tidal and non-tidal estuarine wetlands and activity data used to apply CH_4 flux emission factors (delineation of an 18 ppt boundary) that will need significant improvement to reduce uncertainties. Details on the emission/removal trends and methodologies through time are described in more detail in the introduction and the Methodology section. The combined uncertainty was calculated using the IPCC Approach 1 method of summing the squared uncertainty for each individual source (C-CAP, soil, biomass and CH_4) and taking the square root of that total.

Uncertainty estimates are presented in Table 6-64 for each subsource (i.e., soil C, biomass C and CH_4 emissions). The combined uncertainty across all subsources is +/-36.6 percent, which is primarily driven by the uncertainty in the CH_4 estimates because there is high variability in CH_4 emissions when the salinity is less than 18 ppt. In 2020, the total flux was -6.4 MMT CO_2 Eq., with lower and upper estimates of -8.7 and -4.0 MMT CO_2 Eq.

Table 6-64: IPCC Approach 1 Quantitative Uncertainty Estimates for C Stock Changes and CH_4 Emissions occurring within *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* in 2020 (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Estimate (MMT CO_2 Eq.)		Uncertainty Range Relative to Estimate (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock Change	CO_2	(0.05)	(0.06)	(0.03)	-24.1%	24.1%
Soil C Stock Change	CO_2	(10.2)	(12.0)	(8.4)	-17.8%	17.8%
CH_4 emissions	CH_4	3.8	2.7	5.0	-29.8%	29.8%
Total Flux		**(6.4)**	**(8.7)**	**(4.0)**	**-36.6%**	**36.6%**

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

QA/QC and Verification

NOAA provided National LiDAR Dataset, tide data, and C-CAP land cover and land cover change mapping, all of which are subject to agency internal QA/QC assessment. Acceptance of final datasets into archive and dissemination are contingent upon the product compilation being compliant with mandatory QA/QC requirements (McCombs et al. 2016). QA/QC and verification of soil C stock datasets have been provided by the Smithsonian Environmental Research Center and Coastal Wetland Inventory team leads who reviewed summary tables against reviewed sources. Biomass C stocks are derived from peer-review literature and reviewed by the U.S. Geological Survey prior to publishing, by the peer-review process during publishing, and by the Coastal Wetland Inventory team leads before inclusion in this Inventory. A team of two evaluated and verified there were no computational errors within the calculation worksheets. Soil and biomass C stock change data are based upon peer-reviewed literature and CH_4 emission factors derived from the *Wetlands Supplement*.

Recalculations Discussion

No recalculations were needed for the current Inventory.

Planned Improvements

Administered by the Smithsonian Environmental Research Center, the Coastal Wetland Carbon Research Coordination Network has established a U.S. country-specific database of soil C stock and biomass estimates for coastal wetlands.[65] This dataset will be updated periodically. Refined error analysis combining land cover change and C stock estimates will be provided as new data are incorporated. Through this work, a model is in development to represent updated changes in soil C stocks for estuarine emergent wetlands.

Work is currently underway to examine the feasibility of incorporating seagrass soil and biomass C stocks into the *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands* estimates. Additionally, investigation into quantifying the distribution, area, and emissions resulting from impounded waters (i.e., coastal wetlands where tidal connection to the ocean has been restricted or eliminated completely) is underway.

Emissions from Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands

Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands is a source of emissions from soil, biomass, and DOM C stocks. An estimated 1,488 ha of Vegetated Coastal Wetlands were converted to Unvegetated Open Water Coastal Wetlands in 2020, which largely occurred within estuarine and palustrine emergent wetlands. Prior to 2006, annual conversion to unvegetated open water coastal wetlands was higher than current rates: 1,720 between 1990 and 2000 and 2,515 ha between 2001 and 2005. The Mississippi Delta represents more than 40 percent of the total coastal wetland of the United States, and over 90 percent of the area of *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands*. The drivers of coastal wetlands loss include legacy human impacts on sediment supply through rerouting river flow, direct impacts of channel cutting on hydrology, salinity and sediment delivery, and accelerated subsidence from aquafer extraction. Each of these drivers directly contributes to wetland erosion and subsidence, while also reducing the resilience of the wetland to build with sea-level rise or recover from hurricane disturbance. Over recent decades, the rate of Mississippi Delta wetland loss has slowed, though episodic mobilization of sediment occurs during hurricane events (Couvillion et al. 2011; Couvillion et al. 2016). The land cover analysis between the 2006 and 2011 C-CAP surveys coincides with two such events, hurricanes Katrina and Rita (both making landfall in the late summer of 2005), that occurred between these C-CAP survey dates. The subsequent 2016 C-CAP survey determined that erosion rates had slowed.

Shallow nearshore open water within the U.S. Land Representation is recognized as falling under the Wetlands category within this Inventory. While high resolution mapping of coastal wetlands provides data to support IPCC Approach 2 methods for tracking land cover change, the depth in the soil profile to which sediment is lost is less clear. This Inventory adopts the Tier 1 methodological guidance from the *Wetlands Supplement* for estimating emissions following the methodology for excavation (see Methodology section, below) when Vegetated Coastal Wetlands are converted to Unvegetated Open Water Coastal Wetlands, assuming a 1 m depth of disturbed soil. This 1 m depth of disturbance is consistent with estimates of wetland C loss provided in the literature and the *Wetlands Supplement* (Crooks et al. 2009; Couvillion et al. 2011; Delaune and White 2012; IPCC 2014). The same assumption on depth of soils impacted by erosion has been applied here. It is a reasonable Tier 1 assumption, based on experience, but estimates of emissions are sensitive to the depth to which the assumed disturbances have occurred (Holmquist et al. 2018). A Tier 1 assumption is also adopted in that all mobilized C is immediately returned to the atmosphere (as assumed for terrestrial land use categories), rather than redeposited in long-term C storage. The science is currently under evaluation to adopt more refined emissions factors for mobilized coastal wetland C based upon the geomorphic setting of the depositional environment.

In 2020, there were 1,488 ha of *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* across all wetland types and climates, which resulted in 1.5 MMT CO_2 Eq. (0.4 MMT C) and 0.06 MMT

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[65] See https://serc.si.edu/coastalcarbon; accessed August 2021.

CO_2 Eq. (0.02 MMT C) lost through soil and biomass, respectively, while DOM C stock loss was present it was minimal (Table 6-60, Table 6-65, and Table 6-66). Across the reporting period, the area of vegetated coastal wetlands converted to unvegetated open water coastal wetlands was greatest between the 2006 to 2011 C-CAP reporting period (11,373 ha) and has decreased since then to current levels (Table 6-60).

Table 6-65: Net CO_2 Flux from C Stock Changes in *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* (MMT CO_2 Eq.)

Year	1990	2005	2016	2017	2018	2019	2020
Biomass Flux	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Dead Organic Matter Flux	+	+	+	+	+	+	+
Soil Flux	1.7	2.5	1.5	1.5	1.5	1.5	1.5
Total C Stock Change	**1.8**	**2.6**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 6-66: Net CO_2 Flux from C Stock Changes in *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* (MMT C)

Year	1990	2005	2016	2017	2018	2019	2020
Biomass Flux	+	+	+	+	+	+	+
Dead Organic Matter Flux	+	+	+	+	+	+	+
Soil Flux	0.5	0.7	0.4	0.4	0.4	0.4	0.4
Total C Stock Change	**0.5**	**0.7**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**

+ Absolute value does not exceed 0.05 MMT C.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The following section includes a brief description of the methodology used to estimate changes in soil, biomass and DOM C stocks for *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands*.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020.

Biomass Carbon Stock Changes

Biomass C stock changes for palustrine and estuarine marshes are estimated for *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* on lands below the elevation of high tides (taken to be mean high water spring tide elevation) within the U.S. Land Representation according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2006, 2010, and 2016 NOAA C-CAP surveys. C-CAP areas are calculated at the state/territory level and summed according to climate zone to national values. Publicly-owned and privately-owned lands are represented. Trends in land cover change are extrapolated to 1990 and 2020 from these datasets. The C-CAP database provides peer reviewed country-specific mapping to support IPCC Approach 3 quantification of coastal wetland distribution, including conversion to and from open water. Biomass C stocks are not sensitive to soil organic content but are differentiated based on climate zone. Non-forested aboveground biomass C stock data are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). The aboveground biomass carbon stock for estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017[66]; Table 6-61). Aboveground biomass C stock data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment of a C stock to a

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[66] See https://github.com/Smithsonian/Coastal-Wetland-NGGI-Data-Public; accessed August 2021.

disaggregation of a community class. Root to shoot ratios from the *Wetlands Supplement* were used to account for belowground biomass, which were multiplied by the aboveground carbon stock (Table 6-62; IPCC 2014). Above- and belowground values were summed to obtain total biomass carbon stocks. Conversion to open water results in emissions of all biomass C stocks during the year of conversion; therefore, emissions are calculated by multiplying the C-CAP derived area of vegetated coastal wetlands lost that year in each climate zone by its mean biomass.

Dead Organic Matter

Dead organic matter (DOM) carbon stocks, which include litter and dead wood stocks for subtropical estuarine forested wetlands, are an emission from *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* across all years in the time series. Data on DOM carbon stocks are not currently available for either palustrine or estuarine scrub/shrub wetlands for any climate zone. Data for estuarine forested wetlands in other climate zones are not included since there is no estimated loss of these forests to unvegetated open water coastal wetlands across any year based on C-CAP data. For subtropical estuarine forested wetlands, Tier 1 estimates of mangrove DOM were used (IPCC 2014). Trends in land cover change are derived from the NOAA C-CAP dataset and extrapolated to cover the entire 1990 through 2020 time series. Conversion to open water results in emissions of all DOM C stocks during the year of conversion; therefore, emissions are calculated by multiplying the C-CAP derived area of vegetated coastal wetlands lost that year by its Tier 1 DOM C stock.

Soil Carbon Stock Changes

Soil C stock changes are estimated for *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands*. Country-specific soil C stocks were updated in 2018 based upon analysis of an assembled dataset of 1,959 cores from across the conterminous United States (Holmquist et al. 2018). This analysis demonstrated that it was not justified to stratify C stocks based upon mineral or organic soil classification, climate zone, or wetland classes; therefore, a single soil C stock of 270 t C ha^{-1} was applied to all classes. Following the Tier 1 approach for estimating CO_2 emissions with extraction provided within the *Wetlands Supplement*, soil C loss with conversion of Vegetated Coastal Wetlands to Unvegetated Open Water Coastal Wetlands is assumed to affect soil C stock to one-meter depth (Holmquist et al. 2018) with all emissions occurring in the year of wetland conversion, and multiplied by activity data of vegetated coastal wetland area converted to unvegetated open water wetlands. The methodology follows Eq. 4.6 in the *Wetlands Supplement*.

Soil Methane Emissions

A Tier 1 assumption has been applied that salinity conditions are unchanged and hence CH_4 emissions are assumed to be zero with conversion of Vegetated Coastal Wetlands to Unvegetated Open Water Coastal Wetlands.

Uncertainty

Underlying uncertainties in estimates of soil and biomass C stock changes are associated with country-specific (Tier 2) literature values of these stocks, while the uncertainties with the Tier 1 estimates are associated with subtropical estuarine forested wetland DOM stocks. Assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing data are also included in this uncertainty assessment. The IPCC default assumption of 1 m of soil erosion with anthropogenic activities was adopted to provide standardization in U.S. tidal carbon accounting (Holmquist et al. 2018). This depth of potentially erodible tidal wetland soil has not been comprehensively addressed since most soil cores analyzed were shallow (e.g., less than 50 cm) and do not necessarily reflect the depth to non-wetland soil or bedrock (Holmquist et al. 2018). Uncertainty specific to coastal wetlands include differentiation of palustrine and estuarine community classes, which determines the soil C stock applied. Because mean soil and biomass C stocks for each available community class are in a fairly narrow range, the same overall uncertainty was assigned to each (i.e., applying approach for asymmetrical errors, where the largest uncertainty for any one soil C stock referenced using published literature values for a community class; if multiple values are available for a single parameter, the highest uncertainty value should be applied to the propagation of errors; IPCC 2000). For aboveground biomass C stocks, the mean standard error was very low and largely influenced by the uncertainty associated with the estimated map area (Byrd et al.

2018). Uncertainty for root to shoot ratios, which are used for quantifying belowground biomass, are derived from the *Wetlands Supplement*. Uncertainty for subtropical estuarine forested wetland DOM stocks was derived from those listed for the Tier 1 estimates (IPCC 2014). Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (+/-10 to 15 percent; IPCC 2003). The combined uncertainty was calculated by summing the squared uncertainty for each individual source (C-CAP, soil, biomass, and DOM) and taking the square root of that total.

Details on the emission/removal trends and methodologies through time are described in more detail in the Introduction and Methodology sections.

Uncertainty estimates are presented in Table 6-67 for each subsource (i.e., soil C, biomass C, and DOM emissions). The combined uncertainty across all subsources is +/- 32.0 percent, which is driven by the uncertainty in the soil C estimates. In 2020, the total C flux was 1.5 MMT CO_2 Eq., with lower and upper estimates of 1.0 and 2.0 MMT CO_2 Eq.

Table 6-67: Approach 1 Quantitative Uncertainty Estimates for CO_2 Flux Occurring within *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* in 2020 (MMT CO_2 Eq. and Percent)

Source	2020 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock	0.06	0.05	0.08	-24.1%	24.1%
Dead Organic Matter C Stock	0.0005	0.000	0.001	-25.8%	25.8%
Soil C Stock	1.5	1.3	1.7	-15.0%	15.0%
Total Flux	**1.5**	**1.0**	**2.0**	**-32.0%**	**32.0%**

Note: Totals may not sum due to independent rounding.

QA/QC and Verification

Data provided by NOAA (i.e., National LiDAR Dataset, NOS Tide Data, and C-CAP land cover and land cover change mapping) undergo internal agency QA/QC procedures. Acceptance of final datasets into archive and dissemination are contingent upon assurance that the data product is compliant with mandatory NOAA QA/QC requirements (McCombs et al. 2016). QA/QC and Verification of the soil C stock dataset have been provided by the Smithsonian Environmental Research Center and by the Coastal Wetlands project team leads who reviewed the estimates against primary scientific literature. Biomass C stocks are derived from peer-review literature and reviewed by the U.S. Geological Survey prior to publishing, by the peer-review process during publishing, and by the Coastal Wetland Inventory team leads before inclusion in the Inventory. For subtropical estuarine forested wetlands, Tier 1 estimates of mangrove DOM were used (IPCC 2014) Land cover estimates were assessed to ensure that the total land area did not change over the time series in which the inventory was developed, and were verified by a second QA team. A team of two evaluated and verified there were no computational errors within the calculation worksheets.

Recalculations Discussion

No recalculations were needed for the current Inventory.

Planned Improvements

The depth of soil carbon affected by conversion of vegetated coastal wetlands converted to unvegetated coastal wetlands will be updated from the IPCC default assumption of 1 m of soil erosion when mapping and modeling advancements can quantitatively improve accuracy and precision. Until the time where these more detailed and spatially distributed data are available, the IPCC default assumption that the top 1 m of soil is disturbed by anthropogenic activity will be applied.

More detailed research is in development that provides a longer-term assessment and more highly refined rates of wetlands loss across the Mississippi Delta (e.g., Couvillion et al. 2016). The Mississippi Delta is the largest extent of coastal wetlands in the United States. Higher resolution imagery analysis would improve quantification of conversation to open water, which occurs not only at the edge of the marsh but also within the interior. Improved mapping could provide a more refined regional Approach 2-3 land representation to support the national-scale assessment provided by C-CAP.

An approach for calculating the fraction of remobilized coastal wetland soil C returned to the atmosphere as CO_2 is currently under review and may be included in future reports.

Research by USGS is investigating higher resolution mapping approaches to quantify conversion of coastal wetlands is also underway. Such approaches may form the basis for a full Approach 3 land representation assessment in future years. C-CAP data harmonization with the National Land Cover Dataset (NLCD) will be incorporated into a future iteration of the Inventory.

Stock Changes from Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands

Open water within the U.S. land base, as described in Section 6.1 Representation of the U.S. Land Base, is recognized as Coastal Wetlands within this Inventory. The appearance of vegetated tidal wetlands on lands previously recognized as open water reflects either the building of new vegetated marsh through sediment accumulation or the transition from other lands uses through an intermediary open water stage as flooding intolerant plants are displaced and then replaced by wetland plants. Biomass, DOM and soil C accumulation on *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* begins with vegetation establishment.

Within the United States, conversion of *Unvegetated Open Water Coastal Wetlands to Vegetated Coastal Wetlands* is predominantly due to engineered activities, which include active restoration of wetlands (e.g., wetlands restoration in San Francisco Bay), dam removals or other means to reconnect sediment supply to the nearshore (e.g., Atchafalaya Delta, Louisiana, Couvillion et al. 2011). Wetlands restoration projects have been ongoing in the United States since the 1970s. Early projects were small, a few hectares in size. By the 1990s, restoration projects, each hundreds of hectares in size, were becoming common in major estuaries. In several coastal areas e.g., San Francisco Bay, Puget Sound, Mississippi Delta and south Florida, restoration activities are in planning and implementation phases, each with the goal of recovering tens of thousands of hectares of wetlands.

In 2020, 2,406 ha of unvegetated open water coastal wetlands were converted to vegetated coastal wetlands across all wetland types and climates, which has steadily increased over the reporting period (Table 6-59). This resulted in 0.007 MMT CO_2 Eq. (0.002 MMT C) and 0.1 MMT CO_2 Eq. (0.03 MMT C) sequestered in soil and biomass, respectively (Table 6-68 and Table 6-69). The soil C stock has increased during the Inventory's reporting period, likely due to increasing vegetated coastal wetland restoration over time. While DOM C stock increases are present they are minimal in the early part of the time series and zero in the later because there are no conversions from unvegetated open water coastal wetlands to subtropical estuarine forested wetlands between 2011 and 2016 (and by proxy through 2020), and that is the only coastal wetland type where DOM data is currently available.

Throughout the reporting period, the amount of *Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* has increased over time, reflecting the increase in engineered restoration activities mentioned above.

Table 6-68: CO_2 Flux from C Stock Changes from *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* (MMT CO_2 Eq.)

Year	1990		2005		2016	2017	2018	2019	2020
Biomass C Flux	(+)		(0.1)		(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Organic Matter C Flux	(+)		(+)		0	0	0	0	0
Soil C Flux	(+)		(+)		(+)	(+)	(+)	(+)	(+)

Total C Stock Change	**(+)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Table 6-69: CO_2 Flux from C Stock Changes from *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* (MMT C)

Year	1990	2005	2016	2017	2018	2019	2020
Biomass C Flux	(0.01)	(0.02)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
Dead Organic Matter C Flux	(+)	(+)	0	0	0	0	0
Soil C Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Total C Stock Change	**(0.01)**	**(0.02)**	**(0.03)**	**(0.03)**	**(0.03)**	**(0.03)**	**(0.03)**

+ Absolute value does not exceed 0.005 MMT C.

Note: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The following section includes a brief description of the methodology used to estimate changes in soil, biomass and DOM C stocks, and CH_4 emissions for *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands*.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020.

Biomass Carbon Stock Changes

Quantification of regional coastal wetland biomass C stock changes for palustrine and estuarine marsh vegetation are presented for *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* on lands below the elevation of high tides (taken to be mean high water spring tide elevation) according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2005, 2011, and 2016 NOAA C-CAP surveys. C-CAP areas are calculated at the state/territory level and summed according to climate zone to national values. Privately-owned and publicly-owned lands are represented. Trends in land cover change are extrapolated to 1990 and 2020 from these datasets (Table 6-58). C-CAP provides peer reviewed country-level mapping of coastal wetland distribution, including conversion to and from open water. Biomass C stock is not sensitive to soil organic content but differentiated based on climate zone. Data for non-forested wetlands are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Table 6-61; Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). The aboveground biomass carbon stock for estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017[67]). Aboveground biomass C stock data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment of a C stock to a disaggregation of a community class. Root to shoot ratios from the *Wetlands Supplement* were used to account for belowground biomass, which were multiplied by the aboveground carbon stock (Table 6-62; IPCC 2014). Above- and belowground values were summed to obtain total biomass carbon stocks.

Conversion of open water to Vegetated Coastal Wetlands results in the establishment of a standing biomass C stock; therefore, stock changes that occur are calculated by multiplying the C-CAP derived area gained that year in each climate zone by its mean biomass. While the process of revegetation of unvegetated open water wetlands

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[67] See https://github.com/Smithsonian/Coastal-Wetland-NGGI-Data-Public; accessed August 2021.

can take many years to occur, it is assumed in the calculations that the total biomass is reached in the year of conversion.

Dead Organic Matter

Dead organic matter (DOM) carbon stocks, which include litter and dead wood stocks, are included for subtropical estuarine forested wetlands for *Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands* across all years. Tier 1 default or country-specific data on DOM are not currently available for either palustrine or estuarine scrub/shrub wetlands for any climate zone. Data for estuarine forested wetlands in other climate zones are not included since there is no estimated loss of these forests to unvegetated open water coastal wetlands across any year based on C-CAP data. Tier 1 estimates of subtropical estuarine forested wetland DOM were used (IPCC 2014). Trends in land cover change are derived from the NOAA C-CAP dataset and extrapolated to cover the entire 1990 through 2020 time series. Dead organic matter removals are calculated by multiplying the C-CAP derived area gained that year by its Tier 1 DOM C stock. Similar to biomass C stock gains, gains in DOM can take many years to occur, but for this analysis, the total DOM stock is assumed to accumulate during the first year of conversion.

Soil Carbon Stock Change

Soil C stock changes are estimated for *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands*. Country-specific soil C removal factors associated with soil C accretion, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature and updated this year based upon refined review of the dataset (Lynch 1989; Orson et al. 1990; Kearny & Stevenson 1991; Roman et al. 1997; Craft et al. 1998; Orson et al. 1998; Merrill 1999; Hussein et al. 2004; Church et al. 2006; Koster et al. 2007; Callaway et al. 2012 a & b; Bianchi et al. 2013; Crooks et al. 2014; Weston et al. 2014; Villa & Mitsch 2015; Marchio et al. 2016; Noe et al. 2016). Soil C stock changes are stratified based upon wetland class (Estuarine, Palustrine) and subclass (Emergent Marsh, Scrub Shrub). For soil C stock change no differentiation is made for soil type (i.e., mineral, organic). Soil C removal factors were developed from literature references that provided soil C removal factors disaggregated by climate region and vegetation type by salinity range (estuarine or palustrine) as identified using NOAA C-CAP as described above (see Table 6-63 for values).

Tier 2 level estimates of C stock changes associated with annual soil C accumulation in Vegetated Coastal Wetlands were developed using country-specific soil C removal factors multiplied by activity data on Unvegetated Coastal Wetlands converted to Vegetated Coastal Wetlands. The methodology follows Eq. 4.7, Chapter 4 of the *Wetlands Supplement*, and is applied to the area of Unvegetated Coastal Wetlands converted to Vegetated Coastal Wetlands on an annual basis.

Soil Methane Emissions

A Tier 1 assumption has been applied that salinity conditions are unchanged and hence CH_4 emissions are assumed to be zero with conversion of Vegetated Open Water Coastal Wetlands to Vegetated Coastal Wetlands.

Uncertainty

Underlying uncertainties in estimates of soil and biomass C stock changes include uncertainties associated with country-specific (Tier 2) literature values of these C stocks and assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing data. Uncertainty specific to coastal wetlands include differentiation of palustrine and estuarine community classes that determines the soil C stock applied. Because mean soil and biomass C stocks for each available community class are in a fairly narrow range, the same overall uncertainty was applied to each, respectively (i.e., applying approach for asymmetrical errors, where the largest uncertainty for any one soil C stock referenced using published literature values for a community class; uncertainty approaches provide that if multiple values are available for a single parameter, the highest uncertainty value should be applied to the propagation of errors; IPCC 2000). For aboveground biomass C stocks, the mean standard error was very low and largely influenced by error in estimated map area (Byrd et al.

2018). Uncertainty for root to shoot ratios, which are used for quantifying belowground biomass (Table 6-62), are derived from the *Wetlands Supplement*. Uncertainty for subtropical estuarine forested wetland DOM stocks were derived from those listed for the Tier 1 estimates (IPCC 2014). Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10 to 15 percent; IPCC 2003). The combined uncertainty was calculated by summing the squared uncertainty for each individual source (C-CAP, soil, biomass, and DOM) and taking the square root of that total.

Uncertainty estimates are presented in Table 6-70 for each subsource (i.e., soil C, biomass C and DOM emissions). The combined uncertainty across all subsources is +/-33.4 percent. In 2020, the total C flux was -0.1 MMT CO_2 Eq., with lower and upper estimates of -0.1 and -0.07 MMT CO_2 Eq.

Table 6-70: Approach 1 Quantitative Uncertainty Estimates for C Stock Changes Occurring within *Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands* in 2020 (MMT CO_2 Eq. and Percent)

Source	2020 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range (MMT CO_2 Eq.)		Relative to Flux Estimate (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock Flux	(0.1)	(0.12)	(0.08)	-20.0%	20.0%
Dead Organic Matter C Stock Flux	0	0	0	-25.8%	25.8%
Soil C Stock Flux	(0.007)	(0.008)	(0.005)	-17.8%	17.8%
Total Flux	**(0.1)**	**(0.14)**	**(0.07)**	**-33.4%**	**33.4%**

Notes: Parentheses indicate net sequestration. Totals may not sum due to independent rounding.

QA/QC and Verification

NOAA provided data (i.e., National LiDAR Dataset, NOS Tide Data, and C-CAP land cover and land cover change mapping), which undergo internal agency QA/QC assessment procedures. Acceptance of final datasets into the archive for dissemination are contingent upon assurance that the product is compliant with mandatory NOAA QA/QC requirements (McCombs et al. 2016). QA/QC and Verification of soil C stock dataset has been provided by the Smithsonian Environmental Research Center and Coastal Wetlands project team leads who reviewed the summary tables against primary scientific literature. Aboveground biomass C reference stocks are derived from an analysis by the Blue Carbon Monitoring project and reviewed by U.S. Geological Survey prior to publishing, the peer-review process during publishing, and the Coastal Wetland Inventory team leads before inclusion in the inventory. Root to shoot ratios and DOM data are derived from peer-reviewed literature and undergo review as per IPCC methodology. Land cover estimates were assessed to ensure that the total land area did not change over the time series in which the inventory was developed and verified by a second QA team. A team of two evaluated and verified there were no computational errors within calculation worksheets. Two biogeochemists at the USGS, also members of the NASA Carbon Monitoring System Science Team, corroborated the simplifying assumption that where salinities are unchanged CH_4 emissions are constant with conversion of *Unvegetated Open Water Coastal Wetlands to Vegetated Coastal Wetlands*.

Recalculations Discussion

No recalculations were needed for the current Inventory.

Planned Improvements

Administered by the Smithsonian Environmental Research Center, the Coastal Wetland Carbon Research Coordination Network has established a U.S. country-specific database of published data quantifying soil C stock and biomass in coastal wetlands. Reference values for soil and biomass C stocks will be updated as new data emerge. Refined error analysis combining land cover change, soil and biomass C stock estimates will be updated at those times.

The USGS is investigating higher resolution mapping approaches to quantify conversion of coastal wetlands. Such approaches may form the basis for a full Approach 3 land representation assessment in future years. C-CAP data harmonization with the National Land Cover Dataset (NLCD) will be incorporated into a future iteration of the inventory.

N_2O Emissions from Aquaculture in Coastal Wetlands

Shrimp and fish cultivation in coastal areas increases nitrogen loads resulting in direct emissions of N_2O. Nitrous oxide is generated and emitted as a byproduct of the conversion of ammonia (contained in fish urea) to nitrate through nitrification and nitrate to N_2 gas through denitrification (Hu et al. 2012). Nitrous oxide emissions can be readily estimated from data on fish production (IPCC 2014).

Aquaculture production in the United States has fluctuated slightly from year to year, with resulting N_2O emissions increasing from 0.1 in 1990 to upwards of 0.2 MMT CO_2 Eq. between 1992 and 2010, and reducing again to 0.1 MMT CO_2 Eq. between 2015 and 2020 (Table 6-71). Aquaculture production data were updated through 2018; data through 2020 are not yet available and in this analysis are held constant with 2018 emissions of 0.2 MMT CO_2 Eq. (0.5 Kt N_2O).

Table 6-71: N_2O Emissions from Aquaculture in Coastal Wetlands (MMT CO_2 Eq. and kt N_2O)

Year	1990		2005		2016	2017	2018	2019	2020
Emissions (MMT CO_2 Eq.)	0.1		0.2		0.1	0.1	0.2	0.2	0.2
Emissions (kt N_2O)	0.4		0.6		0.5	0.5	0.5	0.5	0.5

Methodology and Time-Series Consistency

The methodology to estimate N_2O emissions from Aquaculture in Coastal Wetlands follows the Tier 1 guidance in the *Wetlands Supplement* by applying country-specific fisheries production data and the IPCC Tier 1 default emission factor.

Each year NOAA Fisheries document the status of U.S. marine fisheries in the annual report of *Fisheries of the United States* (National Marine Fisheries Service 2021), from which activity data for this analysis is derived.[68] The fisheries report has been produced in various forms for more than 100 years, primarily at the national level, on U.S. recreational catch and commercial fisheries landings and values. In addition, data are reported on U.S. aquaculture production, the U.S. seafood processing industry, imports and exports of fish-related products, and domestic supply and per capita consumption of fisheries products. Within the aquaculture chapter, the mass of production for catfish, striped bass, tilapia, trout, crawfish, salmon and shrimp are reported. While some of these fisheries are produced on land and some in open water cages within coastal wetlands, all have data on the quantity of food stock produced, which is the activity data that is applied to the IPCC Tier 1 default emissions factor to estimate emissions of N_2O from aquaculture. It is not apparent from the data as to the amount of aquaculture occurring above the extent of high tides on river floodplains. While some aquaculture occurs on coastal lowland floodplains, this is likely a minor component of tidal aquaculture production because of the need for a regular source of water for pond flushing. The estimation of N_2O emissions from aquaculture is not sensitive to salinity using IPCC approaches and as such the location of aquaculture ponds within the boundaries of coastal wetlands does not influence the calculations.

Other open water shellfisheries for which no food stock is provided, and thus no additional N inputs, are not applicable for estimating N_2O emissions (e.g., clams, mussels, and oysters) and have not been included in the analysis. The IPCC Tier 1 default emissions factor of 0.00169 kg N_2O-N per kg of fish/shellfish produced is applied to the activity data to calculate total N_2O emissions.

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[68] See https://www.fisheries.noaa.gov/resource/document/fisheries-united-states-2019-report; accessed August 2021.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020.

Uncertainty

Uncertainty estimates are based upon the Tier 1 default 95 percent confidence interval provided in Table 4.15, chapter 4 of the *Wetlands Supplement* for N_2O emissions and on expert judgment of the NOAA *Fisheries of the United States* fisheries production data. Given the overestimate of fisheries production from coastal wetland areas due to the inclusion of fish production in non-coastal wetland areas, this is a reasonable initial first approximation for an uncertainty range.

Uncertainty estimates for N_2O emissions from aquaculture production are presented in Table 6-72 for N_2O emissions. The combined uncertainty is +/-116 percent. In 2020, the total flux was 0.16 MMT CO_2 Eq., with lower and upper estimates of 0.00 and 0.34 MMT CO_2 Eq.

Table 6-72: Approach 1 Quantitative Uncertainty Estimates for N_2O Emissions from Aquaculture Production in Coastal Wetlands in 2020 (MMT CO_2 Eq. and Percent)

Source	2020 Emissions Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emissions Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Combined Uncertainty for N_2O Emissions for Aquaculture Production in Coastal Wetlands	0.16	0.00	0.34	-116%	116%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

NOAA provided internal QA/QC review of reported fisheries data. The Coastal Wetlands Inventory team consulted with the Coordinating Lead Authors of the Coastal Wetlands chapter of the *Wetlands Supplement* to assess which fisheries production data to include in estimating emissions from aquaculture. It was concluded that N_2O emissions estimates should be applied to any fish production to which food supplement is supplied be they pond or coastal open water and that salinity conditions were not a determining factor in production of N_2O emissions.

Recalculations Discussion

A NOAA report was released in 2021 that contains updated fisheries data through 2018 and the 2017 production estimate was revised from 283,808 to 286,287 MT, although it did not affect the resulting emissions (National Marine Fisheries Service 2021). The updated production value was applied for 2017, and the 2018 value was applied in 2019 and 2020. This resulted in an increase of N_2O emissions by 0.02 MMT CO_2 Eq. (0.04 kt N_2O), a 7.7 percent increase, for 2018 and 2019 compared to the previous Inventory.

Flooded Land Remaining Flooded Land

Flooded lands are defined as water bodies where human activities have 1) caused changes in the amount of surface area covered by water, typically through water level regulation (e.g., constructing a dam), 2) waterbodies where human activities have changed the hydrology of existing natural waterbodies thereby altering water residence times and/or sedimentation rates, in turn causing changes to the natural emission of greenhouse gases, and 3) waterbodies that have been created by excavation, such as canals, ditches and ponds (IPCC 2019). Flooded lands include waterbodies with seasonally variable degrees of inundation, but these waterbodies would be expected to retain some inundated area throughout the year under normal conditions.

Flooded lands are broadly classified as “reservoirs” or “other constructed waterbodies” (IPCC 2019). Reservoirs are defined as flooded land greater than 8 ha and includes the seasonally flooded land on the perimeter of permanently flooded land (i.e., inundation areas). IPCC guidance (IPCC 2019) provides default emission factors for reservoirs and several types of “other constructed waterbodies” including freshwater ponds and canals/ditches.

Land that has been flooded for greater than 20 years is defined as Flooded Land Remaining Flooded Land and land flooded for 20 years or less is defined as Land Converted to Flooded Land. The distinction is based on literature reports that CH_4 and CO_2 emissions are high immediately following flooding as labile organic matter is rapidly degraded but declines to a steady background level approximately 20 years after flooding. Emissions of CH_4 are estimated for Flooded Land Remaining Flooded Land, but CO_2 emissions are not included as they are primarily the result of decomposition of organic matter entering the waterbody from the catchment or contained in inundated soils are included elsewhere in the IPCC guidelines (IPCC 2006).

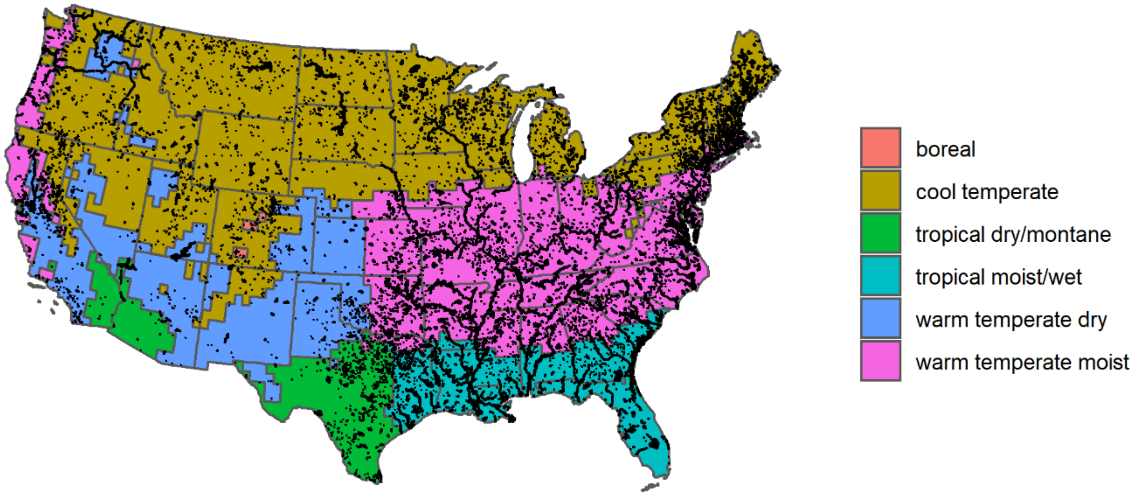
Nitrous oxide emissions from flooded lands are largely related to input of organic or inorganic nitrogen from the watershed. These inputs from runoff/leaching/deposition are largely driven by anthropogenic activities such as land-use change, wastewater disposal or fertilizer application in the watershed or application of fertilizer or feed in aquaculture. These emissions are not included here to avoid double-counting of N_2O emissions which are captured in other source categories, such as indirect N_2O emissions from managed soils (Volume 4, Chapter 11, *2006 IPCC Guidelines*) and wastewater management (Volume 5, Chapter 6, *2006 IPCC Guidelines*).

Emissions from Flooded Land Remaining Flooded Land–Reservoirs

Reservoirs are designed to store water for a wide range of purposes including hydropower, flood control, drinking water, and irrigation. The permanently wetted portion of reservoirs are typically surrounded by periodically inundated land referred to as a “drawdown zone” or “inundation area.” Greenhouse gas emissions from inundation areas are considered significant and similar per unit area to the emissions from the water surface and are therefore included in the total reservoir surface area when estimating greenhouse gas emissions from flooded land. Lakes converted into reservoirs without substantial changes in water surface area or water residence times are not considered to be managed flooded land (see Area Estimates below) (IPCC 2019).

In 2020, the conterminous United States hosted 7.2 million hectares of reservoir and associated inundation areas in the Flooded Land Remaining Flooded Land category (see Methods below for calculation details). These reservoirs are distributed across all six of the aggregated climate zones used to define flooded land emission factors (Figure 6-10) (IPCC 2019). Alaska, Hawaii, and U.S. Territories are not included in this report due to a lack of data (see Methodology).

Figure 6-10: U.S. reservoirs (black polygons) in the Flooded Land Remaining Flooded Land category in 2020. Colors represent climate zone used to derive IPCC default emission factors.



Methane is produced in reservoirs through the microbial breakdown of organic matter. Per unit area, CH_4 emission rates tend to scale positively with temperature and system productivity (i.e., abundance of algae), but negatively with system size (i.e., depth, surface area). Methane produced in reservoirs can be emitted from the surface of reservoirs and inundation areas or downstream of the flooded land as CH_4 enriched water passes through the dam and the downstream river.

Table 6-73 and Table 6-74 below summarize nationally aggregated CH_4 emissions from reservoirs and associated inundation areas. The increase in CH_4 emissions through the time series is attributable to reservoirs matriculating from the Land Converted to Flooded Land category into the Flooded Land Remaining Flooded Land category.

Table 6-73: CH_4 Emissions from Flooded Land Remaining Flooded Land—Reservoirs (MMT CO_2 Eq.)

Source	1990		2005		2016	2017	2018	2019	2020
Reservoirs	**16.0**		**17.4**		**17.5**	**17.5**	**17.5**	**17.5**	**17.5**
Surface Emission	14.7		16.0		16.1	16.1	16.1	16.1	16.1
Downstream Emission	1.3		1.4		1.4	1.4	1.4	1.4	1.4
Inundation Areas	**1.2**		**1.3**		**1.3**	**1.3**	**1.3**	**1.3**	**1.3**
Surface Emission	1.1		1.2		1.2	1.2	1.2	1.2	1.2
Downstream Emission	0.1		0.1		0.1	0.1	0.1	0.1	0.1
Total	**17.2**		**18.7**		**18.8**	**18.8**	**18.8**	**18.8**	**18.8**

Note: Alaska, Hawaii, and U.S. Territories not included.

Table 6-74: CH_4 Emissions from Flooded Land Remaining Flooded Land—Reservoirs (kt CH_4)

Source	1990		2005		2016	2017	2018	2019	2020
Reservoirs	**640**		**696**		**700**	**700**	**700**	**700**	**700**
Surface Emission	587		639		642	642	642	642	642
Downstream Emission	53		57		58	58	58	58	58
Inundation Areas	**48**		**53**		**53**	**53**	**53**	**53**	**53**
Surface Emission	44		48		49	49	49	49	49
Downstream Emission	4		4		4	4	4	4	4
Total	**688**		**749**		**753**	**753**	**753**	**753**	**753**

Note: Alaska, Hawaii, and U.S. Territories not included.

Methane emissions from reservoirs and inundation areas are greatest in Texas (Figure 6-11, Table 6-75) due to 1) the large expanse of reservoirs and inundation areas in the state (Figure 6-10) and 2) the high CH_4 emission factor for the tropical dry/montane climate zone which encompasses a majority of the flooded land area in the state (Figure 6-10, Table 6-75). Florida has the second greatest CH_4 emission from reservoirs and inundation areas in the United States, but the emissions are less than half of that from Texas. Louisiana and Georgia have the third and fourth greatest CH_4 emission, respectively, in accordance with the relatively high extent of flooded lands in the states and the high emission factor for CH_4 in the tropical moist/wet biome.

Twenty five percent of the increase in CH_4 emissions from 1990 to 2005 for this subcategory is due to the transition of Lakes Sakakawea and Oahe in North Dakota and South Dakota to Flooded Land Remaining Flooded Land between 2000 and 2003 (i.e., they were emitting CH_4 prior to 2000 and the emissions were included in the Land Converted to Flooded Land category but these emissions are now included in Land Converted to Flooded Land). Combined, these two large reservoirs have a surface area in excess of 0.25 million hectares.

Figure 6-11: Total CH_4 Emissions (Downstream + Surface) from Reservoirs and Associated Inundation Areas in Flooded Land Remaining Flooded Land (kt CH_4)

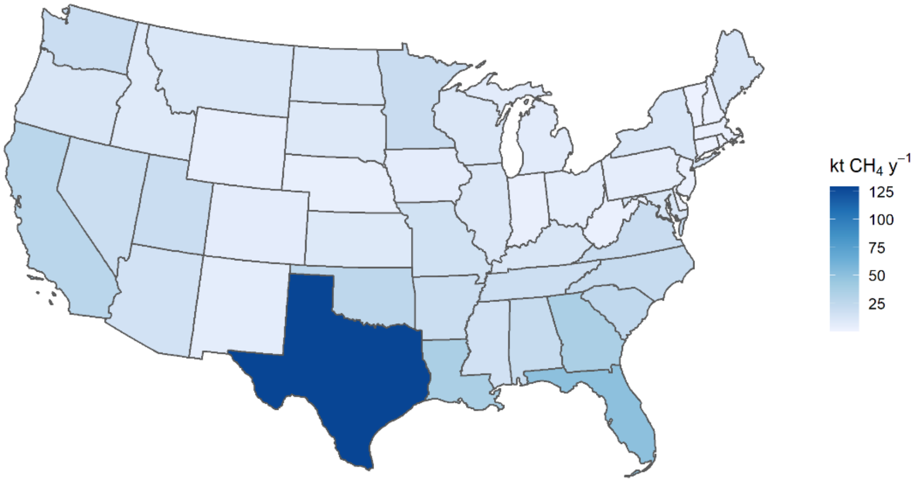


Table 6-75: Surface and Downstream CH_4 Emissions (kt CH_4) from Reservoirs and Associated Inundation Areas in Flooded Land Remaining Flooded Land in 2020

	Reservoir		Inundation area		Total	
State	Downstream	Ssurface	Downstream	Surface	Downstream	Surface
Alabama	2	19	+	+	2	19
Arizona	1	12	+	1	1	14
Arkansas	2	17	+	1	2	17
California	2	24	+	1	2	26
Colorado	+	5	+	+	+	6
Connecticut	+	2	+	+	+	2
Delaware	+	1	NO	NO	+	1
District of Columbia	+	+	NO	NO	+	+
Florida	4	47	NO	NO	4	47
Georgia	3	33	+	+	3	33
Idaho	1	8	+	+	1	8
Illinois	1	9	+	1	1	10
Indiana	+	3	+	1	+	3
Iowa	+	4	+	2	1	6
Kansas	1	6	+	3	1	9
Kentucky	1	10	+	1	1	11

Louisiana	3	33	+	1	3	33
Maine	1	11	NO	NO	1	11
Maryland	1	11	+	+	1	11
Massachusetts	+	3	+	+	+	3
Michigan	1	6	+	+	1	6
Minnesota	2	19	NO	NO	2	19
Mississippi	1	12	+	3	1	15
Missouri	1	13	+	2	1	14
Montana	1	10	+	+	1	10
Nebraska	+	3	+	+	+	3
Nevada	2	18	+	+	2	18
New Hampshire	+	3	+	+	+	3
New Jersey	+	3	NO	NO	+	3
New Mexico	+	3	+	2	+	5
New York	1	10	+	+	1	11
North Carolina	2	19	+	1	2	20
North Dakota	1	10	+	+	1	10
Ohio	+	4	+	1	+	5
Oklahoma	2	19	+	5	2	24
Oregon	1	11	NO	NO	1	11
Pennsylvania	+	4	+	+	+	5
Rhode Island	+	1	NO	NO	+	1
South Carolina	2	23	NO	NO	2	23
South Dakota	1	8	+	+	1	8
Tennessee	1	16	+	1	1	16
Texas	9	99	2	20	11	119
Utah	2	18	+	+	2	18
Vermont	+	2	+	+	+	2
Virginia	2	18	+	+	2	19
Washington	2	18	+	+	2	18
West Virginia	+	2	+	+	+	2
Wisconsin	1	10	NO	NO	1	10
Wyoming	+	4	+	+	+	4

+ Indicates values less than 0.5 kt

NO (Not Occurring)–Indicates no reservoir or inundation area in the state.

Note: Alaska and Hawaii not included.

Methodology and Time-Series Consistency

Estimates of CH_4 emission for reservoirs and associated inundation areas in Flooded Land Remaining Flooded Land follow the Tier 1 methodology in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Methane emissions from the surface of these flooded lands are calculated as the product of flooded land surface area and a climate-specific emission factor (Table 6-76). Downstream emissions are calculated as 9 percent of the surface emission (Tier 1 default). Total CH_4 emissions from reservoirs and inundation areas are calculated as the sum of surface and downstream emissions. National emissions are calculated as the sum of state emissions.

The IPCC default surface emission factors used in the Tier 1 methodology are derived from model predicted (G-res model, Prairie et al. 2017) emission rates for all reservoirs in the Global Reservoir and Dam (GRanD) database (Lehner et al. 2011). Predicted emission rates were aggregated by the 11 IPCC climate zones (IPCC 2019, table 7A.2) which were collapsed into 6 climate zones using a regression tree approach. All six aggregated climate zone are present in the conterminous United States.

Table 6-76: IPCC (2019) Default CH_4 Emission Factors for Surface Emission from Reservoirs and Associated Inundation Areas in Flooded Land Remaining Flooded Land

Climate	Surface emission factor ($MT\ CH_4\ ha^{-1}\ y^{-1}$)
Boreal	0.0136
Cool Temperate	0.054
Warm Temperate Dry	0.1509
Warm Temperate Moist	0.0803
Tropical Dry/Montane	0.2837
Tropical Moist/Wet	0.1411

Area estimates

The Reservoirs in the conterminous United States were identified from the NHDArea and NHDWaterbody layers in the National Hydrography Dataset Plus V2 (NHD),[69] the National Lakes Assessment (NLA)[70] data, the National Inventory of Dams (NID),[71] and the Navigable Waterways (NW)[72] dataset. The NHD and NLA do not include Alaska, Hawaii, or U.S. Territories, thus these areas are not included in the Inventory. Waterbodies in these data sets that were greater than 20 years old, greater than 8 ha in surface area, and not identified as canal/ditch in NHD or NW and met any of the following criteria were considered reservoirs in Flooded Land Remaining Flooded Land: 1) the water body was classified "Reservoir" in the NHDWaterbody layer, 2) the water body name in the NHDWaterbody layer included "reservoir", 3) the waterbody in the NHDWaterbody layer was located in close proximity to a dam in the NID, 4) the water body was deemed "man-made" in the NLA, 5) the waterbody was included in NW, and 6) inundation areas in the NHDArea layer that were associated with water bodies that met any of the above criteria were assumed to represent drawdown zones and were included in the inventory of reservoirs.

The IPCC (2019) allows for the exclusion of reservoirs from the Inventory if the water surface area or residence time was not substantially changed by the construction of the dam. The guidance does not quantify what constitutes a "substantial" change, but here EPA excludes the U.S. Great Lakes from the Inventory based on expert judgment that neither the surface area or water residence time was substantially altered by their associated dams. EPA assumes that all other waterbodies identified through the six criteria described above were substantially impacted by the construction of dams.

EPA assumes that all reservoirs included in the NW are subject to water-level management to maintain minimum water depths required for navigation and are therefore included in the inventory. Reservoir age was determined from the year the dam was completed as reported in the NID (available for 40,012 out of 54,670 reservoirs). When dam completion year was not available, the reservoir was assumed to be greater than 20 years old. Reservoirs were disaggregated by state (using boundaries from the 2016 U.S. Census Bureau[73]) and climate zone. Downstream and surface emissions for cross-state reservoirs were allocated to states based on the surface area that the reservoir occupied in each state. Only the U.S. portion of reservoirs that cross country borders were included in the Inventory. Surface areas for reservoirs and associated inundation areas were taken from NHD or the NW and the final inventory of reservoirs and associated inundation areas was screened to ensure no waterbodies were duplicated.

Many reservoirs are surrounded by land that is dry for a portion of the year but is periodically flooded when water inflows to the reservoir exceed outflows and the reservoir surface area expands into surrounding lands. This can occur for a variety of reasons including high rates of water runoff from the watershed (i.e., snow melt, large precipitation events), deliberate efforts to raise water levels for seasonal recreation or wildlife habitat, and

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[69] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

[70] See https://www.epa.gov/national-aquatic-resource-surveys/nla.

[71] See https://nid.sec.usace.army.mil.

[72] See https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::navigable-waterway-network-lines-1/about.

[73] See https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html.

management efforts to reduce inflows to downstream systems. These periodically flooded lands are represented as "Inundation Areas" in the NHDArea layer (Figure 6-12). Inundation areas are considered equivalent to "drawdown zones" in IPCC (2019) and CH_4 emissions from these lands are estimated using the same methodology as for reservoirs.

The surface area of reservoirs and associated inundation areas in Flooded Land Remaining Flooded Land increased by approximately 10 percent from 1990 to 2020 (Table 6-77) due to reservoirs matriculating into Flooded Land Remaining Flooded Land when they reached 20 years of age.

Figure 6-12: Example of a Reservoir and Associated Inundation Area

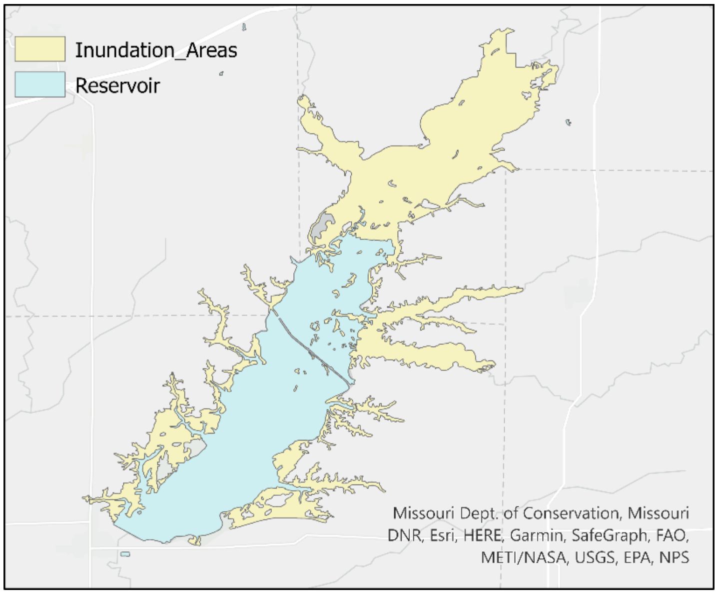

Table 6-77: National Totals of Reservoirs and Associated Inundation Area Surface Area (millions of ha) in Flooded Land Remaining Flooded Land

Surface Area (millions of ha)	1990	2005	2016	2017	2018	2019	2020
Reservoir	6.05	6.70	6.76	6.76	6.76	6.76	6.76
Inundation Area	0.39	0.43	0.44	0.44	0.44	0.44	0.44

Note: Alaska, Hawaii, and U.S. Territories not included.

Table 6-78: State breakdown of Reservoirs and Associated Inundation Area Surface Area (millions of ha) in Flooded Land Remaining Flooded Land

State	1990	2005	2016	2017	2018	2019	2020
Alabama	0.17	0.21	0.21	0.21	0.21	0.21	0.21
Arizona	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Arkansas	0.17	0.20	0.20	0.20	0.20	0.20	0.20
California	0.25	0.26	0.26	0.26	0.26	0.26	0.26
Colorado	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Connecticut	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Delaware	0.02	0.02	0.02	0.02	0.02	0.02	0.02
District of Columbia	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Florida	0.32	0.33	0.33	0.33	0.33	0.33	0.33
Georgia	0.24	0.25	0.25	0.25	0.25	0.25	0.25
Idaho	0.12	0.13	0.13	0.13	0.13	0.13	0.13
Illinois	0.11	0.12	0.13	0.13	0.13	0.13	0.13
Indiana	0.03	0.04	0.04	0.04	0.04	0.04	0.04

Iowa	0.06		0.08		0.08	0.08	0.08	0.08	0.08
Kansas	0.07		0.09		0.09	0.09	0.09	0.09	0.09
Kentucky	0.13		0.13		0.13	0.13	0.13	0.13	0.13
Louisiana	0.22		0.23		0.24	0.24	0.24	0.24	0.24
Maine	0.20		0.21		0.21	0.21	0.21	0.21	0.21
Maryland	0.14		0.14		0.14	0.14	0.14	0.14	0.14
Massachusetts	0.04		0.04		0.04	0.04	0.04	0.04	0.04
Michigan	0.11		0.12		0.12	0.12	0.12	0.12	0.12
Minnesota	0.33		0.34		0.34	0.35	0.35	0.35	0.35
Mississippi	0.14		0.15		0.15	0.15	0.15	0.15	0.15
Missouri	0.12		0.18		0.18	0.18	0.18	0.18	0.18
Montana	0.18		0.19		0.19	0.19	0.19	0.19	0.19
Nebraska	0.04		0.04		0.04	0.04	0.04	0.04	0.04
Nevada	0.10		0.10		0.10	0.10	0.10	0.10	0.10
New Hampshire	0.05		0.05		0.05	0.05	0.05	0.05	0.05
New Jersey	0.03		0.03		0.03	0.03	0.03	0.03	0.03
New Mexico	0.05		0.05		0.05	0.05	0.05	0.05	0.05
New York	0.18		0.18		0.18	0.18	0.18	0.18	0.18
North Carolina	0.23		0.25		0.25	0.25	0.25	0.25	0.25
North Dakota	0.03		0.19		0.19	0.19	0.19	0.19	0.19
Ohio	0.07		0.07		0.07	0.07	0.07	0.07	0.07
Oklahoma	0.25		0.27		0.27	0.27	0.27	0.27	0.27
Oregon	0.15		0.15		0.15	0.15	0.15	0.15	0.15
Pennsylvania	0.07		0.07		0.07	0.07	0.07	0.07	0.07
Rhode Island	0.01		0.01		0.01	0.01	0.01	0.01	0.01
South Carolina	0.19		0.20		0.20	0.20	0.20	0.20	0.20
South Dakota	0.05		0.15		0.15	0.15	0.15	0.16	0.16
Tennessee	0.20		0.20		0.20	0.20	0.20	0.20	0.20
Texas	0.57		0.62		0.62	0.62	0.62	0.62	0.62
Utah	0.13		0.14		0.17	0.17	0.17	0.17	0.17
Vermont	0.03		0.03		0.03	0.03	0.03	0.03	0.03
Virginia	0.23		0.23		0.23	0.23	0.23	0.23	0.23
Washington	0.19		0.19		0.19	0.19	0.19	0.19	0.19
West Virginia	0.03		0.03		0.03	0.03	0.03	0.03	0.03
Wisconsin	0.18		0.18		0.18	0.18	0.18	0.18	0.18
Wyoming	0.07		0.07		0.08	0.08	0.08	0.08	0.08
Total	**6.44**		**7.13**		**7.20**	**7.20**	**7.20**	**7.20**	**7.20**

Note: Alaska, Hawaii, and U.S. Territories not included.

Uncertainty

Uncertainty in estimates of CH_4 emissions from reservoirs and associated inundation areas in Flooded Land Remaining Flooded Land (Table 6-79) are developed using the IPCC Approach 2 and include uncertainty in the default emission factors and land areas. Uncertainty ranges for the emission factors are provided in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Uncertainties in the spatial data include 1) uncertainty in area estimates from the NHD and NW, and 2) uncertainty in the location of dams in the NID. Overall uncertainties in these spatial datasets are unknown, but uncertainty for remote sensing products is assumed to be ±10 to 15 percent based on IPCC guidance (IPCC 2003). An uncertainty range of +/-15 percent for the reservoir and associated inundation area estimates is assumed and is based on expert judgment.

Table 6-79: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Reservoirs and Associated Inundation Areas in Flooded Land Remaining Flooded Land

Source	Gas	2020 Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]			
		(MMT CO_2 Eq.)	(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound

Reservoir						
Surface	CH_4	16.1	15.7	16.4	-2%	2%
Downstream	CH_4	1.5	1.4	1.8	-6.9%	22.4%
Inundation Area						
Surface	CH_4	1.2	1.2	1.2	-2.3%	2.5%
Downstream	CH_4	0.1	0.1	0.1	-10.1%	17.5%
Total	**CH_4**	**18.8**	**18.5**	**19.3**	**-1.8%**	**2.6%**

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

The National Hydrography Data (NHD) is managed by the USGS in collaboration with many other federal, state, and local entities. Extensive QA/QC procedures are incorporated into the curation of the NHD. The National Inventory of Dams (NID) is maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with the Federal Emergency Management Agency (FEMA) and state regulatory offices. USACE resolves duplicative and conflicting data from 68 data sources, which helps obtain the more complete, accurate, and updated NID. The National Lakes Assessment is a survey of U.S. lakes and reservoirs conducted by the U.S. Environmental Protection Agency every 5 years. The program is subject to rigorous QA/QC as detailed in the Quality Assurance Project Plan.[74] The Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation Statistics's (BTS's) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis.

All calculations were executed independently in Excel and R. Ten percent of state and national totals were randomly selected for comparison between the two approaches to ensure there were no computational errors.

Recalculations Discussion

This is a new category in the current Inventory.

Planned Improvements

The EPA is measuring greenhouse gas emissions from 108 flooded lands (reservoirs) in the conterminous United States. The survey is expected to be complete by September 2023 and the data will be used to predict greenhouse gas emission rates for all U.S. flooded lands. The Inventory will be updated at that time using these country-specific emission factors developed through the measurement campaign.

Hawaii, Alaska, and U.S. Territories will be included in the next (i.e., 1990 through 2021) Inventory. Flooded lands area data for these states and territories will be derived from the National Hydrography Dataset Plus High Resolution (NHDPlus HighRes),[75] an enhanced version of the NHD used in this Inventory.

To verify that waterbodies contained in NW are subject to water level management, EPA will overlay the NW with other spatial datasets of water control structures including the inventory of U.S. Army Corps of Engineers locks for water navigation[76] and dams/weirs contained in the NHDPlus HighRes.

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[74] See https://www.epa.gov/national-aquatic-resource-surveys/national-lakes-assessment-2017-quality-assurance-project-plan.

[75] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography/nhdplus-high-resolution.

[76] See https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::locks/about.

Emissions from Flooded Land Remaining Flooded Land–Other Constructed Waterbodies

The IPCC (IPCC 2019) provides emission factors for several types of “other constructed waterbodies” including freshwater ponds and canals/ditches. IPCC (2019) describes ponds as waterbodies that are “…constructed by excavation and/or construction of walls to hold water in the landscape for a range of uses, including agricultural water storage, access to water for livestock, recreation, and aquaculture.” Furthermore, the IPCC “Decision tree for types of Flooded Land” (IPCC 2019, Fig. 7.2) defines a size threshold of 8 ha to distinguish reservoirs from “other constructed waterbodies.” For this Inventory, ponds are defined as managed flooded land that are 1) less than 8 ha in surface area, and 2) not categorized as canals/ditches. IPCC (2019) further distinguishes saline versus brackish ponds, with the former supporting lower CH_4 emissions than the latter. Activity data on pond salinity are not uniformly available for the conterminous United States and all ponds in the inventory are assumed to be freshwater. Ponds often receive high organic matter and nutrient loadings, may have low oxygen levels, and are often sites of substantial CH_4 emissions from anaerobic sediments.

Canals and ditches (terms are used interchangeably) are linear water features constructed to transport water (i.e. stormwater drainage, aqueduct), to irrigate or drain land, to connect two or more bodies of water, or to serve as a waterway for watercraft. The geometry and construction of canals and ditches varies widely and includes narrow earthen channels (<1m wide) and concrete lined aqueducts in excess of 50m wide. Canals and ditches can be extensive in many agricultural, forest and settlement areas, and may also be significant sources of emissions in some circumstances.

Methane emissions from freshwater ponds increased by 14 percent from 1990 to 2020 due to freshwater ponds matriculating from Land Converted to Flooded Land to Flooded Land Remaining Flooded Land (Table 6-80). Methane emissions from canals and ditches have remained constant throughout the time series. Age data are not available for most canals and ditches, and for this Inventory they were all assumed to be greater than 20 years old in 1990 and therefore included in Flooded Land Remaining Flooded Land throughout the time series. Overall, CH_4 emissions from other constructed waterbodies increased 7 percent between 1990 and 2005 but have since stabilized at 2005 levels (Table 6-80 and Table 6-81).

Table 6-80: CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land (MMT CO_2 Eq.)

Source	1990	2005	2016	2017	2018	2019	2020
Other constructed waterbodies							
Canals and ditches	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Freshwater ponds	0.5	0.6	0.6	0.6	0.6	0.6	0.6
Total	**1.0**	**1.1**	**1.1**	**1.1**	**1.1**	**1.1**	**1.1**

Note: Alaska, Hawaii, and U.S. Territories not included.

Table 6-81: CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land (kt CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
Other constructed waterbodies							
Canals and ditches	21.6	21.6	21.6	21.6	21.6	21.6	21.6
Freshwater ponds	19.4	22.0	22.1	22.2	22.2	22.2	22.2
Total	**40.9**	**43.6**	**43.7**	**43.7**	**43.7**	**43.7**	**43.8**

Note: Alaska, Hawaii, and U.S. Territories not included.

States bordering the Gulf of Mexico including Texas, Louisiana, Mississippi, and Florida are the largest source of CH_4 from other constructed waterbodies (Figure 6-13, Table 6-82). Louisiana is the source of over 50 percent of CH_4 emissions from U.S. canals and ditches and Texas is the largest source of CH_4 from freshwater ponds in the United States. These patterns of emissions are in accordance with the distribution of other constructed waterbodies in the United States.

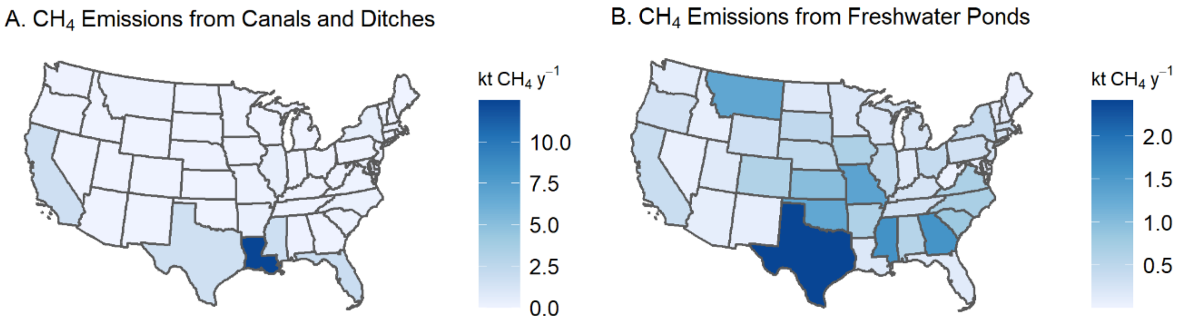
Table 6-82: CH_4 Emissions (kt CH_4) from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land in 2020

State	Canals and Ditches	Freshwater Ponds	Total
Alabama	+	0.6	0.6
Arizona	+	+	+
Arkansas	+	0.6	0.9
California	1.7	+	2.1
Colorado	+	0.6	0.6
Connecticut	+	+	+
Delaware	+	+	+
District of Columbia	+	+	+
Florida	1.9	+	2.0
Georgia	+	1.6	1.6
Idaho	+	+	+
Illinois	+	+	0.8
Indiana	+	+	+
Iowa	+	0.7	0.7
Kansas	+	1.0	1.0
Kentucky	+	+	+
Louisiana	12.5	+	12.7
Maine	+	+	+
Maryland	+	+	+
Massachusetts	+	+	+
Michigan	+	+	+
Minnesota	+	+	+
Mississippi	1.7	1.6	3.3
Missouri	+	1.4	1.5
Montana	+	1.3	1.4
Nebraska	+	+	0.5
Nevada	+	+	+
New Hampshire	+	+	+
New Jersey	+	+	+
New Mexico	+	+	+
New York	+	+	0.9
North Carolina	+	0.7	0.9
North Dakota	+	+	+
Ohio	+	+	+
Oklahoma	+	1.3	1.3
Oregon	+	+	+
Pennsylvania	+	+	+
Rhode Island	+	+	+
South Carolina	+	0.8	0.9
South Dakota	+	+	+
Tennessee	+	+	+
Texas	1.6	2.4	4.0
Utah	+	+	+
Vermont	+	+	+
Virginia	+	0.7	0.7
Washington	+	+	+
West Virginia	+	+	+
Wisconsin	+	+	+
Wyoming	+	+	+
Total	**21.6**	**22.2**	**43.8**

+ Indicates values less than 0.5 kt

Note: Alaska, Hawaii, and U.S. Territories not included.

Figure 6-13: CH_4 Emissions (kt CH_4) from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land in 2020



Methodology and Time-Series Consistency

Estimates of CH_4 emission for other constructed waterbodies in Flooded Land Remaining Flooded Land follow the Tier 1 methodology in IPCC (2019). All calculations are performed at the state level and summed to obtain national estimates. Based on IPCC guidance, methane emissions from the surface of these flooded lands are calculated as the product of flooded land surface area and an emission factor (Table 6-83). Although literature data on greenhouse gas emissions from canals and ditches is relatively sparse, they have the highest default emission factor of all flooded land types (Table 6-83). Default emission factors for freshwater ponds are on the higher end of those for reservoirs. There are insufficient data to support climate specific emission factors for ponds or canals and ditches. Downstream emissions are not inventoried for other constructed waterbodies because 1) many of these systems are not associated with dams (e.g., excavated ponds and ditches), and 2) there are insufficient data to derive downstream emission factors for other constructed waterbodies that are associated with dams (IPCC 2019).

Table 6-83: IPCC (2019) Default CH_4 Emission Factors for Surface Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land

Other Constructed Waterbody	Surface emission factor (MT CH_4 ha^{-1} y^{-1})
Freshwater ponds	0.183
Canals and ditches	0.416

Area estimates

Freshwater ponds in the conterminous United States were identified from the NHDArea and NHDWaterbody layers in the National Hydrography Dataset Plus V2 (NHD),[77] the National Lakes Assessment (NLA)[78] data, the National Inventory of Dams (NID),[79] and the Navigable Waterways (NW)[80] dataset. The NHD and NLA do not include Alaska, Hawaii, or U.S. Territories, thus these areas are not included in the Inventory. Waterbodies in these data sets that were greater than 20 years old, less than 8 ha in surface area, and not identified as canal/ditch in NHD or NW and met any of the following criteria were considered ponds in Flooded Land Remaining Flooded Land: 1) the water body was classified "Reservoir" in the NHDWaterbody layer, 2) the water body name in the NHDWaterbody layer included "reservoir", 3) the water body in the NHDWaterbody layer was located in close proximity to a dam in the

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[77] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

[78] See https://www.epa.gov/national-aquatic-resource-surveys/nla.

[79] See https://nid.sec.usace.army.mil.

[80] See https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::navigable-waterway-network-lines-1/about

NID, 4) the water body was deemed “man made” in the NLA, 5) the waterbody was included in NW, and 6) inundation areas in the NHDArea layer that were associated with water bodies that met any of the above criteria were assumed to represent drawdown zones and were included in the ponds inventory.

Surface areas for ponds and canals/ditches were taken from NHD or the NW. Waterbodies were disaggregated by state (using boundaries from the 2016 U.S. Census Bureau[81]) and the final area inventory was screened to ensure no waterbodies were duplicated. While the distribution of U.S. waterbodies <8 ha is well represented in NHD, it is difficult to determine which of these waterbodies are subject to water level management. The presence or absence of a flow control structure associated with these small waterbodies is typically not documented in NHD, thus EPA used the NID for this purpose. The NID only includes dams that pose a hazard if they were to fail, equal or exceed 25 feet in height and exceed 15 acre-feet in storage, or equal or exceed 50 acre-feet storage and exceed 6 feet in height.[82] The extent to which these criteria fail to capture flow control structures associated with freshwater ponds in the United States in unknown, but the freshwater pond area estimates presented here certainly underestimates the surface area of U.S. freshwater ponds. There is a planned improvement to review other data sources or approaches that could more fully capture all managed freshwater ponds in the United States.

All waterbodies identified as “CANAL/DITCH” in the NHDArea layer of the NHD were classified as `canals and ditches`, a subcategory of other constructed waterbodies (IPCC 2019), for this Inventory. This is an underestimate of U.S. canals and ditches, however, because the majority of canal and ditch length is represented as one dimensional flow lines in the NHDFlowline_Network layer of the NHD. While NHD flowlines can be used to estimate length of ditches and canals, they are one-dimensional features and do not provide area estimates. There is a planned improvement to review other data sources for approaches to better capture the surface area of canals/ditches in the United States.

The age of freshwater ponds was derived from NID when available, otherwise they were assumed to be greater than 20 years old throughout the time series. Age data were not available for canals and ditches and they were assumed to be greater than 20 years old in 1990 and therefore included in Flooded Land Remaining Flooded Land throughout the time series. For the year 2020, this Inventory contains 121,255 ha of freshwater ponds and 51,834 ha of canals and ditches in Flooded Land Remaining Flooded Land. The surface area of freshwater ponds increased by 15 percent from 1990 to 2020 due to flooded lands matriculating from Land Converted to Flooded Land to Flooded Land Remaining Flooded Land. All canals and ditches were assumed to be greater than 20 years old throughout the time series, thus the surface area of these flooded lands is constant throughout the time series. Overall, the surface area of other constructed waterbodies increased 10 percent between 1990 and 2020, with most of the increase occurring by 2005 (Table 6-84).

Table 6-84: National Surface Area (ha) Totals in Flooded Land Remaining Flooded Land - Other Constructed Waterbodies

	1990	2005	2016	2017	2018	2018	2020
Canals and ditches	51,834	51,834	51,834	51,834	51,834	51,834	51,834
Freshwater ponds	105,859	120,373	121,014	121,067	121,167	121,215	121,255
Total	**157,693**	**172,207**	**172,848**	**172,901**	**173,001**	**173,049**	**173,089**

Note: Alaska, Hawaii, and U.S. Territories not included.

Canals and ditches in the conterminous United States are most abundant in the Gulf Coast states and California (Figure 6-14A). Louisiana contains over half of all U.S. canal and ditch surface area, most of which was created to drain swamps and wetlands for agricultural production (Davis 1973). Freshwater ponds are more widely distributed across the United States. (Figure 6-14B). Texas has the greatest surface area of freshwater ponds, equivalent to 11 percent of all freshwater pond surface area in the United States. Texas also had the largest increase in freshwater pond surface area during the time series.

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[81] See https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html.

[82] See https://nid.sec.usace.army.mil.

Figure 6-14: Surface Area (hectares) of Other Constructed Waterbodies in Flooded Land Remaining Flooded Land in 2020

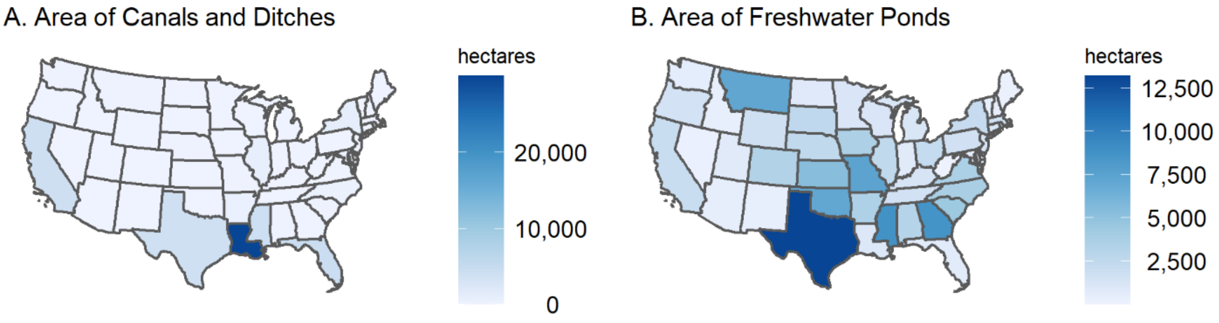

Table 6-85: State Totals of Surface Area (ha) in Flooded Land Remaining Flooded Land—Other Constructed Waterbodies

State	1990	2005	2016	2017	2018	2019	2020
Alabama	3,007	3,244	3,252	3,252	3,255	3,255	3,255
Arizona	459	488	488	488	493	493	493
Arkansas	3,796	4,051	4,051	4,051	4,051	4,051	4,051
California	6,022	6,106	6,120	6,120	6,120	6,122	6,122
Colorado	3,227	3,367	3,381	3,381	3,390	3,390	3,390
Connecticut	1,180	1,226	1,226	1,226	1,226	1,226	1,226
Delaware	481	488	488	488	488	488	488
District of Columbia	6	6	6	6	6	6	6
Florida	5,169	5,214	5,225	5,225	5,225	5,228	5,228
Georgia	8,069	8,673	8,687	8,687	8,687	8,687	8,687
Idaho	389	433	433	433	433	433	433
Illinois	2,998	3,318	3,344	3,345	3,350	3,350	3,350
Indiana	756	836	843	843	843	843	843
Iowa	2,529	3,574	3,596	3,596	3,596	3,600	3,607
Kansas	3,724	5,357	5,381	5,388	5,404	5,411	5,411
Kentucky	1,143	1,327	1,327	1,330	1,330	1,330	1,330
Louisiana	30,900	30,991	30,995	30,995	30,995	30,995	30,995
Maine	224	243	247	247	247	247	247
Maryland	574	609	615	615	615	615	615
Massachusetts	1,813	1,871	1,897	1,902	1,908	1,912	1,919
Michigan	1,082	1,172	1,183	1,185	1,185	1,185	1,185
Minnesota	1,042	1,133	1,137	1,137	1,137	1,137	1,151
Mississippi	12,445	12,852	12,874	12,888	12,888	12,893	12,901
Missouri	5,312	7,684	7,700	7,700	7,700	7,700	7,700
Montana	7,113	7,411	7,411	7,411	7,411	7,416	7,416
Nebraska	1,844	2,590	2,605	2,605	2,630	2,630	2,630
Nevada	242	242	260	262	262	262	262
New Hampshire	451	497	517	517	517	517	517
New Jersey	1,381	1,396	1,396	1,396	1,399	1,399	1,399
New Mexico	444	453	453	453	453	453	453
New York	3,071	3,232	3,294	3,294	3,294	3,294	3,294
North Carolina	3,977	4,178	4,216	4,216	4,216	4,216	4,218
North Dakota	784	837	866	866	873	873	873
Ohio	2,008	2,201	2,229	2,238	2,238	2,238	2,238
Oklahoma	6,138	7,139	7,162	7,162	7,165	7,172	7,172
Oregon	1,448	1,520	1,533	1,533	1,536	1,536	1,536
Pennsylvania	1,483	1,610	1,630	1,630	1,631	1,631	1,631

Rhode Island	257	258	258	258	258	258	258
South Carolina	4,172	4,617	4,638	4,640	4,640	4,640	4,642
South Dakota	2,403	2,500	2,537	2,539	2,539	2,548	2,548
Tennessee	1,372	1,562	1,569	1,569	1,576	1,579	1,579
Texas	14,634	17,052	17,082	17,086	17,090	17,091	17,091
Utah	784	829	829	829	829	829	829
Vermont	311	368	372	372	372	372	372
Virginia	3,549	3,721	3,721	3,721	3,721	3,721	3,721
Washington	653	727	759	759	761	761	761
West Virginia	124	124	124	124	124	124	124
Wisconsin	1,009	1,158	1,170	1,170	1,170	1,170	1,170
Wyoming	1,693	1,721	1,721	1,721	1,721	1,721	1,721
Total	**157,693**	**172,207**	**172,848**	**172,901**	**173,001**	**173,049**	**173,089**

Note: Alaska, Hawaii, and U.S. Territories not included.

Uncertainty

Uncertainty in estimates of CH_4 emissions from other constructed waterbodies (ponds, canals/ditches) in Flooded Land Remaining Flooded Land (Table 6-86) are estimated using IPCC Approach 2 and include uncertainty in the default emission factors and the flooded land area inventory. Uncertainty in emission factors is provided in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Uncertainties in the spatial data include 1) uncertainty in area estimates from the NHD and NW, and 2) uncertainty in the location of dams in the NID. Overall uncertainties in these spatial datasets are unknown, but uncertainty for remote sensing products is assumed to be ±10 to 15 percent based on IPCC guidance (IPCC 2003). An uncertainty range of +/-15 percent for the flooded land area estimates is assumed and is based on expert judgment. These uncertainties do not include the underestimate of pond and canal/ditch surface areas discussed above, see Planned Improvements for a discussion on steps being taken to improve the area estimates.

Table 6-86: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land

Source	Gas	2020 Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]			
		(MMT CO_2 Eq.)	(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Canals and ditches	CH_4	0.54	0.45	0.62	-15.9%	15.8%
Freshwater pond	CH_4	0.55	0.55	0.56	-0.3%	0.3%
Total	**CH_4**	**1.09**	**1.01**	**1.18**	**-8%**	**7.9%**

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

The National Hydrography Data (NHD) is managed by the USGS in collaboration with many other federal, state, and local entities. Extensive QA/QC procedures are incorporated into the curation of the NHD. The National Inventory of Dams (NID) is maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with the Federal Emergency Management Agency (FEMA) and state regulatory offices. USACE resolves duplicative and conflicting data from 68 data sources, which helps obtain the more complete, accurate, and updated NID. The National Lakes Assessment is a survey of U.S. lakes and reservoirs conducted by the U.S. Environmental Protection Agency every 5 years. The program is subject to rigorous QA/QC as detailed in the Quality Assurance Project Plan.[83] The Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation

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[83] See https://www.epa.gov/national-aquatic-resource-surveys/national-lakes-assessment-2017-quality-assurance-project-plan.

Statistics's (BTS's) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis.

All calculations were executed independently in Excel and R. Ten percent of state and national totals were randomly selected for comparison between the two approaches to ensure there were no computational errors.

Recalculations Discussion

This is a new category in the current Inventory.

Planned Improvements

EPA is unaware of ongoing work that could be used to develop country-specific emission factors for Other Constructed Waterbodies but is working to improve land use representation of canals and ditches. Canals and ditches are represented as both flow lines and area polygons in NHD. The area polygons are used in this Inventory, but flow lines only contain the length of the feature and therefore cannot be directly used to calculate surface area. EPA is researching methods for associating flow lines with a width, which would enable the area calculations needed for the Inventory.

Canal and ditch surface area included here may overlap with ditches and canals included in CH_4 emission estimates for ditches draining inland organic soils (IPCC 2013, section 2.2.2.1). EPA plans to reconcile ditch/canal surface areas between the two managed land types (flooded land vs drained inland organic soils) in the next (i.e., 1990 through 2021) Inventory.

U.S. waterbodies less than 8 ha are well represented in NHD, but the presence or absence of water level control structures associated with these small waterbodies is not well documented in national data sources. To improve the representation of managed ponds in future Inventories, EPA will attempt to locate state or county records on small dam construction permits and/or inspection records to supplement records in the NID. EPA will also use surrounding land use as a proxy for management. For example, a pond surrounded by cultivated land is likely subject to water level management and should be included in the inventory. Even if the pond were not subject to water level management, greenhouse gas emissions from the system are likely enhanced by elevated nutrient and sediment inputs from the surrounding managed lands, thus the emissions should be considered anthropogenic and included in the inventory.

Hawaii, Alaska, and U.S. Territories will be included in the (i.e., 1990 through 2021) Inventory. Flooded lands area data for these states and territories will be derived from the National Hydrography Dataset Plus High Resolution (NHDPlus HighRes),[84] an enhanced version of the NHD used in this Inventory.

6.9 Land Converted to Wetlands (CRF Source Category 4D2)

Emissions and Removals from Land Converted to Vegetated Coastal Wetlands

Land Converted to Vegetated Coastal Wetlands occurs as a result of inundation of unprotected low-lying coastal areas with gradual sea-level rise, flooding of previously drained land behind hydrological barriers, and through active restoration and creation of coastal wetlands through removal of hydrological barriers. All other land

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[84] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography/nhdplus-high-resolution.

categories (i.e., Forest Land, Cropland, Grassland, Settlements and Other Lands) are identified as having some area converting to Vegetated Coastal Wetlands. Between 1990 and 2020 the rate of annual transition for *Land Converted to Vegetated Coastal Wetlands* ranged from 0 to 2,650 ha per year, depending on the type of land converted.[85] Conversion rates from Forest Land were relatively consistent between 1990 and 2010 (ranging between 2,409 and 2,650 ha) and decreased to 625 ha starting in 2011; the majority of these conversions resulted in increases in the area of palustrine wetlands, which also initiates CH_4 emissions when lands are inundated with fresh water.[86] Little to no conversion of Cropland, Grassland, Settlement, or Other Lands to vegetated coastal wetlands occurred during the reporting period, with converted areas ranging from 0 to 25 ha per year.

At the present stage of Inventory development, Coastal Wetlands are not explicitly shown in the Land Representation analysis while work continues harmonizing data from NOAA's Coastal Change Analysis Program (C-CAP) with NRI, FIA and NLDC data used to compile the Land Representation (NOAA OCM 2020).

In this Inventory, biomass, dead organic material (DOM) and soil C stock changes as well as CH_4 emissions are quantified as a result of the land use conversion to coastal wetlands and the land is assumed to be held in this category for up to 20 years after which it is classified as *Coastal Wetlands Remaining Coastal Wetlands*. Estimates of emissions and removals are based on emission factor data that have been applied to assess changes in each respective flux for *Land Converted to Vegetated Coastal Wetlands*. Following conversion to Vegetated Coastal Wetlands, it is assumed there is a loss of biomass C stocks from the converted Forest Land, Cropland and Grassland and as well as the loss of DOM C stocks from Forest Land. Converted lands are held in this land category for up to 20 years and the assumption is that the C stock losses from biomass and DOM all occur in the year of conversion. There are no soil C losses from land use conversion. Carbon stock increases in coastal wetlands as a result of gains in plant biomass and DOM on these converted lands are also included during the year of transition even though the entire C stock accrual takes many years to occur. Soil C accumulation and CH_4 emissions are quantified using an annual rate in this Inventory and thus are occurring over the period under which lands are held in this category; therefore, the soil C removals and CH_4 emissions presented for a given year include the cumulative removals/emissions for the new area that was converted during that year and the area held in this category for the prior 19 years. At salinities less than half that of seawater, the transition from upland dry soils to wetland soils results in CH_4 emissions. The United States calculates emissions and removals based upon stock change.

Conversion to coastal wetlands resulted in a biomass C stock loss of 0.1 MMT CO_2 Eq. (0.03 MMT C) in 2020 (Table 6-87 and Table 6-88). Loss of forest biomass through conversion of Forest Lands to Vegetated Coastal Wetlands is the primary driver behind biomass C stock change being a source rather than a sink across the time series. Conversion of Cropland, Grassland, Settlement and Other Lands result in a net increase in biomass stocks. Conversion of lands to vegetated coastal wetlands resulted in a DOM loss of 0.03 MMT CO_2 Eq. (0.008 MMT C) in 2020 (Table 6-87 and Table 6-88), which is driven by the loss of DOM when Forest Land is converted to Vegetated Coastal Wetlands. This is likely an overestimate of loss because wetlands inherently preserve dead organic material. Conversion of Cropland, Grassland, Settlement and Other Land results in a net increase in DOM. Once Tier 1 or 2 DOM values are collated and accounted for in estuarine and palustrine scrub shrub coastal wetlands and estuarine forested wetlands (in climates other than subtropical), the carbon emissions will decrease. Across all time periods, soil C accumulation resulting from *Lands Converted to Vegetated Coastal Wetlands* is a carbon sink and has ranged between -0.2 and -0.3 MMT CO_2 Eq. (-0.04 and -0.07 MMT C; Table 6-87 and Table 6-88). Conversion of lands to coastal wetlands resulted in CH_4 emissions of 0.2 MMT CO_2 Eq. (6.7 kt CH_4) in 2020 (Table 6-89). Methane emissions due to the conversion of *Lands to Vegetated Coastal Wetlands* are largely the result of Forest Land converting to palustrine emergent and scrub shrub coastal wetlands in warm temperate climates. Emissions were the highest between 1990 and 2001 (0.2 MMT CO_2 Eq., 10.0 kt CH_4) and have continually decreased to current levels.

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[85] Data from C-CAP; see https://coast.noaa.gov/digitalcoast/tools/. Accessed August 2021.

[86] Currently, the C-CAP dataset categorizes coastal wetlands as either palustrine (fresh water) or estuarine (presence of saline water). This classification does not differentiate between estuarine wetlands with salinity ≤ 18 ppt (when methanogenesis begins to occur) and those that are >18 ppt (where negligible to no CH_4 is produced); therefore, it is not possible at this time to account for CH_4 emissions from estuarine wetlands in the Inventory.

Table 6-87: Net CO_2 Flux from C Stock Changes in *Land Converted to Vegetated Coastal Wetlands* (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2016	2017	2018	2019	2020
Cropland Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Forest Land Converted to Vegetated Coastal Wetlands	**0.49**	**0.50**	**(0.02)**	**(0.01)**	**+**	**0.01**	**0.02**
Biomass C Stock	0.62	0.62	0.13	0.13	0.13	0.13	0.13
Dead Organic Matter C Flux	0.11	0.12	0.03	0.03	0.03	0.03	0.03
Soil C Stock	(0.23)	(0.24)	(0.18)	(0.17)	(0.16)	(0.15)	(0.14)
Grassland Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Other Land Converted to Vegetated Coastal Wetlands	**(0.03)**	**(0.03)**	**(0.02)**	**(0.02)**	**(0.02)**	**(0.02)**	**(0.02)**
Biomass C Stock	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Soil C Stock	(0.01)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Settlements Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Total Biomass Flux	**0.60**	**0.60**	**0.12**	**0.12**	**0.12**	**0.12**	**0.12**
Total Dead Organic Matter Flux	**0.11**	**0.12**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**
Total Soil C Flux	**(0.25)**	**(0.25)**	**(0.19)**	**(0.18)**	**(0.18)**	**(0.17)**	**(0.16)**
Total Flux	**0.46**	**0.47**	**(0.04)**	**(0.03)**	**(0.01)**	**(0.02)**	**(+)**

+ Absolute value does not exceed 0.005 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration

Table 6-88: Net CO_2 Flux from C Stock Changes in *Land Converted to Vegetated Coastal Wetlands* (MMT C)

Land Use/Carbon Pool	1990	2005	2016	2017	2018	2019	2020
Cropland Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Forest Land Converted to Vegetated Coastal Wetlands	**0.13**	**0.14**	**(0.00)**	**(+)**	**+**	**+**	**0.01**
Biomass C Stock	0.17	0.17	0.04	0.04	0.04	0.04	0.04
Dead Organic Matter C Flux	0.03	0.03	0.01	0.01	0.01	0.01	0.01
Soil C Stock	(0.06)	(0.06)	(0.05)	(0.05)	(0.04)	(0.04)	(0.04)
Grassland Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Other Land Converted to Vegetated Coastal Wetlands	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**	**(0.01)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Settlements Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Total Biomass Flux	**0.16**	**0.16**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**

Total Dead Organic Matter Flux	**0.03**	**0.03**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
Total Soil C Flux	**(0.07)**	**(0.07)**	**(0.05)**	**(0.05)**	**(0.05)**	**(0.05)**	**(0.04)**
Total Flux	**0.13**	**0.13**	**(0.01)**	**(0.01)**	**(0.01)**	**(+)**	**(+)**

\+ Absolute value does not exceed 0.005 MMT C.

Note: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-89: CH_4 Emissions from *Land Converted to Vegetated Coastal Wetlands* (MMT CO_2 Eq. and kt CH_4)

Land Use/Carbon Pool	1990	2005	2016	2017	2018	2019	2020
Cropland Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	+	+	+	+	+
CH_4 Emissions (kt CH_4)	+	0.01	0.04	0.04	0.04	0.04	0.05
Forest Land Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	0.25	0.24	0.19	0.18	0.17	0.16	0.15
CH_4 Emissions (kt CH_4)	9.88	9.74	7.60	7.22	6.85	6.48	6.10
Grassland Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	+	+	+	+	+
CH_4 Emissions (kt CH_4)	0.01	0.01	0.05	0.06	0.07	0.07	0.08
Other Land Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	0.01	0.01	0.01	0.01	0.01
CH_4 Emissions (kt CH_4)	0.08	0.14	0.37	0.40	0.43	0.47	0.50
Settlements Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	+	+	+	+	+
CH_4 Emissions (kt CH_4)	0.01	+	+	+	+	+	+
Total CH_4 Emissions (MMT CO_2 Eq.)	**0.25**	**0.25**	**0.20**	**0.19**	**0.18**	**0.18**	**0.17**
Total CH_4 Emissions (kt CH_4)	**9.98**	**9.91**	**8.05**	**7.72**	**7.39**	**7.06**	**6.73**

\+ Absolute value does not exceed 0.005 MMT CO_2 Eq. or 0.005 kt CH_4.

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

The following section provides a description of the methodology used to estimate changes in biomass, dead organic matter and soil C stocks and CH_4 emissions for *Land Converted to Vegetated Coastal Wetlands*.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020.

Biomass Carbon Stock Changes

Biomass C stocks for *Land Converted to Vegetated Coastal Wetlands* are estimated for palustrine and estuarine marshes for land below the elevation of high tides (taken to be mean high water spring tide elevation) and as far seawards as the extent of intertidal vascular plants within the U.S. Land Representation according to the national LiDAR dataset, the national network of tide gauges and land use histories recorded in the 1996, 2001, 2005, 2011, and 2016 NOAA C-CAP surveys (NOAA OCM 2020). Both federal and non-federal lands are represented. Delineating Vegetated Coastal Wetlands from ephemerally flooded upland Grasslands represents a particular challenge in remote sensing. Moreover, at the boundary between wetlands and uplands, which may be gradual on low lying coastlines, the presence of wetlands may be ephemeral depending upon weather and climate cycles and as such impacts on the emissions and removals will vary over these time frames. Trends in land cover change are extrapolated to 1990 and 2020 from these datasets using the C-CAP change data closest in date to a given year. Based upon NOAA C-CAP, wetlands are subdivided into freshwater (Palustrine) and saline (Estuarine) classes and further subdivided into emergent marsh, scrub shrub and forest classes. Biomass is not sensitive to soil organic content. Aboveground biomass carbon stocks for non-forested coastal wetlands are derived from a national assessment combining field plot data and aboveground biomass mapping by remote sensing (Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). Aboveground biomass C removal data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment to a disaggregation of a community class. The aboveground biomass carbon stock for estuarine forested wetlands (dwarf mangroves that are not classified as forests due to their stature) is derived from a meta-analysis by Lu and Megonigal (2017[87]). Root to shoot ratios from the *Wetlands Supplement* were used to account for belowground biomass, which were multiplied by the aboveground carbon stock (IPCC 2014), and summed with aboveground biomass to obtain total biomass carbon stocks. Aboveground biomass C stocks for Forest Land, Cropland, and Grassland that are lost with the conversion to *Vegetated Coastal Wetlands* were derived from Tier 1 default values (IPCC 2006; IPCC 2019). Biomass carbon stock changes are calculated by subtracting the biomass C stock values of each land use category (i.e., Forest Land, Cropland, and Grassland) from those of *Vegetated Coastal Wetlands* in each climate zone and multiplying that value by the corresponding C-CAP derived area gained that year in each climate zone. The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. The total coastal wetland biomass C stock change is accounted for during the year of conversion; therefore, no interannual changes are calculated during the remaining years it is in the category.

Dead Organic Matter

Dead organic matter (DOM) carbon stocks, which include litter and dead wood stocks, are accounted for in subtropical estuarine forested wetlands for *Lands Converted to Vegetated Coastal Wetlands* across all years. Tier 1 estimates of mangrove DOM C stocks were used for subtropical estuarine forested wetlands (IPCC 2014). Neither Tier 1 or 2 data on DOM are currently available for either palustrine or estuarine scrub/shrub wetlands for any climate zone or estuarine forested wetlands in climates other than subtropical climates. Tier 1 DOM C stocks for Forest Land converted to Vegetated Coastal Wetlands were derived from IPCC (2019) to account for the loss of DOM that occurs with conversion. Changes in DOM are assumed to negligible for other land use conversions (i.e., other than Forest Land) to coastal wetlands based on the Tier 1 method in IPCC (2006). Trends in land cover change are derived from the NOAA C-CAP dataset and extrapolated to cover the entire 1990 through 2020 time series. Dead organic matter removals are calculated by multiplying the C-CAP derived area gained that year by the difference between Tier 1 DOM C stocks for Vegetated Coastal Wetlands and Forest Land. The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion. The coastal wetland DOM stock is assumed to be in steady state once established in the year of conversion; therefore, no interannual changes are calculated.

Soil Carbon Stock Changes

Soil C removals are estimated for *Land Converted to Vegetated Coastal Wetlands* across all years. Soil C stock changes, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature (Lynch 1989; Orson et al. 1990; Kearny & Stevenson 1991; Roman et al. 1997; Craft et al. 1998; Orson et al. 1998; Merrill 1999; Hussein et al. 2004; Church et al. 2006; Koster et al. 2007; Callaway et al. 2012 a & b; Bianchi et al. 2013; Crooks et al. 2014; Weston et al. 2014; Villa & Mitsch 2015; Marchio et al. 2016; Noe et al. 2016). To estimate soil C stock changes, no differentiation is made for soil type (i.e., mineral, organic). Soil C removal data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment to a disaggregation of a community class.

As per IPCC (2014) guidance, *Land Converted to Vegetated Coastal Wetlands* is assumed to remain in this category for up to 20 years before transitioning to *Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands*. Tier 2 level estimates of soil C stock changes associated with annual soil C accumulation from *Land Converted to Vegetated Coastal Wetlands* were developed using country-specific soil C removal factors multiplied by activity data of land area for *Land Converted to Vegetated Coastal Wetlands* for a given year in addition to the previous 19-year cumulative area. Guidance from the *Wetlands Supplement* allows for the rate of soil C accumulation to be

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[87] See https://github.com/Smithsonian/Coastal-Wetland-NGGI-Data-Public; accessed October 2020.

instantaneously equivalent to that in natural settings and that soil C accumulation is initiated when natural vegetation becomes established; this is assumed to occur in the first year of conversion. No loss of soil carbon as a result of land conversion to coastal wetlands is assumed to occur. Since the C-CAP coastal wetland area dataset begins in 1996, the area converted prior to 1996 is assumed to be the same as in 1996. Similarly, the coastal wetland area data for 2017 through 2020 is assumed to be the same as in 2016. The methodology follows Eq. 4.7, Chapter 4 of the *IPCC Wetlands Supplement* (IPCC 2014), and is applied to the area of *Land Converted to Vegetated Coastal Wetlands* on an annual basis.

Soil Methane Emissions

Tier 1 estimates of CH_4 emissions for *Land Converted to Vegetated Coastal Wetlands* are derived from the same wetland map used in the analysis of wetland soil C fluxes for palustrine wetlands, and are produced from C-CAP, LiDAR and tidal data, in combination with default CH_4 emission factors provided in Table 4.14 of the *IPCC Wetlands Supplement.* The methodology follows Eq. 4.9, Chapter 4 of the *IPCC Wetlands Supplement*. Because *Land Converted to Vegetated Coastal Wetlands* is held in this category for up to 20 years before transitioning to *Vegetated Coastal Wetlands Remaining to Vegetated Coastal Wetlands,* CH_4 emissions in a given year represent the cumulative area held in this category for that year and the prior 19 years.

Uncertainty

Underlying uncertainties in estimates of soil C removal factors, biomass change, DOM, and CH_4 emissions include error in uncertainties associated with Tier 2 literature values of soil C removal estimates, biomass stocks, DOM, and IPCC default CH_4 emission factors, uncertainties linked to interpretation of remote sensing data, as well as assumptions that underlie the methodological approaches applied.

Uncertainty specific to coastal wetlands include differentiation of palustrine and estuarine community classes, which determines what flux is applied. Because mean soil and biomass C removal for each available community class are in a fairly narrow range, the same overall uncertainty was assigned to each, respectively (i.e., applying approach for asymmetrical errors, the largest uncertainty for any soil C stock value should be applied in the calculation of error propagation; IPCC 2000). Uncertainties for CH_4 flux are the Tier 1 default values reported in the *Wetlands Supplement*. Overall uncertainty of the NOAA C-CAP remote sensing product is 15 percent. This is in the range of remote sensing methods (±10 to 15 percent; IPCC 2003). However, there is significant uncertainty in salinity ranges for tidal and non-tidal estuarine wetlands and activity data used to estimate the CH_4 flux (e.g., delineation of an 18 ppt boundary), which will need significant improvement to reduce uncertainties. The combined uncertainty was calculated by summing the squared uncertainty for each individual source (C-CAP, soil, biomass, and DOM) and taking the square root of that total.

Uncertainty estimates are presented in Table 6-90 for each carbon pool and the CH_4 emissions. The combined uncertainty is +/-42.2 percent. In 2020, the total flux was 0.16 MMT CO_2 Eq., with lower and upper estimates of 0.09 and 0.23 MMT CO_2 Eq.

Table 6-90: Approach 1 Quantitative Uncertainty Estimates for C Stock Changes occurring within *Land Converted to Vegetated Coastal Wetlands* in 2020 (MMT CO_2 Eq. and Percent)

Source	2020 Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Estimate[a] (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Biomass C Stock Flux	0.12	0.1	0.15	-20.0%	20.0%
Dead Organic Matter Flux	0.03	0.02	0.03	-25.8%	25.8%
Soil C Stock Flux	(0.16)	(0.2)	(0.1)	-17.8%	17.8%
Methane Emissions	0.17	0.12	0.22	-29.9%	29.9%
Total Uncertainty	**0.16**	**0.09**	**0.23**	**-42.2%**	**42.2%**

[a] Range of flux estimates based on error propagation at 95 percent confidence interval.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

QA/QC and Verification

NOAA provided National LiDAR Dataset, tide data, and C-CAP land cover and land cover change mapping, all of which are subject to agency internal mandatory QA/QC assessment (McCombs et al. 2016). QA/QC and verification of soil C stock dataset has been provided by the Smithsonian Environmental Research Center and Coastal Wetland Inventory team leads. Biomass C stocks are derived from peer-review literature, reviewed by U.S. Geological Survey prior to publishing, by the peer-review process during publishing, and by the Coastal Wetland Inventory team leads prior to inclusion in the inventory and from IPCC reports. As a QC step, a check was undertaken confirming that Coastal Wetlands recognized by C-CAP represent a subset of Wetlands recognized by the NRI for marine coastal states. Land cover estimates were assessed to ensure that the total land area did not change over the time series in which the inventory was developed, and verified by a second QA team. A team of two evaluated and verified there were no computational errors within the calculation worksheets. Soil C stock, emissions/removals data are based upon peer-reviewed literature and CH_4 emission factors are derived from the *Wetlands Supplement*.

Recalculations Discussion

No recalculations were needed for the current Inventory.

Planned Improvements

Administered by the Smithsonian Environmental Research Center, the Coastal Wetland Carbon Research Coordination Network has established a U.S. country-specific database of soil C stocks and biomass for coastal wetlands.[88] This dataset will be updated periodically. Refined error analysis combining land cover change and C stock estimates will be provided as new data are incorporated. Through this work, a model is in development to represent changes in soil C stocks and will be incorporated into the next (i.e., 2023) Inventory submission.

Currently, the only coastal wetland conversion that is reported in the Inventory is *Lands Converted to Vegetated Coastal Wetlands*. The next (2023) submission will include C stock change data for *Lands Converted to Unvegetated Open Water Coastal Wetlands*.

Land Converted to Flooded Land

Flooded lands are defined as water bodies where human activities have 1) caused changes in the amount of surface area covered by water, typically through water level regulation (e.g., constructing a dam), 2) waterbodies where human activities have changed the hydrology of existing natural waterbodies thereby altering water residence times and/or sedimentation rates, in turn causing changes to the natural production of greenhouse gases, and 3) waterbodies that have been created by excavation, such as canals, ditches and ponds (IPCC 2019). Flooded lands include waterbodies with seasonally variable degrees of inundation but would be expected to retain some inundated area throughout the year under normal conditions.

Flooded lands are broadly classified as “reservoirs” or “other constructed waterbodies” (IPCC 2019). Reservoirs are defined as flooded land greater than 8 ha and includes the seasonally flooded land on the perimeter of permanently flooded land (i.e., inundation areas). IPCC guidance (IPCC 2019) provides default emission factors for reservoirs and several types of “other constructed waterbodies” including freshwater ponds and canals/ditches.

Land that has been flooded for 20 years or greater is defined as Flooded Land Remaining Flooded Land and land flooded for less than 20 years is defined as Land Converted to Flooded Land. The distinction is based on literature reports that CO_2 and CH_4 emissions are high immediately following flooding as labile organic matter is rapidly degraded but decline to a steady background level approximately 20 years after flooding. Both CO_2 and CH_4 emissions are inventoried for Land Converted to Flooded Land.

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[88] See https://serc.si.edu/coastalcarbon; accessed August 2021.

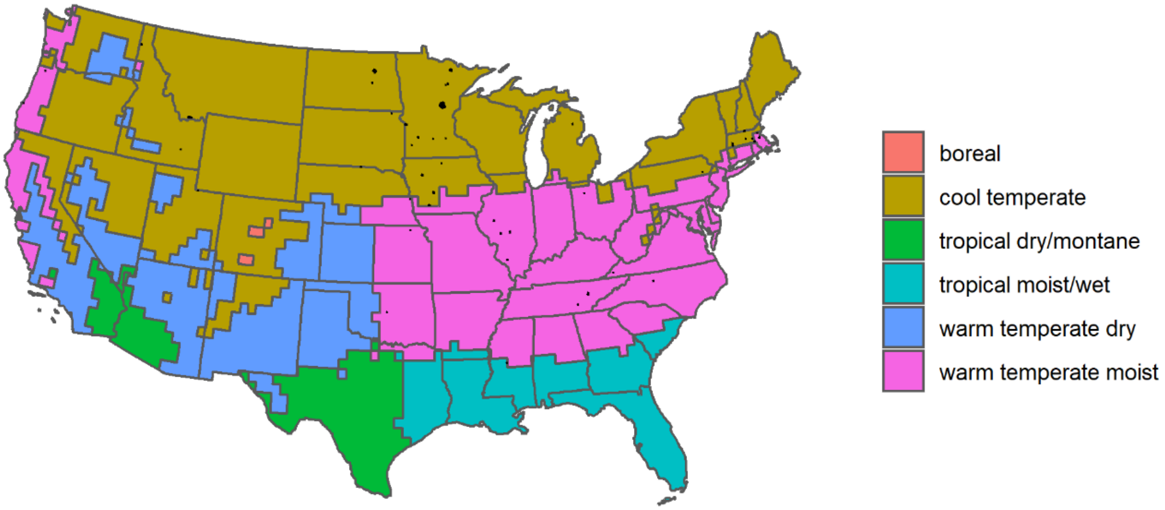
Nitrous oxide emissions from flooded lands are largely related to input of organic or inorganic nitrogen from the watershed. These inputs from runoff/leaching/deposition are largely driven by anthropogenic activities such as land-use change, wastewater disposal or fertilizer application in the watershed or application of fertilizer or feed in aquaculture. These emissions are not inventoried here to avoid double-counting N_2O emissions which are captured in other source categories, such as indirect N_2O emissions from managed soils (Volume 4, Chapter 11, *2006 IPCC Guidelines*) and wastewater management (Volume 5, Chapter 6, *2006 IPCC Guidelines*).

Emissions from Land Converted to Flooded Land–Reservoirs

Reservoirs are designed to store water for a wide range of purposes including hydropower, flood control, drinking water, and irrigation. The permanently wetted portion of reservoirs are typically surrounded by periodically inundated land referred to as a "drawdown zone" or "inundation area." Greenhouse gas emissions from inundation areas are considered significant and similar per unit area to the emissions from the water surface and are therefore included in the total reservoir surface area when estimating greenhouse gas emissions from flooded land. Lakes converted into reservoirs without substantial changes in water surface area or water residence times are not considered to be managed flooded land (see Area Estimates below) (IPCC 2019).

In 2020 the conterminous United States hosted 74,292 hectares of reservoir surface area in Land Converted to Flooded Land (see Methodology and Time-Series Consistency below for calculation details) distributed across four of the six aggregated climate zones used to define flooded land emission factors (Figure 6-15) (IPCC 2019). Alaska, Hawaii, and U.S. Territories are not included in this report due to a lack of data (see the Methodology and Time-Series Consistency section).

Figure 6-15: U.S. Reservoirs (black polygons) in the Land Converted to Flooded Land Category in 2020



Note: Colors represent climate zone used to derive IPCC default emission factors.

Methane and CO_2 are produced in reservoirs through the natural breakdown of organic matter. Per unit area emission rates tend to scale positively with temperature and system productivity (i.e., abundance of algae). Greenhouse gases produced in reservoirs can be emitted directly from the water surface and inundation areas or as greenhouse gas-enriched water passes through the dam and the downstream river. Sufficient information exists to estimate downstream CH_4 emissions using Tier 1 IPCC guidance (IPCC 2019), but no guidance is provided for downstream CO_2 emissions. Table 6-91 and Table 6-92 below summarize nationally aggregated CH_4 and CO_2 emissions from reservoirs and associated inundation areas in Land Converted to Flooded Land. The decrease in CO_2

and CH_4 emissions through the time series is attributable to reservoirs matriculating from the Land Converted to Flooded Land category into the Flooded Land Remaining Flooded Land Category. Emissions have been stable since 2005, reflecting the low rate of new flooded land creation over the past 15 years.

Table 6-91: CH_4 Emissions from Reservoirs and Inundation Areas in Land Converted to Flooded Land (MMT CO_2 Eq.)

Source	1990	2005	2016	2017	2018	2019	2020
Reservoirs	**2.3**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**
Surface Emissions	2.1	0.2	0.2	0.2	0.2	0.2	0.2
Downstream Emissions	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Inundation Areas	**0.2**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
Surface Emissions	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Downstream Emissions	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	**2.5**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**

Note: Alaska, Hawaii, and U.S. Territories are not included.

Table 6-92: CH_4 Emissions from Reservoirs and Inundation Areas in Land Converted to Flooded Land (kt CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
Reservoirs	**93**	**8**	**7**	**7**	**7**	**7**	**7**
Surface Emissions	86	7	6	6	6	6	6
Downstream Emissions	8	1	1	1	1	1	1
Inundation Areas	**7**	**0**	**0**	**0**	**0**	**0**	**0**
Surface Emissions	6	0	0	0	0	0	0
Downstream Emissions	1	0	0	0	0	0	0
Total	**100**	**8**	**7**	**7**	**7**	**7**	**7**

Note: Alaska, Hawaii, and U.S. Territories are not included.

Table 6-93: CO_2 Emissions from Reservoirs and Inundation Areas in Land Converted to Flooded Land (MMT CO_2)

Source	1990	2005	2016	2017	2018	2019	2020
Reservoir	3.5	0.3	0.3	0.3	0.3	0.3	0.3
Inundation Area	0.3	+	+	+	+	+	+
Total	**3.8**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**

+Indicates values less than 0.05 MMT CO_2

Note: Alaska, Hawaii, and U.S. Territories are not included.

Table 6-94: CO_2 Emissions from Reservoirs and Inundation Areas in Land Converted to Flooded Land (MMT C)

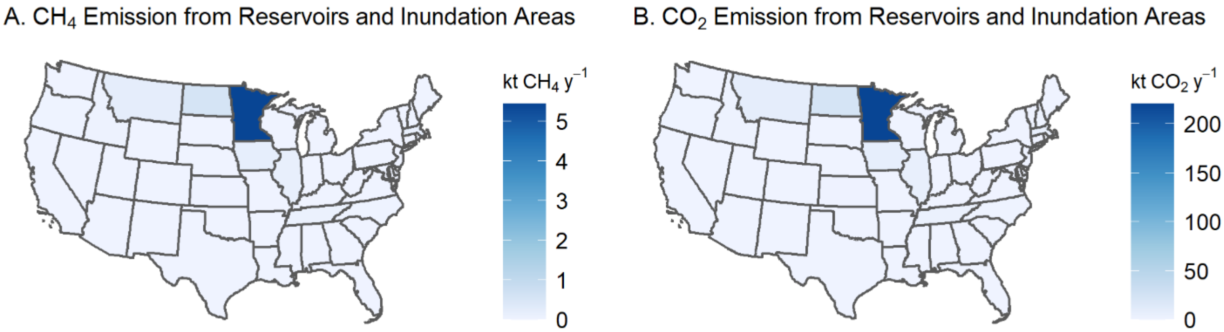
Source	1990	2005	2016	2017	2018	2019	2020
Reservoir	1.0	0.1	0.1	0.1	0.1	0.1	0.1
Inundation Area	0.1	+	+	+	+	+	+
Total	**1.0**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**

+Indicates values less than 0.05 MMT C

Note: Alaska, Hawaii, and U.S. Territories are not included.

Methane and CO_2 emissions from reservoirs and inundated areas in Minnesota were nearly 5 and 10-fold greater than any other state, respectively (Figure 6-16 and Table 6-95). This is attributed to nine dams built in Minnesota after 2001 which impound 58,875 ha of water, 88 percent of which is located in Mille Lacs lake. North Dakota is the second largest source of CO_2 and CH_4 from reservoirs and inundated areas in Land Converted to Flooded Land. Ninety five percent of Land Converted to Flooded Land reservoir surface area in North Dakota is attributed to Devils Lake. Both Mille Lacs and Devils Lakes are natural waterbodies provisioned with dams for water level management.

Figure 6-16: 2020 A) CH_4 and B) CO_2 Emissions from U.S. Reservoirs and Inundation Areas in Land Converted to Flooded Land


A. CH_4 Emission from Reservoirs and Inundation Areas

B. CO_2 Emission from Reservoirs and Inundation Areas

Table 6-95: Methane and CO_2 Emissions (kt) from Reservoirs and Associated Inundation Areas in Land Converted to Flooded Land in 2020

	Reservoir			Inundation Area			Total		
	CH_4		CO_2[a]	CH_4		CO_2[a]	CH_4		CO_2[a]
State	Downstream	Surface	Surface	Downstream	Surface	Surface	Downstream	Surface	Surface
Alabama	0	0	0	0	0	0	0	0	0
Arizona	0	0	0	0	0	0	0	0	0
Arkansas	0	0	0	0	0	0	0	0	0
California	+	+	+	0	0	0	+	+	+
Colorado	+	+	+	0	0	0	+	+	+
Connecticut	+	+	+	0	0	0	+	+	+
Delaware	0	0	0	0	0	0	0	0	0
District of Columbia	0	0	0	0	0	0	0	0	0
Florida	0	0	0	0	0	0	0	0	0
Georgia	0	0	0	0	0	0	0	0	0
Idaho	+	+	1	0	0	0	+	+	1
Illinois	+	+	6	0	0	0	+	+	6
Indiana	0	0	0	0	0	0	0	0	0
Iowa	+	+	8	0	0	0	+	+	8
Kansas	+	+	1	0	0	0	+	+	1
Kentucky	0	0	0	0	0	0	0	0	0
Louisiana	+	+	+	0	0	0	+	+	+
Maine	+	+	+	0	0	0	+	+	+
Maryland	0	0	0	0	0	0	0	0	0
Massachusetts	+	+	5	0	0	0	+	+	5
Michigan	+	+	+	0	0	0	+	+	+
Minnesota	+	5	215	+	+	5	+	5	220
Mississippi	+	+	+	0	0	0	+	+	+
Missouri	0	0	0	0	0	0	0	0	0
Montana	+	+	7	+	+	3	+	+	9
Nebraska	+	+	+	0	0	0	+	+	+
Nevada	+	+	+	0	0	0	+	+	+
New Hampshire	+	+	1	0	0	0	+	+	1
New Jersey	0	0	0	0	0	0	0	0	0
New Mexico	+	+	+	0	0	0	+	+	+
New York	+	+	+	0	0	0	+	+	+
North Carolina	+	+	1	0	0	0	+	+	1
North Dakota	+	1	23	0	0	0	+	1	23
Ohio	+	+	+	0	0	0	+	+	+

Oklahoma	+	+	+	0	0	0	+	+	+
Oregon	+	+	1	0	0	0	+	+	1
Pennsylvania	+	+	+	0	0	0	+	+	+
Rhode Island	0	0	0	0	0	0	0	0	0
South Carolina	0	0	0	0	0	0	0	0	0
South Dakota	+	+	+	0	0	0	+	+	+
Tennessee	+	+	3	0	0	0	+	+	3
Texas	+	+	+	0	0	0	+	+	+
Utah	+	+	+	0	0	0	+	+	+
Vermont	0	0	0	0	0	0	0	0	0
Virginia	+	+	+	0	0	0	+	+	+
Washington	+	+	+	0	0	0	+	+	+
West Virginia	0	0	0	0	0	0	0	0	0
Wisconsin	0	0	0	0	0	0	0	0	0
Wyoming	0	0	0	0	0	0	0	0	0

+ Indicates values less than 0.5 kt.

[a] CO_2: Only surface CO_2 emissions are included in the Inventory.

Note: Alaska, Hawaii, and U.S. Territories are not included.

Methodology and Time-Series Consistency

Estimates of CH_4 and CO_2 emissions for reservoirs and associated inundation areas in Land Converted to Flooded Land follow the Tier 1 methodology in the IPCC guidance (IPCC 2019). All calculations are performed at the state level and summed to obtain national estimates. Emissions from the surface of these flooded lands are calculated as the product of flooded land surface area and a climate specific emission factor (Table 6-96). Downstream CH_4 emissions are calculated as 9 percent of the surface CH_4 emission (Tier 1 default). The IPCC guidance (IPCC 2019) does not address downstream CO_2 emissions, presumably because there are insufficient data in the literature to estimate this emission pathway.

The IPCC default surface emission factors are derived from model predicted (G-res model, Prairie et al. 2017) emission rates for all reservoirs in the Global Reservoir and Dam (GRanD) database (Lehner et al. 2011). Predicted emission rates were aggregated by the 11 IPCC climate zones (IPCC 2019, Table 7A.2) which were collapsed into six climate zones using a regression tree approach. All six aggregated climate zone are present in the conterminous United States.

Table 6-96: IPCC (2019) Default CH_4 and CO_2 Emission Factors for Surface Emissions from Reservoirs and Associated Inundation Areas in Land Converted to Flooded Land

	Surface emission factor	
Climate	**MT CH_4 ha^{-1} y^{-1}**	**MT CO_2 ha^{-1} y^{-1}**
Boreal	0.0277	3.45
Cool Temperate	0.0847	3.74
Warm Temperate Dry	0.1956	6.23
Earm Temperate Moist	0.1275	5.35
Tropical Dry/Montane	0.3923	10.82
Tropical Moist/Wet	0.2516	10.16

Area Estimates

Reservoirs in the conterminous United States were identified from the NHDArea and NHDWaterbody layers in the National Hydrography Dataset Plus V2 (NHD),[89] the National Lakes Assessment (NLA)[90] data, the National

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[89] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

[90] See https://www.epa.gov/national-aquatic-resource-surveys/nla.

Inventory of Dams (NID),[91] and the Navigable Waterways (NW)[92] dataset. The NHD and NLA do not include Alaska, Hawaii, or U.S. Territories, thus these areas are not included in the Inventory. Waterbodies less than 20 years old, greater than 8 ha in surface area, and not identified as canal/ditch in NHD or NW and met any of the following criteria were considered reservoirs in Land Converted to Flooded Land: 1) the water body was classified "Reservoir" in the NHDWaterbody layer, 2) the water body name in the NHDWaterbody layer included "reservoir", 3) the water body in the NHDWaterbody layer was located in close proximity to a dam in the NID, 4) the water body was deemed "man-made" in the NLA, 5) the waterbody was included in NW, and 6) inundation areas in the NHDArea layer that were associated with water bodies that met any of the above criteria were assumed to represent drawdown zones and were included in the flooded land inventory. Surface areas for identified flooded lands were taken from NHD or the NW.

IPCC (2019) allows for the exclusion of reservoirs from the inventory if the water surface area or residence time was not substantially changed by the construction of the dam. The guidance does not quantify what constitutes a "substantial" change, but here EPA excludes the U.S. Great Lakes from the inventory based on expert judgment that neither the surface area or water residence time was substantially altered by their associated dams. EPA assumes that all other waterbodies identified through the six criteria described above were substantially impacted by the construction of dams.

EPA assumes that all reservoirs included in the NW are subject to water-level management to maintain minimum water depths required for navigation and are therefore managed flooded lands. Reservoir age was determined from the year the dam was completed as reported in the NID (available for 40,012 out of 54,670 reservoirs). When dam completion year was not available, the reservoir was assumed to be greater than 20 years old. Reservoirs were disaggregated by state (using boundaries from the 2016 U.S. Census Bureau[93]) and climate zone. Downstream and surface emissions for cross-state reservoirs were allocated to states based on the surface area that the reservoir occupied in each state. Only the U.S. portion of reservoirs that cross country borders were included in the inventory. Surface areas for reservoirs and associated inundation areas were taken from NHD or the NW and the final inventory of reservoirs and associated inundation areas was screened to ensure no waterbodies were duplicated.

Many reservoirs are surrounded by land that is dry for a portion of the year but is periodically flooded when water inflows to the reservoir exceed outflows and the reservoir surface area expands into surrounding lands. This can occur for a variety of reasons including high rates of water runoff from the watershed (i.e., snow melt, large precipitation events), deliberate efforts to raise water levels for seasonal recreation or wildlife habitat, and management efforts to reduce inflows to downstream systems. These periodically flooded lands are represented as "Inundation Areas" in the NHDArea layer (Figure 6-17). Inundation areas are considered equivalent to "drawdown zones" in IPCC (2019) and CO_2 and CH_4 emissions from these lands are estimated using the same methodology as for reservoirs.

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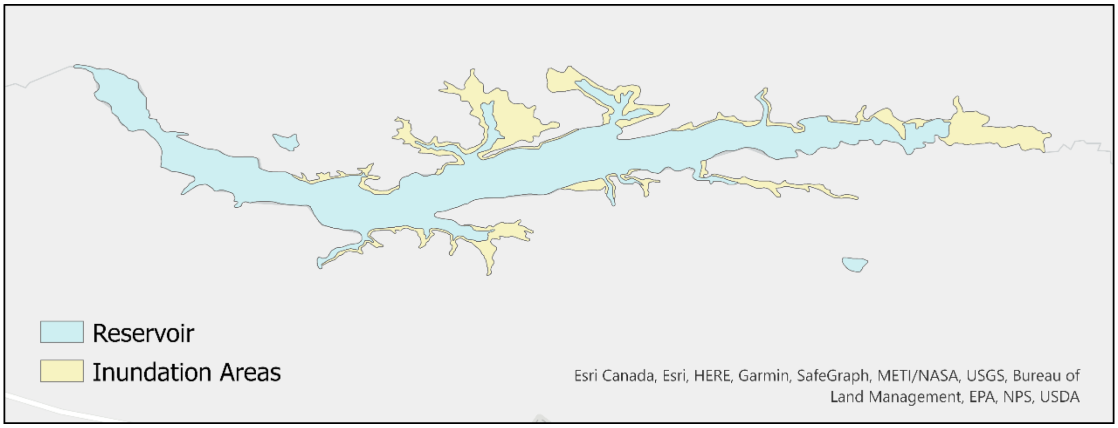
[91] See https://nid.sec.usace.army.mil.

[92] See https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::navigable-waterway-network-lines-1/about.

[93] See https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html.

Figure 6-17: Example of a Reservoir and Associated Inundation Area in Land Converted to Flooded Land



Esri Canada, Esri, HERE, Garmin, SafeGraph, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, USDA

The surface area of reservoirs and inundation areas in Land Converted to Flooded Land decreased by approximately 90 percent from 1990 to 2020 (Table 6-97). This is due to reservoirs that were less than 20 years old at beginning of time series entering the Flooded Land Remaining Flooded Land category when they reached 20 years of age. The rate at which flooded land has aged out of the Land Converted to Flooded Land category has outpaced the rate of new dam construction. New dam construction has slowed considerably during the time series with no new dams entering the inventory since 2017 (Figure 6-18).

Lakes Sakakawea and Oahe in North Dakota and South Dakota are notable examples of reservoirs that matriculated out of Land Converted to Flooded Land during the time series. These Missouri River impoundments have a combined surface area in excess of 0.25 million hectares and aged out of Land Converted to Flooded Land between 2000 and 2003, but in 2020 North Dakota still had the second largest expanse of surface area in this category due primarily to a new dam on Devils Lake.

Table 6-97: National Totals of Reservoir and Associated Inundation Areas Surface Area (thousands of ha) in Land Converted to Flooded Land

Surface Area (thousands of ha)	1990	2005	2016	2017	2018	2019	2020
Reservoir	699	75	74	73	73	72	72
Inundation Area	51	3	2	2	2	2	2

Note: Alaska, Hawaii, and U.S. Territories are not included.

Figure 6-18: Number of dams built per year from 1990-2020

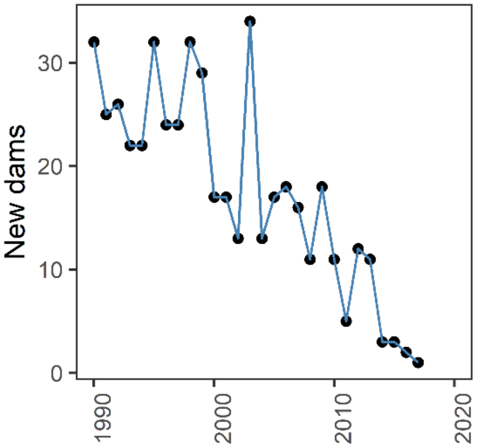


Table 6-98: State breakdown of Reservoirs and Associated Inundation Area Surface Area (thousands of ha) in Land Converted to Flooded Land

State	1990	2005	2016	2017	2018	2019	2020
Alabama	32.3	0.1	0.0	0.0	0.0	0.0	0.0
Arizona	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Arkansas	32.1	0.0	0.0	0.0	0.0	0.0	0.0
California	10.7	0.5	0.4	0.4	0.4	0.1	0.0
Colorado	5.8	0.1	0.1	0.1	0.1	0.1	0.1
Connecticut	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Delaware	0.0	0.0	0.0	0.0	0.0	0.0	0.0
District of Columbia	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Florida	10.4	0.2	0.0	0.0	0.0	0.0	0.0
Georgia	10.2	0.0	0.0	0.0	0.0	0.0	0.0
Idaho	10.1	0.8	0.4	0.4	0.4	0.4	0.4
Illinois	19.6	3.1	1.3	1.2	1.2	1.1	1.1
Indiana	6.2	2.3	0.0	0.0	0.0	0.0	0.0
Iowa	11.4	1.9	2.1	2.1	2.1	2.1	2.1
Kansas	26.7	0.4	0.3	0.3	0.2	0.2	0.2
Kentucky	0.6	0.0	0.0	0.0	0.0	0.0	0.0
Louisiana	16.9	3.0	0.0	0.0	0.0	0.0	0.0
Maine	13.2	3.4	0.1	0.1	0.1	0.1	0.1
Maryland	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Massachusetts	1.0	0.6	1.3	1.3	1.3	1.2	1.2
Michigan	12.8	2.7	0.1	0.1	0.1	0.1	0.1
Minnesota	9.0	9.1	59.7	58.9	58.9	58.9	58.9
Mississippi	6.0	0.1	0.0	0.0	0.0	0.0	0.0
Missouri	56.7	0.0	0.0	0.0	0.0	0.0	0.0
Montana	8.5	3.8	2.5	2.5	2.5	2.5	2.5
Nebraska	5.5	1.3	0.2	0.2	0.2	0.2	0.1
Nevada	1.3	0.3	0.0	0.0	0.0	0.0	0.0
New Hampshire	0.4	0.2	0.2	0.2	0.2	0.2	0.2
New Jersey	0.3	0.0	0.0	0.0	0.0	0.0	0.0
New Mexico	0.2	0.0	0.0	0.0	0.0	0.0	0.0
New York	2.4	0.9	0.1	0.1	0.1	0.1	0.1
North Carolina	19.2	0.5	0.1	0.1	0.1	0.1	0.1
North Dakota	159.4	2.5	6.7	6.2	6.2	6.2	6.2

Ohio	3.1	0.0	0.0	0.0	0.0	0.0	0.0
Oklahoma	19.6	0.2	0.0	0.0	0.0	0.0	0.0
Oregon	3.9	0.2	0.2	0.2	0.1	0.1	0.1
Pennsylvania	3.2	0.3	0.3	0.3	0.1	0.1	0.1
Rhode Island	0.2	0.0	0.0	0.0	0.0	0.0	0.0
South Carolina	6.0	0.0	0.0	0.0	0.0	0.0	0.0
South Dakota	106.5	0.0	0.0	0.0	0.0	0.0	0.0
Tennessee	2.7	0.0	0.6	0.6	0.6	0.6	0.6
Texas	49.5	0.1	0.0	0.0	0.0	0.0	0.0
Utah	43.0	37.0	0.0	0.0	0.0	0.0	0.0
Vermont	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Virginia	5.8	0.0	0.0	0.0	0.0	0.0	0.0
Washington	3.0	0.2	0.0	0.0	0.0	0.0	0.0
West Virginia	2.9	1.6	0.0	0.0	0.0	0.0	0.0
Wisconsin	1.9	0.4	0.0	0.0	0.0	0.0	0.0
Wyoming	9.1	0.3	0.0	0.0	0.0	0.0	0.0
Total	**750.0**	**78.5**	**76.7**	**75.3**	**75.0**	**74.5**	**74.3**

Note: Alaska, Hawaii, and U.S. Territories are not included.

Uncertainty

Uncertainty in estimates of CH_4 and CO_2 emissions from reservoirs on Land Converted to Flooded Land were developed using IPCC Approach 2 and include uncertainty in the default emission factors and the flooded land area inventory (Table 6-99). Uncertainty in emission factors is provided in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Uncertainties in the spatial data include 1) uncertainty in area estimates from the NHD and NW, and 2) uncertainty in the location of dams in the NID. Overall uncertainties in these spatial datasets are unknown, but uncertainty for remote sensing products is assumed to be ±10 to 15 percent based on IPCC guidance (IPCC 2003). An uncertainty range of ±15 percent for the flooded land area estimates is assumed and is based on expert judgment.

Table 6-99: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Reservoirs and Associated Inundation Areas in Land Converted to Flooded Land

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Reservoir						
Surface	CH_4	0.2	0.1	0.2	-12.7%	12.5%
Surface	CO_2	0.3	0.2	0.3	-13.4%	13.5%
Downstream	CH_4	+	+	0.1	-57.1%	287.3
Inundation Area						
Surface	CH_4	+	+	+	-13.1%	12.9%
Surface	CO_2	+	+	+	-13.0%	14.1%
Downstream	CH_4	+	+	+	-56.9%	290.7%
Total		**0.5**	**0.4**	**0.5**	**-13.1%**	**16.0%**

+ Indicates values less than 0.05 MMT CO_2 Eq.

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.

QA/QC and Verification

The National Hydrography Data (NHD) is managed by the USGS in collaboration many other federal, state, and local entities. Extensive QA/QC procedures are incorporated into the curation of the NHD. The National Inventory of Dams (NID) is maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with the Federal Emergency Management Agency (FEMA) and state regulatory offices. USACE resolves duplicative and conflicting data from 68 data sources, which helps obtain the more complete, accurate, and updated NID. The National Lakes

Assessment is a survey of U.S. lakes and reservoirs conducted by the U.S. Environmental Protection Agency every 5 years. The program is subject to rigorous QA/QC as detailed in the Quality Assurance Project Plan.[94] The Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation Statistics's (BTS's) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis.

All calculations were executed independently in Excel and R. Ten percent of state and national totals were randomly selected for comparison between the two approaches to ensure there were no computational errors.

Recalculations Discussion

This is a new category in the current Inventory.

Planned Improvements

EPA is measuring greenhouse gas emissions from 108 flooded lands (reservoirs) in the conterminous United States. The survey will be complete by September 2023 and the data will be used to predict greenhouse gas emission rates for all U.S. flooded lands. The Inventory will be updated at that time using these country-specific emission factors developed through the measurement campaign.

Hawaii, Alaska and U.S. Territories will be included in the next (i.e., 1990 through 2021) Inventory. Flooded lands area data for these states and territories will be derived from the National Hydrography Dataset Plus High Resolution (NHDPlus HighRes),[95] an enhanced version of the NHD used in this Inventory.

To verify that waterbodies contained in NW are subject to water level management, EPA will overlay the NW with other spatial datasets of water control structures including the inventory of U.S. Army Corps of Engineers locks for water navigation[96] and dams/weirs contained in the NHDPlus HighRes.

Emissions from Land Converted to Flooded Land–Other Constructed Waterbodies

Freshwater ponds are the only type of flooded lands within the “other constructed waterbodies” subcategory of Land Converted to Flooded Land that are included in this Inventory (see Methodology for details). IPCC (2019) describes ponds as waterbodies that are “…constructed by excavation and/or construction of walls to hold water in the landscape for a range of uses, including agricultural water storage, access to water for livestock, recreation, and aquaculture.” The IPCC “Decision tree for types of Flooded Land” (IPCC 2019, Fig. 7.2) elaborates on this description by defining waterbodies less than 8 ha as a subset of “other constructed waterbodies.” For this inventory, ponds are defined as managed flooded land not flagged as “canal/ditch” in the NHD (see Methods below) with surface area less than 8 ha. IPCC (2019) further distinguishes saline versus brackish ponds, with the former supporting lower CH_4 emission rates than the latter. Activity data on pond salinity is not uniformly available for the conterminous United States and all ponds in Land Converted to Flooded Land are assumed to be freshwater. Ponds often receive high organic matter and nutrient loadings, may have low oxygen levels, and are sites of substantial CH_4 and CO_2 emissions from anaerobic sediments.

Methane and CO_2 emissions from freshwater ponds decreased 98 percent from 1990 to 2020 due to flooded land matriculating from Land Converted to Flooded Land to Flooded Land Remaining Flooded Land. Much of this decline occurred by 2000, but declines have continued through 2020. In 2020, Massachusetts, Mississippi, and Kansas

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[94] See https://www.epa.gov/national-aquatic-resource-surveys/national-lakes-assessment-2017-quality-assurance-project-plan.

[95] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography/nhdplus-high-resolution.

[96] See https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::locks/about.

have the greatest CO_2 and CH_4 emissions for freshwater ponds in Land Converted to Flooded Land (Table 6-100 through Table 6-104, Figure 6-19).

Table 6-100: CH_4 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (MMT CO_2 Eq.)

Source	1990	2005	2016	2017	2018	2019	2020
Freshwater Ponds	0.1	+	+	+	+	+	+

+ Indicates values less than 0.05 MMT CO_2 Eq.

Note: Alaska, Hawaii, and U.S. Territories are not included.

Table 6-101: CH_4 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (kt CH_4)

Source	1990	2005	2016	2017	2018	2019	2020
Freshwater Ponds	3	+	+	+	+	+	+

+ Indicates values less than 0.5 kt

Note: Alaska, Hawaii, and U.S. Territories are not included.

Table 6-102: CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (MMT CO_2)

Source	1990	2005	2016	2017	2018	2019	2020
Freshwater Ponds	0.1	+	+	+	+	+	+

+ Indicates values less than 0.5 MMT CO_2 Eq.

Note: Alaska, Hawaii, and U.S. Territories are not included.

Table 6-103: CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (MMT C)

Source	1990	2005	2016	2017	2018	2019	2020
Freshwater Ponds	0.02	+	+	+	+	+	+

+ Indicates values less than 0.005 MMT C

Note: Alaska, Hawaii, and U.S. Territories are not included.

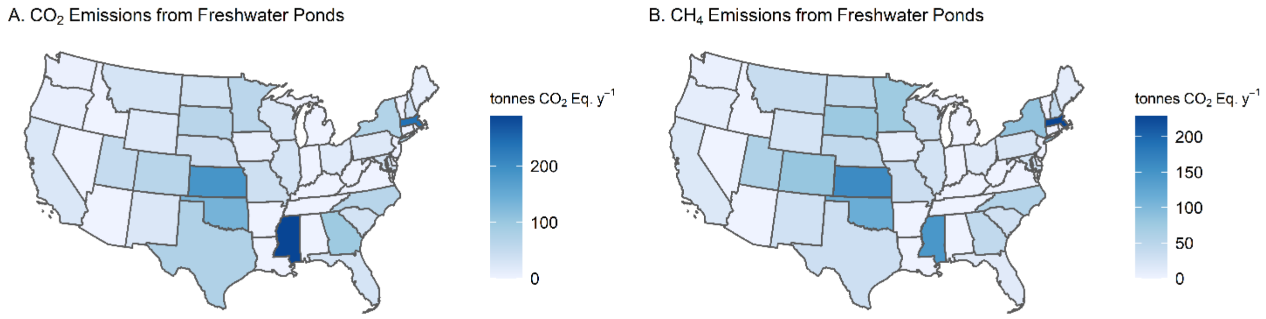
Table 6-104: CH_4 and CO_2 Emissions (MT CO_2 Eq.) from Other Constructed Waterbodies in Land Converted to Flooded Land in 2020

	Freshwater Ponds		
State	**CH_4**	**CO_2**	**Total**
Alabama	0	0	0
Arizona	0	0	0
Arkansas	0	0	0
California	18	25	43
Colorado	82	65	147
Connecticut	0	0	0
Delaware	0	0	0
District of Columbia	0	0	0
Florida	14	30	44
Georgia	43	96	139
Idaho	0	0	0
Illinois	26	31	57
Indiana	0	0	0
Iowa	8	10	18
Kansas	160	187	347
Kentucky	0	0	0
Louisiana	0	0	0
Maine	11	9	19
Maryland	26	31	57

Massachusetts	229	239	468
Michigan	0	0	0
Minnesota	75	61	137
Mississippi	146	288	434
Missouri	33	38	71
Montana	37	30	68
Nebraska	43	39	82
Nevada	0	0	0
New Hampshire	41	34	75
New Jersey	0	0	0
New Mexico	29	24	53
New York	85	72	157
North Carolina	56	65	121
North Dakota	43	35	78
Ohio	14	16	30
Oklahoma	115	135	250
Oregon	9	7	16
Pennsylvania	21	20	40
Rhode Island	0	0	0
South Carolina	28	33	60
South Dakota	78	64	142
Tennessee	0	0	0
Texas	32	75	107
Utah	60	49	109
Vermont	0	0	0
Virginia	0	0	0
Washington	5	5	10
West Virginia	0	0	0
Wisconsin	30	25	55
Wyoming	24	19	43
Total	**1,619**	**1,857**	**3,477**

Note: Alaska, Hawaii, and U.S. Territories are not included.

Figure 6-19: CH_4 and CO_2 Emissions (MT CO_2 Eq.) from Other Constructed Waterbodies in Land Converted to Flooded Land in 2020



Methodology and Time-Series Consistency

Estimates of CH_4 and CO_2 emissions for other constructed waterbodies in Land Converted to Flooded Land follow the Tier 1 methodology in IPCC (2019). All calculations are performed at the state level and summed to obtain national estimates. Greenhouse gas emissions from the surface of these flooded lands are calculated as the product of flooded land surface area and an emission factor (Table 6-105). Due to a lack of empirical data on CO_2 emissions from recently created ponds, IPCC (2019) states "For all types of ponds created by damming, the methodology described above to estimate CO_2 emissions from land converted to reservoirs may be used." This

Inventory uses IPCC default CO_2 emission factors for land converted to reservoirs when estimating CO_2 emissions from land converted to freshwater ponds. IPCC guidance also states that "there is insufficient information available to derive separate CH_4 emission factors for recently constructed ponds…" and allows for the use of IPCC default CH_4 emission factors for land remaining flooded land. Downstream emissions are not inventoried for other constructed waterbodies because 1) many of these systems are not associated with dams (e.g., excavated ponds and ditches), and 2) there are insufficient data to derive downstream emission factors for other constructed waterbodies that are associated with dams (IPCC 2019).

Table 6-105: IPCC Default Methane and CO_2 Emission Factors for Other Constructed Waterbodies in Land Converted to Flooded Land

		Emission Factor	
Other Constructed Waterbody	**Climate Zone**	**MT CH_4 ha^{-1} y^{-1}**	**MT CO_2 ha^{-1} y^{-1}**
Freshwater ponds	Boreal	0.183	3.45
Freshwater ponds	Cool Temperate	0.183	3.74
Freshwater ponds	Warm Temperate Dry	0.183	6.23
Freshwater ponds	Warm Temperate Moist	0.183	5.35
Freshwater ponds	Tropical Dry/Montane	0.183	10.82
Freshwater ponds	Tropical Moist/Wet	0.183	10.16

Area estimates

Freshwater ponds in the conterminous United States were identified from the NHDArea and NHDWaterbody layers in the National Hydrography Dataset Plus V2 (NHD),[97] the National Lakes Assessment (NLA)[98] data, the National Inventory of Dams (NID),[99] and the Navigable Waterways (NW)[100] dataset. The NHD and NLA do not include Alaska, Hawaii, or U.S. Territories, thus these areas are not included in the Inventory.

Waterbodies less than 20 years old, less than 8 Ha in surface area, and not identified as canal/ditch in NHD or NW and met any of the following criteria were considered ponds in Land Converted to Flooded Land: 1) the water body was classified "Reservoir" in the NHDWaterbody layer, 2) the water body name in the NHDWaterbody layer included "reservoir", 3) the water body in the NHDWaterbody layer was located in close proximity to a dam in the NID, 4) the water body was deemed "man-made" in the NLA, 5) the waterbody was included in NW, and 6) inundation areas in the NHDArea layer that were associated with water bodies that met any of the above criteria were assumed to represent drawdown zones and were included in the flooded land inventory. Flooded lands that met any one of these criteria and 1) had a surface area less than 8 ha and 2) were not classified as CANALS/DITCHES in the NHD, were classified as freshwater ponds, a subcategory of other constructed waterbodies (IPCC 2019).

Surface areas for ponds were taken from NHD or the NW. Waterbodies were further disaggregated by state (using boundaries from the 2016 U.S. Census Bureau[101]) and the final area inventory was screened to ensure no waterbodies were duplicated.

While the distribution of U.S. waterbodies <8 ha is well represented in NHD, it is difficult to determine which of these waterbodies are subject to water level management. The presence or absence of a flow control structure associated with these small waterbodies is typically not documented in NHD, thus EPA used the NID for this purpose. The NID only includes dams that pose a hazard if they were to fail, equal or exceed 25 feet in height and exceed 15 acre-feet in storage, or equal or exceed 50 acre-feet storage and exceed 6 feet in height.[102] The extent

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[97] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography.

[98] See https://www.epa.gov/national-aquatic-resource-surveys/nla.

[99] See https://nid.sec.usace.army.mil.

[100] See https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::navigable-waterway-network-lines-1/about.

[101] See https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html.

[102] See https://nid.sec.usace.army.mil.

to which these criteria fail to capture flow control structures associated with freshwater ponds in the United States in unknown, but the freshwater pond area inventory presented here is an underestimate. There is a planned improvement to review other data sources or approaches that could more fully capture all managed freshwater ponds in the United States.

IPCC (2019) provides guidance for estimating CH_4 emissions from canals and ditches, a subcategory of other constructed waterbodies, in Land Converted to Flooded Land. While U.S. canals and ditches can be identified in the data sources described above, the age of these systems cannot. EPA assumes that all U.S. canals and ditches are greater than 20 years old and therefore are not included in Land Converted to Flooded Land.

For the year 2020, this Inventory contains 354 ha of freshwater ponds in Land Converted to Flooded Land. The surface area of freshwater ponds decreased by 98 percent from 1990 to 2020 due to flooded lands aging out of Land Converted to Flooded Land more quickly than new flooded lands entered the category. The greatest reduction in freshwater pond surface area occurred in Texas, Missouri, and Kansas (Table 6-107). Freshwater ponds in the 2020 inventory are most abundant in Massachusetts, Kansas, and Mississippi, but show no overarching geographical pattern (Figure 6-20).

Table 6-106: National Surface Area (ha) Totals of Other Constructed Waterbodies in Land Converted to Flooded Land

Other Constructed Waterbody	1990	2005	2016	2017	2018	2019	2020
Freshwater Ponds	14,846	1015	590	542	442	393	354

Note: Alaska, Hawaii, and U.S. Territories are not included.

Figure 6-20: Surface Area (ha) of Other Constructed Waterbodies in Land Converted to Flooded Land

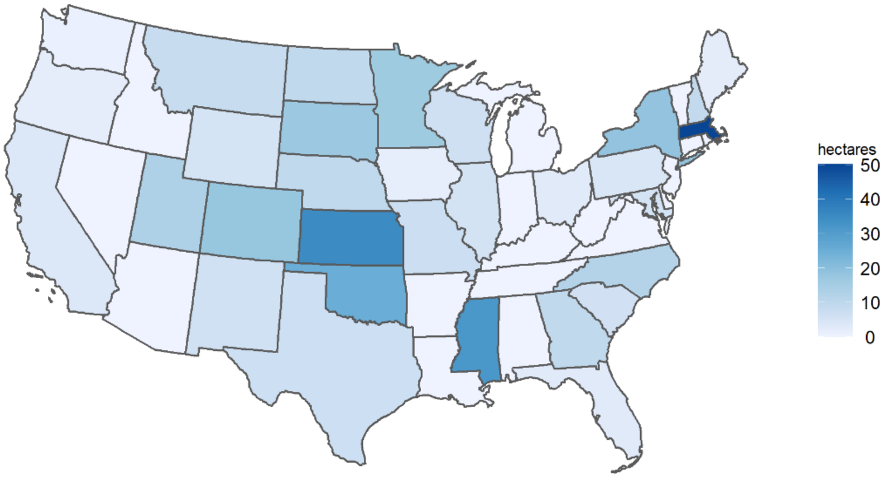

Table 6-107: State Surface Area (ha) Totals of Other Constructed Waterbodies in Land Converted to Flooded Land

State	1990	2005	2016	2017	2018	2019	2020
Alabama	240	11	3	3	0	0	0
Arizona	29	5	5	5	0	0	0
Arkansas	255	0	0	0	0	0	0
California	98	16	5	5	5	4	4
Colorado	140	27	27	27	18	18	18
Connecticut	46	0	0	0	0	0	0
Delaware	7	0	0	0	0	0	0
District of Columbia	0	0	0	0	0	0	0

Florida	46		16		6	6	6	3	3
Georgia	611		17		9	9	9	9	9
Idaho	44		0		0	0	0	0	0
Illinois	333		38		12	11	6	6	6
Indiana	81		7		0	0	0	0	0
Iowa	1,062		33		13	13	13	9	2
Kansas	1,636		74		65	58	42	35	35
Kentucky	184		2		2	0	0	0	0
Louisiana	95		5		0	0	0	0	0
Maine	23		4		2	2	2	2	2
Maryland	38		6		6	6	6	6	6
Massachusetts	70		65		72	67	61	57	50
Michigan	99		13		2	0	0	0	0
Minnesota	96		25		30	30	30	30	16
Mississippi	421		70		59	44	44	39	32
Missouri	2,375		23		7	7	7	7	7
Montana	298		5		13	13	13	8	8
Nebraska	751		44		35	35	9	9	9
Nevada	7		20		2	0	0	0	0
New Hampshire	62		20		9	9	9	9	9
New Jersey	15		3		3	3	0	0	0
New Mexico	9		0		6	6	6	6	6
New York	193		70		19	19	19	19	19
North Carolina	225		41		14	14	14	14	12
North Dakota	66		41		17	17	9	9	9
Ohio	202		38		13	3	3	3	3
Oklahoma	1,012		52		35	35	32	25	25
Oregon	81		18		5	5	2	2	2
Pennsylvania	137		20		5	5	5	5	5
Rhode Island	1		0		0	0	0	0	0
South Carolina	462		26		11	9	9	9	6
South Dakota	112		48		28	26	26	17	17
Tennessee	198		16		9	9	2	0	0
Texas	2,428		45		17	12	8	7	7
Utah	45		0		8	13	13	13	13
Vermont	61		4		0	0	0	0	0
Virginia	171		0		0	0	0	0	0
Washington	98		33		3	3	1	1	1
West Virginia	0		0		0	0	0	0	0
Wisconsin	154		11		7	7	7	7	7
Wyoming	28		3		5	5	5	5	5
TOTAL	**14,846**		**1,015**		**590**	**542**	**442**	**393**	**354**

Note: Alaska, Hawaii, and U.S. Territories are not included.

Uncertainty

Uncertainty in estimates of CO_2 and CH_4 emissions from Land Converted to Flooded Land–*Other Constructed Water Bodies* include uncertainty in the default emission factors and the flooded land area inventory. Uncertainty in emission factors is provided in the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019). Uncertainties in the spatial data include 1) uncertainty in area estimates from the NHD and NW, and 2) uncertainty in the location of dams in the NID. Overall uncertainties in the NHD, NID, and NW are unknown, but uncertainty for remote sensing products is ±10 to 15 percent (IPCC 2003). EPA assumes an uncertainty of ±15 percent for the flooded land area inventory based on expert judgment. These uncertainties do not include the underestimate of pond surface area discussed above.

Table 6-108: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land

Source	Gas	2020 Emission Estimate	Uncertainty Range Relative to Emission Estimate[a]			
		(kt CO_2 Eq.)	(kt CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Freshwater ponds	CH_4	2	2	2	-4.5%	5.0%
Freshwater ponds	CO_2	2	2	2	-4.1%	3.6%
Total		**3**	**3**	**4**	**-3.6%**	**4.1%**

[a] Range of emission estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.
Note: Totals may not sum due to independent rounding.

QA/QC and Verification

The National Hydrography Data (NHD) is managed by the USGS with collaboration from many other federal, state, and local entities. Extensive QA/QC procedures are incorporated into the curation of the NHD. The National Inventory of Dams (NID) is maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with the Federal Emergency Management Agency (FEMA) and state regulatory offices. USACE resolves duplicative and conflicting data from 68 data sources, which helps obtain the more complete, accurate, and updated NID. The National Lakes Assessment is a survey of U.S. lakes and reservoirs conducted by the U.S. Environmental Protection Agency every 5 years. The program is subject to rigorous QA/QC as detailed in the Quality Assurance Project Plan.[103] The Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation Statistics' (BTS's) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis.

All calculations were executed independently in Excel and R. Ten percent of state and national totals were randomly selected for comparison between the two approaches to ensure there were no computational errors.

Recalculations Discussion

This is a new category in the current Inventory.

Planned Improvements

The distribution of U.S. waterbodies less than 8 ha is well known, but the presence or absence of water level control structures associated with these small waterbodies is not well documented in national data sources. To improve the representation of managed ponds in future inventories, EPA will attempt to locate state or county records on small dam construction permits and/or inspection records to supplement records in the NID. EPA will also use surrounding land use as a proxy for management. For example, a pond surrounded by cultivated land is likely subject to water level management and should be included in the inventory. Even if the pond were not subject to water level management, greenhouse gas emissions from the system are likely enhanced by elevated nutrient and sediment inputs from the surrounding managed lands, thus the emissions should be considered anthropogenic and included in the inventory.

Hawaii, Alaska, and U.S. Territories will be included in the next (i.e., 1990 through 2021) Inventory. Flooded lands area data for these states and territories will be derived from the National Hydrography Dataset Plus High Resolution (NHDPlus HighRes),[104] an enhanced version of the NHD used in this Inventory.

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[103] See https://www.epa.gov/national-aquatic-resource-surveys/national-lakes-assessment-2017-quality-assurance-project-plan.

[104] See https://www.usgs.gov/core-science-systems/ngp/national-hydrography/nhdplus-high-resolution.

6.10 Settlements Remaining Settlements (CRF Category 4E1)

Soil Carbon Stock Changes (CRF Category 4E1)

Soil organic C stock changes for *Settlements Remaining Settlements* occur in both mineral and organic soils. However, the United States does not estimate changes in soil organic C stocks for mineral soils in *Settlements Remaining Settlements*. This approach is consistent with the assumption of the Tier 1 method in the *2006 IPCC Guidelines* (IPCC 2006) that inputs equal outputs, and therefore the soil organic C stocks do not change. This assumption may be re-evaluated in the future if funding and resources are available to conduct an analysis of soil organic C stock changes for mineral soils in *Settlements Remaining Settlements*.

Drainage of organic soils is common when wetland areas have been developed for settlements. Organic soils, also referred to as *Histosols*, include all soils with more than 12 to 20 percent organic C by weight, depending on clay content (NRCS 1999; Brady and Weil 1999). The organic layer of these soils can be very deep (i.e., several meters), and form under inundated conditions that results in minimal decomposition of plant residues. Drainage of organic soils leads to aeration of the soil that accelerates decomposition rate and CO_2 emissions.[105] Due to the depth and richness of the organic layers, C loss from drained organic soils can continue over long periods of time, which varies depending on climate and composition (i.e., decomposability) of the organic matter (Armentano and Menges 1986).

Settlements Remaining Settlements includes all areas that have been settlements for a continuous time period of at least 20 years according to the 2015 United States Department of Agriculture (USDA) National Resources Inventory (NRI) (USDA-NRCS 2018)[106] or according to the National Land Cover Dataset (NLCD) for federal lands (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015). The Inventory includes settlements on privately-owned lands in the conterminous United States and Hawaii. Alaska and the small amount of settlements on federal lands are not included in this Inventory even though these areas are part of the U.S. managed land base. This leads to a discrepancy with the total amount of managed area in *Settlements Remaining Settlements* (see Section 6.1 Representation of the U.S. Land Base) and the settlements area included in the Inventory analysis. There is a planned improvement to include CO_2 emissions from drainage of organic soils in settlements of Alaska and federal lands as part of a future Inventory.

CO_2 emissions from drained organic soils in settlements are 15.9 MMT CO_2 Eq. (4.3 MMT C) in 2020 (See Table 6-109 and Table 6-110). Although the flux is relatively small, the amount has increased by over 40 percent since 1990 due to an increase in area of drained organic soils in settlements.

Table 6-109: Net CO_2 Flux from Soil C Stock Changes in *Settlements Remaining Settlements* (MMT CO_2 Eq.)

Soil Type	1990		2005		2016	2017	2018	2019	2020
Organic Soils	11.3		12.2		16.0	16.0	15.9	15.9	15.9

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[105] N_2O emissions from soils are included in the N_2O Emissions from Settlement Soils section.

[106] NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an overestimation of *Settlements Remaining Settlements* in the early part of the time series to the extent that some areas are converted to settlements between 1971 and 1978.

Table 6-110: Net CO_2 Flux from Soil C Stock Changes in *Settlements Remaining Settlements* (MMT C)

Soil Type	1990		2005		2016	2017	2018	2019	2020
Organic Soils	3.1		3.3		4.4	4.4	4.3	4.3	4.3

Methodology and Time-Series Consistency

An IPCC Tier 2 method is used to estimate soil organic C stock changes for organic soils in *Settlements Remaining Settlements* (IPCC 2006). Organic soils in *Settlements Remaining Settlements* are assumed to be losing C at a rate similar to croplands due to deep drainage, and therefore emission rates are based on country-specific values for cropland (Ogle et al. 2003).

The land area designated as settlements is based primarily on the 2018 NRI (USDA-NRCS 2018) with additional information from the NLCD (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015). It is assumed that all settlement area on organic soils is drained, and those areas are provided in Table 6-111 (See Section 6.1, Representation of the U.S. Land Base for more information). The area of drained organic soils is estimated from the NRI spatial weights and aggregated to the country (Table 6-111). The area of land on organic soils in *Settlements Remaining Settlements* has increased from 220 thousand hectares in 1990 to over 303 thousand hectares in 2015. The area of land on organic soils are not currently available from NRI for *Settlements Remaining Settlements* after 2015.

Table 6-111: Thousands of Hectares of Drained Organic Soils in *Settlements Remaining Settlements*

Year	Area (Thousand Hectares)
1990	220
2005	235
2014	291
2015	303
2016	ND
2017	ND
2018	ND
2019	ND
2020	ND

Note: No NRI data are available after 2015, designated as ND (No data).

To estimate CO_2 emissions from drained organic soils across the time series from 1990 to 2015, the total area of organic soils in *Settlements Remaining Settlements* is multiplied by the country-specific emission factors for *Cropland Remaining Cropland* under the assumption that there is deep drainage of the soils. The emission factors are 11.2 MT C per ha in cool temperate regions, 14.0 MT C per ha in warm temperate regions, and 14.3 MT C per ha in subtropical regions (see Annex 3.12 for more information).

In order to ensure time-series consistency, the same methods are applied from 1990 to 2015, and a linear extrapolation method is used to approximate emissions for the remainder of the 2016 to 2020 time series (See Box 6-4 in Cropland Remaining Cropland). The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2015 emissions data, and is a standard data splicing method for estimating emissions at the end of a time series if activity data are not available (IPCC 2006). The Tier 2 method described previously will be applied in future Inventories to recalculate the estimates beyond 2015 as activity data become available.

Uncertainty

Uncertainty for the Tier 2 approach is derived using a Monte Carlo approach, along with additional uncertainty propagated through the Monte Carlo Analysis for 2016 to 2020 based on the linear time series model. The results of the Approach 2 Monte Carlo uncertainty analysis are summarized in Table 6-112. Soil C losses from drained organic soils in *Settlements Remaining Settlements* for 2020 are estimated to be between 7.4 and 24.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 53 percent below and 53 percent above the 2020 emission estimate of 15.9 MMT CO_2 Eq.

Table 6-112: Uncertainty Estimates for CO_2 Emissions from Drained Organic Soils in *Settlements Remaining Settlements* (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Organic Soils	CO_2	15.9	7.4	24.4	-53%	53%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. No errors were found in this Inventory.

Recalculations Discussion

There were no recalculations to the 1990 through 2019 time series in this Inventory.

Planned Improvements

This source will be updated to include CO_2 emissions from drainage of organic soils in settlements of Alaska and federal lands in order to provide a complete inventory of emissions for this category. See Table 6-113 for the amount of managed land area in *Settlements Remaining Settlements* that is not included in the Inventory due to these omissions. The managed settlements area that is not included in the Inventory is in the range of 150 to 160 thousand hectares each year. These improvements will be made as funding and resources are available to expand the inventory for this source category.

Table 6-113: Area of Managed Land in *Settlements Remaining Settlements* that is not included in the current Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	SRS Managed Land Area (Section 6.1)	SRS Area Included in Inventory	SRS Area Not Included in Inventory
1990	30,585	30,425	159
1991	30,589	30,430	159
1992	30,593	30,434	159
1993	30,505	30,346	159
1994	30,423	30,264	159
1995	30,365	30,206	159
1996	30,316	30,157	158
1997	30,264	30,105	158
1998	30,200	30,041	159

1999	30,144	29,992	152
2000	30,101	29,949	152
2001	30,041	29,889	152
2002	30,034	29,882	152
2003	30,530	30,378	152
2004	31,011	30,859	152
2005	31,522	31,370	152
2006	31,964	31,812	152
2007	32,469	32,317	152
2008	33,074	32,922	152
2009	33,646	33,494	152
2010	34,221	34,069	152
2011	34,814	34,662	152
2012	35,367	35,215	152
2013	36,308	36,156	152
2014	37,281	37,129	152
2015	38,210	38,058	152
2016	ND	ND	ND
2017	ND	ND	ND
2018	ND	ND	ND
2019	ND	ND	ND
2020	ND	ND	ND

Note: NRI data are not available after 2015, and these years are designated as ND (No data).

Changes in Carbon Stocks in Settlement Trees (CRF Source Category 4E1)

Settlements are land uses where human populations and activities are concentrated. In these areas, the anthropogenic impacts on tree growth, stocking and mortality are particularly pronounced (Nowak 2012) in comparison to forest lands where non-anthropogenic forces can have more significant impacts. Trees in settlement areas of the United States are estimated to account for an average annual net sequestration of 116.3 MMT CO_2 Eq. (31.7 MMT C) over the period from 1990 through 2020. Net C sequestration from settlement trees in 2020 is estimated to be 129.8 MMT CO_2 Eq. (35.4 MMT C) (Table 6-114). Dominant factors affecting carbon flux trends for settlement trees are changes in the amount of settlement area (increasing sequestration due to more land and trees) and net changes in tree cover (e.g., tree losses vs tree gains through planting and natural regeneration), with percent tree cover trending downward recently. In addition, changes in species composition, tree sizes and tree densities affect base C flux estimates. Annual sequestration increased by 35 percent between 1990 and 2020 due to increases in settlement area and changes in tree cover.

Trees in settlements often grow faster than forest trees because of their relatively open structure (Nowak and Crane 2002). Because tree density in settlements is typically much lower than in forested areas, the C storage per hectare of land is in fact smaller for settlement areas than for forest areas. Also, percent tree cover in settlement areas are less than in forests and this tree cover varies significantly across the United States (e.g., Nowak and Greenfield 2018a). To quantify the C stored in settlement trees, the methodology used here requires analysis per unit area of tree cover, rather than per unit of total land area (as is done for *Forest Lands).*

Table 6-114: Net Flux from Trees in *Settlements Remaining Settlements* (MMT CO_2 Eq. and MMT C)[a]

Year	MMT CO_2 Eq.	MMT C
1990	(96.4)	(26.3)
2005	(117.4)	(32.0)

2016	(129.8)	(35.4)
2017	(129.8)	(35.4)
2018	(129.8)	(35.4)
2019	(129.8)	(35.4)
2020	(129.8)	(35.4)

[a] These estimates include net CO_2 and C flux from trees on *Settlements Remaining Settlements* and Land Converted to Settlements as it is not possible to report on these separately at this time.

Note: Parentheses indicate net sequestration.

Methodology and Time-Series Consistency

To estimate net carbon sequestration in settlement areas, three types of data are required for each state:

1. Settlement area
2. Percent tree cover in settlement areas
3. Carbon sequestration density per unit of tree cover

Settlement Area

Settlements area is defined in Section 6.1 Representation of the U.S. Land Base as a land-use category representing developed areas. The data used to estimate settlement area within Section 6.1 comes from the NRI as updated through 2015 with the extension of the time series through 2018 based on assuming the settlements area is the same as 2015, while harmonizing these data with the FIA dataset, which are available through 2018, and the NLCD dataset, which is available through 2016. Settlement areas for 2020 are held constant with the 2018 values. This process of combining the datasets extends the time series to ensure that there is a complete and consistent representation of land use data for all source categories in the LULUCF sector. Annual estimates of CO_2 flux (Table 6-114) were developed based on estimates of annual settlement area and tree cover derived from NLCD developed lands. Developed land, which was used to estimate tree cover in settlement areas, is about six percent higher than the area categorized as *Settlements* in the Representation of the U.S. Land Base developed for this report.

Percent Tree Cover in Settlement Areas

Percent tree cover in settlement area by state is needed to convert settlement land area to settlement tree cover area. Converting to tree cover area is essential as tree cover, and thus carbon estimates, can vary widely among states in settlement areas due to variations in the amount of tree cover (e.g., Nowak and Greenfield 2018a). However, since the specific geography of settlement area is unknown because they are based on NRI sampling methods, NLCD developed land was used to estimate the percent tree cover to be used in settlement areas. NLCD developed classes 21-24 (developed, open space (21), low intensity (22), medium intensity (23), and high intensity (24)) were used to estimate percent tree cover in settlement area by state (U.S. Department of Interior 2018; MRLC 2013).

a) “Developed, Open Space – areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20 percent of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.” Plots designated as either park, recreation, cemetery, open space, institutional or vacant land were classified as Developed Open Space.

b) “Developed, Low Intensity – areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20 to 49 percent of total cover. These areas most commonly include single-family housing units.” Plots designated as single family or low-density residential land were classified as Developed, Low Intensity.

c) “Developed, Medium Intensity – areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50 to 79 percent of the total cover. These areas most commonly include single-family housing units.” Plots designated as medium density residential, other urban or mixed urban were classified as Developed, Medium Intensity.

d) “Developed High Intensity – highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80 to 100 percent of the total cover.” Plots designated as either commercial, industrial, high density residential, downtown, multi-family residential, shopping, transportation or utility were classified as Developed, High Intensity.

As NLCD is known to underestimate tree cover (Nowak and Greenfield 2010), photo-interpretation of tree cover within NLCD developed lands was conducted for the years of c. 2011 and 2016 using 1,000 random points to determine an average adjustment factor for NLCD tree cover estimates in developed land and determine recent tree cover changes. This photo-interpretation of change followed methods detailed in Nowak and Greenfield (2018b). Percent tree cover (%TC) in settlement areas by state was estimated as:

%TC in state = state NLCD %TC x national photo-interpreted %TC / national NLCD %TC

Percent tree cover in settlement areas by year was set as follows:

- 1990 to 2011: used 2011 NLCD tree cover adjusted with 2011 photo-interpreted values
- 2012 to 2015: used 2011 NLCD tree cover adjusted with photo-interpreted values, which were interpolated from values between 2011 and 2016
- 2016 to 2020: used 2011 NLCD tree cover adjusted with 2016 photo-interpreted values

Carbon Sequestration Density per Unit of Tree Cover

Methods for quantifying settlement tree biomass, C sequestration, and C emissions from tree mortality and decomposition were taken directly from Nowak et al. (2013), Nowak and Crane (2002), and Nowak (1994). In general, net C sequestration estimates followed three steps, each of which is explained further in the paragraphs below. First, field data from cities and urban areas within entire states were used to estimate C in tree biomass from field data on measured tree dimensions. Second, estimates of annual tree growth and biomass increment were generated from published literature and adjusted for tree condition, crown competition, and growing season to generate estimates of gross C sequestration in settlement trees for all 50 states and the District of Columbia. Third, estimates of C emissions due to mortality and decomposition were subtracted from gross C sequestration estimates to obtain estimates of net C sequestration. Carbon storage, gross and net sequestration estimates were standardized per unit tree cover based on tree cover in the study area.

Settlement tree carbon estimates are based on published literature (Nowak et al. 2013; Nowak and Crane 2002; Nowak 1994) as well as newer data from the i-Tree database[107] and Forest Service urban forest inventory data (e.g., Nowak et al. 2016, 2017) (Table 6-115). These data are based on collected field measurements in several U.S. cities between 1989 and 2017. Carbon storage and sequestration in these cities were estimated using the U.S. Forest Service’s i-Tree Eco model (Nowak et al. 2008). This computer model uses standardized field data from randomly located plots, along with local hourly air pollution and meteorological data to quantify urban forest structure, monetary values of the urban forest, and environmental effects, including total C stored and annual C sequestration (Nowak et al. 2013).

In each city, a random sample of plots were measured to assess tree stem diameter, tree height, crown height and crown width, tree location, species, and canopy condition. The data for each tree were used to estimate total dry-weight biomass using allometric models, a root-to-shoot ratio to convert aboveground biomass estimates to whole tree biomass, and wood moisture content. Total dry weight biomass was converted to C by dividing by two (50 percent carbon content). An adjustment factor of 0.8 was used for open grown trees to account for settlement

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[107] See http://www.itreetools.org.

trees having less aboveground biomass for a given stem diameter than predicted by allometric models based on forest trees (Nowak 1994). Carbon storage estimates for deciduous trees include only C stored in wood. Estimated C storage was divided by tree cover in the area to estimate carbon storage per square meter of tree cover.

Table 6-115: Carbon Storage (kg C/m^2 tree cover), Gross and Net Sequestration (kg C/m^2 tree cover/year) and Tree Cover (percent) among Sampled U.S. Cities (see Nowak et al. 2013)

			Sequestration						
City	**Storage**	**SE**	**Gross**	**SE**	**Net**	**SE**	**Ratio[a]**	**Tree Cover**	**SE**
Adrian, MI	12.17	1.88	0.34	0.04	0.13	0.07	0.36	22.1	2.3
Albuquerque, NM	5.61	0.97	0.24	0.03	0.20	0.03	0.82	13.3	1.5
Arlington, TX	6.37	0.73	0.29	0.03	0.26	0.03	0.91	22.5	0.3
Atlanta, GA	6.63	0.54	0.23	0.02	0.18	0.03	0.76	53.9	1.6
Austin, TX	3.57	0.25	0.17	0.01	0.13	0.01	0.73	30.8	1.1
Baltimore, MD	10.30	1.24	0.33	0.04	0.20	0.04	0.59	28.5	1.0
Boise, ID	7.33	2.16	0.26	0.04	0.16	0.06	0.64	7.8	0.2
Boston, MA	7.02	0.96	0.23	0.03	0.17	0.02	0.73	28.9	1.5
Camden, NJ	11.04	6.78	0.32	0.20	0.03	0.10	0.11	16.3	9.9
Casper, WY	6.97	1.50	0.22	0.04	0.12	0.04	0.54	8.9	1.0
Chester, PA	8.83	1.20	0.39	0.04	0.25	0.05	0.64	20.5	1.7
Chicago (region), IL	9.38	0.59	0.38	0.02	0.26	0.02	0.70	15.5	0.3
Chicago, IL	6.03	0.64	0.21	0.02	0.15	0.02	0.70	18.0	1.2
Corvallis, OR	10.68	1.80	0.22	0.03	0.20	0.03	0.91	32.6	4.1
El Paso, TX	3.93	0.86	0.32	0.05	0.23	0.05	0.72	5.9	1.0
Freehold, NJ	11.50	1.78	0.31	0.05	0.20	0.05	0.64	31.2	3.3
Gainesville, FL	6.33	0.99	0.22	0.03	0.16	0.03	0.73	50.6	3.1
Golden, CO	5.88	1.33	0.23	0.05	0.18	0.04	0.79	11.4	1.5
Grand Rapids, MI	9.36	1.36	0.30	0.04	0.20	0.05	0.65	23.8	2.0
Hartford, CT	10.89	1.62	0.33	0.05	0.19	0.05	0.57	26.2	2.0
Houston, TX	4.55	0.48	0.31	0.03	0.25	0.03	0.83	18.4	1.0
Indiana[b]	8.80	2.68	0.29	0.08	0.27	0.07	0.92	20.1	3.2
Jersey City, NJ	4.37	0.88	0.18	0.03	0.13	0.04	0.72	11.5	1.7
Kansas[b]	7.42	1.30	0.28	0.05	0.22	0.04	0.78	14.0	1.6
Kansas City (region), MO/KS	7.79	0.85	0.39	0.04	0.26	0.04	0.67	20.2	1.7
Lake Forest Park, WA	12.76	2.63	0.49	0.07	0.42	0.07	0.87	42.4	0.8
Las Cruces, NM	3.01	0.95	0.31	0.14	0.26	0.14	0.86	2.9	1.0
Lincoln, NE	10.64	1.74	0.41	0.06	0.35	0.06	0.86	14.4	1.6
Los Angeles, CA	4.59	0.51	0.18	0.02	0.11	0.02	0.61	20.6	1.3
Milwaukee, WI	7.26	1.18	0.26	0.03	0.18	0.03	0.68	21.6	1.6
Minneapolis, MN	4.41	0.74	0.16	0.02	0.08	0.05	0.52	34.1	1.6
Moorestown, NJ	9.95	0.93	0.32	0.03	0.24	0.03	0.75	28.0	1.6
Morgantown, WV	9.52	1.16	0.30	0.04	0.23	0.03	0.78	39.6	2.2
Nebraska[b]	6.67	1.86	0.27	0.07	0.23	0.06	0.84	15.0	3.6
New York, NY	6.32	0.75	0.33	0.03	0.25	0.03	0.76	20.9	1.3
North Dakota[b]	7.78	2.47	0.28	0.08	0.13	0.08	0.48	2.7	0.6
Oakland, CA	5.24	0.19	NA	NA	NA	NA	NA	21.0	0.2
Oconomowoc, WI	10.34	4.53	0.25	0.10	0.16	0.06	0.65	25.0	7.9
Omaha, NE	14.14	2.29	0.51	0.08	0.40	0.07	0.78	14.8	1.6
Philadelphia, PA	8.65	1.46	0.33	0.05	0.29	0.05	0.86	20.8	1.8
Phoenix, AZ	3.42	0.50	0.38	0.04	0.35	0.04	0.94	9.9	1.2
Roanoke, VA	9.20	1.33	0.40	0.06	0.27	0.05	0.67	31.7	3.3
Sacramento, CA	7.82	1.57	0.38	0.06	0.33	0.06	0.87	13.2	1.7
San Francisco, CA	9.18	2.25	0.24	0.05	0.22	0.05	0.92	16.0	2.6
Scranton, PA	9.24	1.28	0.40	0.05	0.30	0.04	0.74	22.0	1.9
Seattle, WA	9.59	0.98	0.67	0.06	0.55	0.05	0.82	27.1	0.4

South Dakota[b]	3.14	0.66	0.13	0.03	0.11	0.02	0.87	16.5	2.2
Syracuse, NY	9.48	1.08	0.30	0.03	0.22	0.04	0.72	26.9	1.3
Tennessee[b]	6.47	0.50	0.34	0.02	0.30	0.02	0.89	37.7	0.8
Washington, DC	8.52	1.04	0.26	0.03	0.21	0.03	0.79	35.0	2.0
Woodbridge, NJ	8.19	0.82	0.29	0.03	0.21	0.03	0.73	29.5	1.7

SE (Standard Error)
NA (Not Available)
[a] Ratio of net to gross sequestration
[b] Statewide assessment of urban areas

To determine gross sequestration rates, tree growth rates need to be estimated. Base growth rates were standardized for open-grown trees in areas with 153 days of frost-free length based on measured data on tree growth (Nowak et al. 2013). These growth rates were adjusted to local tree conditions based on length of frost-free season, crown competition (as crown competition increased, growth rates decreased), and tree condition (as tree condition decreased, growth rates decreased). Annual growth rates were applied to each sampled tree to estimate gross annual sequestration – that is, the difference in C storage estimates between year 1 and year (x + 1) represents the gross amount of C sequestered. These annual gross C sequestration rates for each tree were then scaled up to city estimates using tree population information. Total C sequestration was divided by total tree cover to estimate a gross carbon sequestration density (kg C/m^2 of tree cover/year). The area of assessment for each city or state was defined by its political boundaries; parks and other forested urban areas were thus included in sequestration estimates.

Where gross C sequestration accounts for all C sequestered, net C sequestration for settlement trees considers C emissions associated with tree death and removals. The third step in the methodology estimates net C emissions from settlement trees based on estimates of annual mortality, tree condition, and assumptions about whether dead trees were removed from the site. Estimates of annual mortality rates by diameter class and condition class were obtained from a study of street-tree mortality (Nowak 1986). Different decomposition rates were applied to dead trees left standing compared with those removed from the site. For removed trees, different rates were applied to the removed/aboveground biomass in contrast to the belowground biomass (Nowak et al. 2002). The estimated annual gross C emission rates for each plot were then scaled up to city estimates using tree population information.

The full methodology development is described in the underlying literature, and key details and assumptions were made as follows. The allometric models applied to the field data for the Nowak methodology for each tree were taken from the scientific literature (see Nowak 1994, Nowak et al. 2002), but if no allometric model could be found for the particular species, the average result for the genus or botanical relative was used. The adjustment (0.8) to account for less live tree biomass in open-grown urban trees was based on information in Nowak (1994). Measured tree growth rates for street (Frelich 1992; Fleming 1988; Nowak 1994), park (deVries 1987), and forest (Smith and Shifley 1984) trees were standardized to an average length of growing season (153 frost free days) and adjusted for site competition and tree condition. Standardized growth rates of trees of the same species or genus were then compared to determine the average difference between standardized street tree growth and standardized park and forest growth rates. Crown light exposure (CLE) measurements (number of sides and/or top of tree exposed to sunlight) were used to represent forest, park, and open (street) tree growth conditions. Local tree base growth rates were then calculated as the average standardized growth rate for open-grown trees multiplied by the number of frost-free days divided by 153. Growth rates were then adjusted for CLE. The CLE adjusted growth rate was then adjusted based on tree condition to determine the final growth rate. Assumptions for which dead trees would be removed versus left standing were developed specific to each land use and were based on expert judgment of the authors. Decomposition rates were based on literature estimates (Nowak et al. 2013).

Estimates of gross and net sequestration rates for each of the 50 states and the District of Columbia (Table 6-116) were compiled in units of C sequestration per unit area of tree canopy cover. These rates were used in conjunction with estimates of state settlement area and developed land percent tree cover data to calculate each state's annual net C sequestration by urban trees. This method was described in Nowak et al. (2013) and has been modified here to incorporate developed land percent tree cover data.

Net annual C sequestration estimates were obtained for all 50 states and the District of Columbia by multiplying the gross annual emission estimates by 0.73, the average ratio for net/gross sequestration (Table 6-116). However, state specific ratios were used where available.

State Carbon Sequestration Estimates

The gross and net annual C sequestration values for each state were multiplied by each state's settlement area of tree cover, which was the product of the state's settlement area and the state's tree cover percentage based on NLCD developed land. The model used to calculate the total carbon sequestration amounts for each state, can be written as follows:

Equation 6-1: Net State Annual Carbon Sequestration

Net state annual C sequestration (t C/yr) = Gross state sequestration rate (t C/ha/yr) × Net to Gross state sequestration ratio × state settlement Area (ha) × % state tree cover in settlement area

The results for all 50 states and the District of Columbia are given in Table 6-116. This approach is consistent with the default IPCC Gain-Loss methodology in IPCC (2006), although sufficient field data are not yet available to separately determine interannual gains and losses in C stocks in the living biomass of settlement trees. Instead, the methodology applied here uses estimates of net C sequestration based on modeled estimates of decomposition, as given by Nowak et al. (2013).

Table 6-116: Estimated Annual C Sequestration (Metric Tons C/Year), Tree Cover (Percent), and Annual C Sequestration per Area of Tree Cover (kg C/m^2/ year) for settlement areas in United States by State and the District of Columbia (2020)

State	Gross Annual Sequestration	Net Annual Sequestration	Tree Cover	Gross Annual Sequestration per Area of Tree Cover	Net Annual Sequestration per Area of Tree Cover	Net: Gross Annual Sequestration Ratio
Alabama	2,060,001	1,501,070	53.5	0.376	0.274	0.73
Alaska	111,722	81,409	47.4	0.169	0.123	0.73
Arizona	172,750	125,878	4.6	0.388	0.283	0.73
Arkansas	1,266,164	922,622	48.9	0.362	0.264	0.73
California	2,007,869	1,463,083	16.9	0.426	0.311	0.73
Colorado	142,719	103,996	8.0	0.216	0.157	0.73
Connecticut	618,683	450,818	58.7	0.262	0.191	0.73
Delaware	97,533	71,070	24.4	0.366	0.267	0.73
DC	11,995	8,741	25.1	0.366	0.267	0.73
Florida	4,322,610	3,149,776	40.3	0.520	0.379	0.73
Georgia	3,411,478	2,485,857	56.3	0.387	0.282	0.73
Hawaii	285,700	208,182	41.7	0.637	0.464	0.73
Idaho	59,611	43,437	7.4	0.201	0.146	0.73
Illinois	662,891	483,032	15.5	0.310	0.226	0.73
Indiana	472,905	437,275	17.1	0.274	0.254	0.92
Iowa	177,692	129,480	8.6	0.263	0.191	0.73
Kansas	290,461	226,027	10.8	0.310	0.241	0.78
Kentucky	926,269	674,949	36.8	0.313	0.228	0.73
Louisiana	1,512,145	1,101,861	47.0	0.435	0.317	0.73
Maine	394,471	287,441	55.5	0.242	0.176	0.73
Maryland	818,044	596,088	40.1	0.353	0.257	0.73
Massachusetts	1,002,723	730,659	57.2	0.278	0.203	0.73
Michigan	1,343,325	978,847	34.7	0.241	0.175	0.73
Minnesota	313,364	228,340	13.1	0.251	0.183	0.73
Mississippi	1,518,448	1,106,454	57.3	0.377	0.275	0.73
Missouri	850,492	619,732	23.2	0.313	0.228	0.73
Montana	48,911	35,640	4.9	0.201	0.147	0.73
Nebraska	98,584	83,192	7.3	0.261	0.220	0.84

Nevada	41,181	30,008	4.8	0.226	0.165	0.73
New Hampshire	363,989	265,229	59.3	0.238	0.174	0.73
New Jersey	904,868	659,355	40.7	0.321	0.234	0.73
New Mexico	177,561	129,384	10.2	0.288	0.210	0.73
New York	1,531,415	1,115,903	39.9	0.263	0.192	0.73
North Carolina	3,064,797	2,233,239	54.1	0.341	0.249	0.73
North Dakota	18,492	8,787	1.8	0.244	0.116	0.48
Ohio	1,248,841	909,999	28.2	0.271	0.198	0.73
Oklahoma	699,044	509,376	22.1	0.364	0.265	0.73
Oregon	682,468	497,297	39.9	0.265	0.193	0.73
Pennsylvania	1,794,939	1,307,927	40.2	0.267	0.195	0.73
Rhode Island	121,940	88,855	50.0	0.283	0.206	0.73
South Carolina	1,801,029	1,312,364	53.8	0.370	0.269	0.73
South Dakota	29,489	25,573	2.9	0.258	0.224	0.87
Tennessee	1,591,278	1,422,789	41.1	0.332	0.297	0.89
Texas	4,239,494	3,089,211	28.5	0.403	0.294	0.73
Utah	118,880	86,625	11.7	0.235	0.172	0.73
Vermont	176,564	128,658	50.6	0.234	0.170	0.73
Virginia	1,968,537	1,434,422	52.9	0.321	0.234	0.73
Washington	1,063,871	775,216	37.6	0.282	0.206	0.73
West Virginia	699,320	509,577	64.1	0.264	0.192	0.73
Wisconsin	697,863	508,515	25.9	0.246	0.180	0.73
Wyoming	29,984	21,849	4.7	0.199	0.145	0.73
Total	**48,065,406**	**35,405,113**				

Uncertainty

Uncertainty associated with changes in C stocks in settlement trees includes the uncertainty associated with settlement area, percent tree cover in developed land and how well it represents percent tree cover in settlement areas, and estimates of gross and net C sequestration for each of the 50 states and the District of Columbia. A 10 percent uncertainty was associated with settlement area estimates based on expert judgment. Uncertainty associated with estimates of percent settlement tree coverage for each of the 50 states was based on standard error associated with the photo-interpretation of national tree cover in developed lands. Uncertainty associated with estimates of gross and net C sequestration for each of the 50 states and the District of Columbia was based on standard error estimates for each of the state-level sequestration estimates (Table 6-117). These estimates are based on field data collected in each of the 50 states and the District of Columbia, and uncertainty in these estimates increases as they are scaled up to the national level.

Additional uncertainty is associated with the biomass models, conversion factors, and decomposition assumptions used to calculate C sequestration and emission estimates (Nowak et al. 2002). These results also exclude changes in soil C stocks, and there is likely some overlap between the settlement tree C estimates and the forest tree C estimates (e.g., Nowak et al. 2013). Due to data limitations, urban soil flux is not quantified as part of this analysis, while reconciliation of settlement tree and forest tree estimates will be addressed through the land-representation effort described in the Planned Improvements section of this chapter.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate in 2020. The results of this quantitative uncertainty analysis are summarized in Table 6-117. The change in C stocks in *Settlement Trees* in 2020 was estimated to be between -195.4 and -62.2 MMT CO_2 Eq. at a 95 percent confidence level. This analysis indicates a range of 51 percent more sequestration to 52 percent less sequestration than the 2020 flux estimate of -129.8 MMT CO_2 Eq.

Table 6-117: Approach 2 Quantitative Uncertainty Estimates for Net CO_2 Flux from Changes in C Stocks in Settlement Trees (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Changes in C Stocks in Settlement Trees	CO_2	(129.8)	(195.42)	(62.22)	-51%	52%

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation with a 95 percent confidence interval.

Note: Parentheses indicate negative values or net sequestration.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for settlement trees included checking input data, documentation, and calculations to ensure data were properly handled through the inventory process. Errors that were found during this process were corrected as necessary.

Recalculations Discussion

There were no recalculations to the 1990 through 2019 time series in this Inventory.

Planned Improvements

A consistent representation of the managed land base in the United States is discussed in Section 6.1 Representation of the U.S. Land Base, and discusses a planned improvement by the USDA Forest Service to reconcile the overlap between *Settlement Trees* and the forest land categories. Estimates for *Settlement Trees* are based on tree cover in settlement areas. What needs to be determined is how much of this settlement area tree cover might also be accounted for in "forest" area assessments as some of these forests may fall within settlement areas. For example, "forest" as defined by the USDA Forest Service Forest Inventory and Analysis (FIA) program fall within urban areas. Nowak et al. (2013) estimates that 1.5 percent of forest plots measured by the FIA program fall within land designated as Census urban, suggesting that approximately 1.5 percent of the C reported in the Forest source category might also be counted in the urban areas. The potential overlap with settlement areas is unknown. Future research may also enable more complete coverage of changes in the C stock of trees for all settlements land.

To provide more accurate emissions estimates in the future, the following actions will be taken:

a) Photo-interpret settlement tree cover in 2021 to update tree cover estimates and trends
b) Update photo-interpretation for settlement areas using 2016 NLCD developed land information
c) Develop spatially explicit and spatially continuous representations of land to eliminate the overlap between forest and settlement areas, as well as allow for improved estimates in "settlement areas."

N_2O Emissions from Settlement Soils (CRF Source Category 4E1)

Of the synthetic N fertilizers applied to soils in the United States, approximately 1 to 2 percent are currently applied to lawns, golf courses, and other landscaping within settlement areas, and contributes to soil N_2O emissions. The area of settlements is considerably smaller than other land uses that are managed with fertilizer, particularly cropland soils, and therefore, settlements account for a smaller proportion of total synthetic fertilizer application in the United States. In addition to synthetic N fertilizers, a portion of surface applied biosolids (i.e., treated sewage sludge) is used as an organic fertilizer in settlement areas, and drained organic soils (i.e., soils with high organic matter content, known as *Histosols*) also contribute to emissions of soil N_2O.

N additions to soils result in direct and indirect N_2O emissions. Direct emissions occur on-site due to the N additions in the form of synthetic fertilizers and biosolids as well as enhanced mineralization of N in drained organic soils. Indirect emissions result from fertilizer and biosolids N that is transformed and transported to another location in a form other than N_2O (i.e., ammonia [NH_3] and nitrogen oxide [NO_x] volatilization, nitrate [NO_3^-] leaching and runoff), and later converted into N_2O at the off-site location. The indirect emissions are assigned to settlements because the management activity leading to the emissions occurred in settlements.

Total N_2O emissions from soils in *Settlements Remaining Settlements*[108] are 2.5 MMT CO_2 Eq. (8 kt of N_2O) in 2020. There is an overall increase of 23 percent from 1990 to 2020 due to an expanding settlement area leading to more synthetic N fertilizer applications that peaked in the mid-2000s. Inter-annual variability in these emissions is directly attributable to variability in total synthetic fertilizer consumption, area of drained organic soils, and biosolids applications in the United States. Emissions from this source are summarized in Table 6-118.

Table 6-118: N_2O Emissions from Soils in *Settlements Remaining Settlements* (MMT CO_2 Eq. and kt N_2O)

	1990		2005		2016	2017	2018	2019	2020
MMT CO_2 Eq.									
Direct N_2O Emissions from Soils	**1.6**		**2.5**		**1.9**	**2.0**	**2.0**	**2.1**	**2.1**
Synthetic Fertilizers	0.8		1.6		0.9	1.0	1.0	1.1	1.1
Biosolids	0.2		0.2		0.2	0.2	0.2	0.2	0.2
Drained Organic Soils	0.6		0.7		0.8	0.8	0.8	0.8	0.8
Indirect N_2O Emissions from Soils	**0.4**		**0.6**		**0.3**	**0.4**	**0.4**	**0.4**	**0.4**
Total	**2.0**		**3.1**		**2.2**	**2.3**	**2.4**	**2.4**	**2.5**
kt N_2O									
Direct N_2O Emissions from Soils	**6**		**9**		**6**	**7**	**7**	**7**	**7**
Synthetic Fertilizers	3		6		3	3	4	4	4
Biosolids	1		1		1	1	1	1	1
Drained Organic Soils	2		2		3	3	3	3	3
Indirect N_2O Emissions from Soils	**1**		**2**		**1**	**1**	**1**	**1**	**1**
Total	**7**		**10**		**8**	**8**	**8**	**8**	**8**

Note: Totals may not sum due to independent rounding.

Methodology and Time-Series Consistency

For settlement soils, the IPCC Tier 1 approach is used to estimate soil N_2O emissions from synthetic N fertilizer, biosolids additions, and drained organic soils. Estimates of direct N_2O emissions from soils in settlements are based on the amount of N in synthetic commercial fertilizers applied to settlement soils, the amount of N in biosolids applied to non-agricultural land and surface disposal (see Section 7.1—Wastewater Treatment and Discharge for a detailed discussion of the methodology for estimating biosolids available for non-agricultural land application), and the area of drained organic soils within settlements.

Nitrogen applications to settlement soils are estimated using data compiled by the USGS (Brakebill and Gronberg 2017). The USGS estimated on-farm and non-farm fertilizer use is based on sales records at the county level from 1987 through 2012 (Brakebill and Gronberg 2017). Non-farm N fertilizer is assumed to be applied to settlements and forest lands; values for 2013 through 2020 are based on 2012 values adjusted for annual total N fertilizer sales in the United States because there are no activity data on non-farm application after 2012. Settlement application is calculated by subtracting forest application from total non-farm fertilizer use. The total amount of fertilizer N

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[108] Estimates of Soil N_2O for *Settlements Remaining Settlements* include emissions from Land Converted to Settlements because it was not possible to separate the activity data.

applied to settlements is multiplied by the IPCC default emission factor (1 percent) to estimate direct N_2O emissions (IPCC 2006) for 1990 to 2012.

Biosolids applications are derived from national data on biosolids generation, disposition, and N content (see Section 7.2, Wastewater Treatment for further detail). The total amount of N resulting from these sources is multiplied by the IPCC default emission factor for applied N (one percent) to estimate direct N_2O emissions (IPCC 2006) for 1990 to 2020.

The IPCC (2006) Tier 1 method is also used to estimate direct N_2O emissions due to drainage of organic soils in settlements at the national scale. Estimates of the total area of drained organic soils are obtained from the 2015 NRI (USDA-NRCS 2018) using soils data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2011). To estimate annual emissions from 1990 to 2015, the total area is multiplied by the IPCC default emission factor for temperate regions (IPCC 2006). This Inventory does not include soil N_2O emissions from drainage of organic soils in Alaska and federal lands, although this is a planned improvement for a future Inventory.

For indirect emissions, the total N applied from fertilizer and biosolids is multiplied by the IPCC default factors of 10 percent for volatilization and 30 percent for leaching/runoff to calculate the amount of N volatilized and the amount of N leached/runoff. The amount of N volatilized is multiplied by the IPCC default factor of one percent for the portion of volatilized N that is converted to N_2O off-site and the amount of N leached/runoff is multiplied by the IPCC default factor of 0.075 percent for the portion of leached/runoff N that is converted to N_2O off-site. The resulting estimates are summed to obtain total indirect emissions from 1990 to 2015 for fertilizer and from 1990 to 2020 for biosolids.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020 for biosolids. For synthetic fertilizer and drainage of organic soils, the methods described above are applied for 1990 to 2015, and a linear extrapolation method is used to approximate emissions for the remainder of the 2016 to 2020 time series (See Box 6-4 in *Cropland Remaining Cropland*). The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2015 emissions data, and is a standard data splicing method for estimating emissions at the end of a time series if activity data are not available (IPCC 2006). The time series will be recalculated for the years beyond 2015 in a future Inventory with the methods described above for 1990 to 2015. This Inventory does incorporate updated activity data on biosolids application in settlements through 2020.

Uncertainty

The amount of N_2O emitted from settlement soils depends not only on N inputs and area of drained organic soils, but also on a large number of variables that can influence rates of nitrification and denitrification, including organic C availability; rate, application method, and timing of N input; oxygen gas partial pressure; soil moisture content; pH; temperature; and irrigation/watering practices. The effect of the combined interaction of these variables on N_2O emissions is complex and highly uncertain. The IPCC default methodology does not explicitly incorporate any of these variables, except variation in the total amount of fertilizer N and biosolids application, which in turn, leads to uncertainty in the results.

Uncertainties exist in both the fertilizer N and biosolids application rates in addition to the emission factors. Uncertainty in fertilizer N application is assigned a default level of ±50 percent.[109] Uncertainty in the area of drained organic soils is based on the estimated variance from the NRI survey (USDA-NRCS 2018). For 2016 to 2020, there is also additional uncertainty associated with the fit of the linear regression model for the data splicing methods.

For biosolids, there is uncertainty in the amounts of biosolids applied to non-agricultural lands and used in surface disposal. These uncertainties are derived from variability in several factors, including: (1) N content of biosolids; (2) total sludge applied in 2000; (3) wastewater existing flow in 1996 and 2000; and (4) the biosolids disposal practice

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[109] No uncertainty is provided with the USGS fertilizer consumption data (Brakebill and Gronberg 2017) so a conservative ±50 percent is used in the analysis. Biosolids data are also assumed to have an uncertainty of ±50 percent.

distributions to non-agricultural land application and surface disposal. In addition, there is uncertainty in the direct and indirect emission factors that are provided by IPCC (2006).

Uncertainty is propagated through the calculations of N_2O emissions from fertilizer N and drainage of organic soils based on a Monte Carlo analysis. The results are combined with the uncertainty in N_2O emissions from the biosolids application using simple error propagation methods (IPCC 2006). The results are summarized in Table 6-119. Direct N_2O emissions from soils in *Settlements Remaining Settlements* in 2020 are estimated to be between 1.3 and 2.5 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 38 percent below to 22 percent above the 2020 emission estimate of 2.1 MMT CO_2 Eq. Indirect N_2O emissions in 2020 are between 0.2 and 0.5 MMT CO_2 Eq., ranging from 38 percent below to 38 percent above the estimate of 0.4 MMT CO_2 Eq.

Table 6-119: Quantitative Uncertainty Estimates of N_2O Emissions from Soils in *Settlements Remaining Settlements* (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Emissions (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
Settlements Remaining Settlements			**Lower Bound**	**Upper Bound**	**Lower Bound**	**Upper Bound**
Direct N_2O Emissions from Soils	N_2O	2.1	1.3	2.5	-38%	22%
Indirect N_2O Emissions from Soils	N_2O	0.4	0.2	0.5	-38%	38%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Note: These estimates include direct and indirect N_2O emissions from *Settlements Remaining Settlements* and Land Converted to Settlements because it was not possible to separate the activity data.

QA/QC and Verification

The spreadsheet containing fertilizer, drainage of organic soils, and biosolids applied to settlements and calculations for N_2O and uncertainty ranges have been checked. An error was found in the uncertainty calculation that was corrected.

Recalculations Discussion

Recalculations are associated with updated estimates for 2019 using the linear extrapolation method. As a result, N_2O Emissions from Settlement Soils has a smaller emission of 0.04 MMT CO_2 Eq. in 2019. This represents less than 1 percent decrease in emissions compared to the previous Inventory.

Planned Improvements

This source will be extended to include soil N_2O emissions from drainage of organic soils in settlements of Alaska and federal lands in order to provide a complete inventory of emissions for this category. Data on fertilizer amount and area of drained organic soils will be compiled to update emissions estimates from 2016 to 2020 in a future Inventory.

Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (CRF Category 4E1)

In the United States, yard trimmings (i.e., grass clippings, leaves, and branches) and food scraps account for a significant portion of the municipal waste stream, and a large fraction of the collected yard trimmings and food scraps are put in landfills. Carbon (C) contained in landfilled yard trimmings and food scraps can be stored for very long periods.

Carbon storage estimates within the Inventory are associated with particular land uses. For example, harvested wood products are reported under *Forest Land Remaining Forest Land* because these wood products originated from the forest ecosystem. Similarly, C stock changes in yard trimmings and food scraps are reported under *Settlements Remaining Settlements* because the bulk of the C, which comes from yard trimmings, originates from settlement areas. While the majority of food scraps originate from cropland and grassland, in this Inventory they are reported with the yard trimmings in the *Settlements Remaining Settlements* section. Additionally, landfills are considered part of the managed land base under settlements (see Section 6.1 Representation of the U.S. Land Base), and reporting these C stock changes that occur entirely within landfills fits most appropriately within the *Settlements Remaining Settlements* section.

Both the estimated amount of yard trimmings collected annually and the fraction that is landfilled have been declining. In 1990, over 53 million metric tons (wet weight) of yard trimmings and food scraps are estimated to have been generated (i.e., put at the curb for collection to be taken to disposal sites or to composting facilities) (EPA 2020). Since then, programs banning or discouraging yard trimmings disposal have led to an increase in backyard composting and the use of mulching mowers, and a consequent estimated 1.1 percent increase between 1990 and 2020 in the tonnage of yard trimmings generated (i.e., collected for composting or disposal in landfills) per year. At the same time, an increase in the number of municipal composting facilities has reduced the proportion of collected yard trimmings that are discarded in landfills per year—from 72 percent in 1990 to 30 percent in 2020. The net effect of the slight increase in generation and the increase in composting is a 58 percent decrease in the quantity of yard trimmings disposed of in landfills since 1990.

Food scrap generation has grown by an estimated 165 percent since 1990, and while the proportion of total food scraps generated that are eventually discarded in landfills has decreased, from an estimated 82 percent in 1990 to 55 percent in 2020, the tonnage disposed of in landfills has increased considerably (by an estimated 78 percent) due to the increase in food scrap generation. Although the total tonnage of food scraps disposed of in landfills has increased from 1990 to 2020, the difference in the amount of food scraps added from one year to the next generally decreased, and consequently the annual carbon stock *net changes* from food scraps have generally decreased as well (as shown in Table 6-120 and Table 6-121). As described in the Methodology section, the carbon stocks are modeled using data on the amount of food scraps landfilled since 1960. These food scraps decompose over time, producing CH_4 and CO_2. Decomposition happens at a higher rate initially, then decreases. As decomposition decreases, the carbon stock becomes more stable. Because the cumulative carbon stock left in the landfill from previous years is (1) not decomposing as much as the carbon introduced from food scraps in a single more recent year; and (2) is much larger than the carbon introduced from food scraps in a single more recent year, the total carbon stock in the landfill is primarily driven by the more stable "older" carbon stock, thus resulting in less annual change in later years.

Overall, the decrease in the landfill disposal rate of yard trimmings has more than compensated for the increase in food scrap disposal in landfills, and the net result is a decrease in annual *net change* landfill C storage from 24.5 MMT CO_2 Eq. (6.7 MMT C) in 1990 to 12.2 MMT CO_2 Eq. (3.3 MMT C) in 2020 (Table 6-120 and Table 6-121), a decrease of 50 percent over the time series.

Table 6-120: Net Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (MMT CO_2 Eq.)

Carbon Pool	1990	2005	2016	2017	2018	2019	2020
Yard Trimmings	**(20.1)**	**(7.5)**	**(6.3)**	**(8.3)**	**(8.3)**	**(8.2)**	**(8.1)**
Grass	(1.7)	(0.6)	(0.5)	(0.8)	(0.8)	(0.8)	(0.7)
Leaves	(8.7)	(3.4)	(3.0)	(3.8)	(3.8)	(3.8)	(3.7)
Branches	(9.8)	(3.4)	(2.8)	(3.7)	(3.7)	(3.7)	(3.6)
Food Scraps	**(4.4)**	**(3.9)**	**(3.7)**	**(5.6)**	**(5.2)**	**(4.8)**	**(4.1)**
Total Net Flux	**(24.5)**	**(11.4)**	**(10.0)**	**(13.8)**	**(13.4)**	**(13.1)**	**(12.2)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Table 6-121: Net Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (MMT C)

Carbon Pool	1990	2005	2016	2017	2018	2019	2020
Yard Trimmings	**(5.5)**	**(2.0)**	**(1.7)**	**(2.3)**	**(2.3)**	**(2.2)**	**(2.2)**
Grass	(0.5)	(0.2)	(0.1)	(0.2)	(0.2)	(0.2)	(0.2)
Leaves	(2.4)	(0.9)	(0.8)	(1.0)	(1.0)	(1.0)	(1.0)
Branches	(2.7)	(0.9)	(0.8)	(1.0)	(1.0)	(1.0)	(1.0)
Food Scraps	**(1.2)**	**(1.1)**	**(1.0)**	**(1.5)**	**(1.4)**	**(1.3)**	**(1.1)**
Total Net Flux	**(6.7)**	**(3.1)**	**(2.7)**	**(3.8)**	**(3.7)**	**(3.6)**	**(3.3)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net sequestration.

Methodology and Time-Series Consistency

When wastes of biogenic origin (such as yard trimmings and food scraps) are landfilled and do not completely decompose, the C that remains is effectively removed from the C cycle. Empirical evidence indicates that yard trimmings and food scraps do not completely decompose in landfills (Barlaz 1998, 2005, 2008; De la Cruz and Barlaz 2010), and thus the stock of C in landfills can increase, with the net effect being a net atmospheric removal of C. Estimates of net C flux resulting from landfilled yard trimmings and food scraps were developed by estimating the change in landfilled C stocks between inventory years and are based on methodologies presented for the *Land Use, Land-Use Change, and Forestry* sector in IPCC (2003) and the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). Carbon stock estimates were calculated by determining the mass of landfilled C resulting from yard trimmings and food scraps discarded in a given year; adding the accumulated landfilled C from previous years; and subtracting the mass of C that was landfilled in previous years and has since decomposed and been emitted as CO_2 and CH_4.

To determine the total landfilled C stocks for a given year, the following data and factors were assembled:

(1) The composition of the yard trimmings;

(2) The mass of yard trimmings and food scraps discarded in landfills;

(3) The C storage factor of the landfilled yard trimmings and food scraps; and

(4) The rate of decomposition of the degradable C.

The composition of yard trimmings was assumed to be 30 percent grass clippings, 40 percent leaves, and 30 percent branches on a wet weight basis (Oshins and Block 2000). The yard trimmings were subdivided, because each component has its own unique adjusted C storage factor (i.e., moisture content and C content) and rate of decomposition. The mass of yard trimmings and food scraps disposed of in landfills was estimated by multiplying the quantity of yard trimmings and food scraps discarded by the proportion of discards managed in landfills. Data on discards (i.e., the amount generated minus the amount diverted to centralized composting facilities) for both yard trimmings and food scraps were taken primarily from *Advancing Sustainable Materials Management: Facts and Figures 2018* (EPA 2020), which provides data for 1960, 1970, 1980, 1990, 2000, 2005, 2010, 2015, 2017 and 2018. To provide data for some of the missing years, detailed backup data were obtained from the 2012, 2013, and 2014, 2015, and 2017 versions of the *Advancing Sustainable Materials Management: Facts and Figures* reports (EPA 2019), as well as historical data tables that EPA developed for 1960 through 2012 (EPA 2016). Remaining years in the time series for which data were not provided were estimated using linear interpolation. Since the *Advancing Sustainable Materials Management: Facts and Figures* reports for 2019 and 2020 were unavailable, landfilled material generation, recovery, and disposal data for 2019 and 2020 were proxied equal to 2018 values.

The amount of C disposed of in landfills each year, starting in 1960, was estimated by converting the discarded landfilled yard trimmings and food scraps from a wet weight to a dry weight basis, and then multiplying by the initial (i.e., pre-decomposition) C content (as a fraction of dry weight). The dry weight of landfilled material was calculated using dry weight to wet weight ratios (Tchobanoglous et al. 1993, cited by Barlaz 1998) and the initial C contents and the C storage factors were determined by Barlaz (1998, 2005, 2008) (Table 6-122).

The amount of C remaining in the landfill for each subsequent year was tracked based on a simple model of C fate. As demonstrated by Barlaz (1998, 2005, 2008), a portion of the initial C resists decomposition and is essentially persistent in the landfill environment. Barlaz (1998, 2005, 2008) conducted a series of experiments designed to measure biodegradation of yard trimmings, food scraps, and other materials, in conditions designed to promote decomposition (i.e., by providing ample moisture and nutrients). After measuring the initial C content, the materials were placed in sealed containers along with methanogenic microbes from a landfill. Once decomposition was complete, the yard trimmings and food scraps were re-analyzed for C content; the C remaining in the solid sample can be expressed as a proportion of the initial C (shown in the row labeled "C Storage Factor, Proportion of Initial C Stored (%)" in Table 6-122).

The modeling approach applied to simulate U.S. landfill C flows builds on the findings of Barlaz (1998, 2005, 2008). The proportion of C stored is assumed to persist in landfills. The remaining portion is assumed to degrade over time, resulting in emissions of CH_4 and CO_2. (The CH_4 emissions resulting from decomposition of yard trimmings and food scraps are reported in the *Waste* chapter.) The degradable portion of the C is assumed to decay according to first-order kinetics. The decay rates for each of the materials are shown in Table 6-122.

The first-order decay rates, *k*, for each waste component are derived from De la Cruz and Barlaz (2010):

- De la Cruz and Barlaz (2010) calculate first-order decay rates using laboratory data published in Eleazer et al. (1997), and a correction factor, *f*, is calculated so that the weighted average decay rate for all components is equal to the EPA AP-42 default decay rate (0.04) for mixed MSW for regions that receive more than 25 inches of rain annually (EPA 1995). Because AP-42 values were developed using landfill data from approximately 1990, De la Cruz and Barlaz used 1990 waste composition for the United States from EPA's *Characterization of Municipal Solid Waste in the United States: 1990 Update* (EPA 1991) to calculate *f*. De la Cruz and Barlaz multiplied this correction factor by the Eleazer et al. (1997) decay rates of each waste component to develop field-scale first-order decay rates.
- De la Cruz and Barlaz (2010) also use other assumed initial decay rates for mixed MSW in place of the AP-42 default value based on different types of environments in which landfills in the United States are located, including dry conditions (less than 25 inches of rain annually, *k*=0.02) and bioreactor landfill conditions (moisture is controlled for rapid decomposition, *k*=0.12).

Similar to the methodology in the Landfills section of the Inventory (Section 7.1), which estimates CH_4 emissions, the overall MSW decay rate is estimated by partitioning the U.S. landfill population into three categories based on annual precipitation ranges of: (1) Less than 20 inches of rain per year, (2) 20 to 40 inches of rain per year, and (3) greater than 40 inches of rain per year. These correspond to overall MSW decay rates of 0.020, 0.038, and 0.057 year^{-1}, respectively. De la Cruz and Barlaz (2010) calculate component-specific decay rates corresponding to the first value (0.020 year^{-1}), but not for the other two overall MSW decay rates.

To maintain consistency between landfill methodologies across the Inventory, EPA developed correction factors (*f*) for decay rates of 0.038 and 0.057 year^{-1} through linear interpolation. A weighted national average component-specific decay rate is calculated by assuming that waste generation is proportional to population (the same assumption used in the landfill methane emission estimate), based on population data from the 2000 U.S. Census. The percent of census population is calculated for each of the three categories of annual precipitation (noted in the previous paragraph); the population data are used as a surrogate for the number of landfills in each annual precipitation category. Precipitation range percentages weighted by population are updated over time as new Census data are available, to remain consistent with percentages used in Section 7.1. The component-specific decay rates are shown in Table 6-122.

De la Cruz and Barlaz (2010) also use other assumed initial decay rates for mixed MSW in place of the AP-42 default value based on different types of environments in which landfills in the United States are located, including dry conditions (less than 25 inches of rain annually, *k*=0.02) and bioreactor landfill conditions (moisture is controlled for rapid decomposition, *k*=0.12).

For each of the four materials (grass, leaves, branches, food scraps), the stock of C in landfills for any given year is calculated according to Equation 6-2:

Equation 6-2: Total C Stock for Yard Trimmings and Food Scraps in Landfills

$$LFC_{i,t} = \sum_{n}^{t} W_{i,n} \times (1 - MC_i) \times ICC_i \times \{[CS_i \times ICC_i] + [(1 - (CS_i \times ICC_i)) \times e^{-k(t-n)}]\}$$

where,

t = Year for which C stocks are being estimated (year),
i = Waste type for which C stocks are being estimated (grass, leaves, branches, food scraps),
$LFC_{i,t}$ = Stock of C in landfills in year *t*, for waste *i* (metric tons),
$W_{i,n}$ = Mass of waste *i* disposed of in landfills in year *n* (metric tons, wet weight),
n = Year in which the waste was disposed of (year, where $1960 < n < t$),
MC_i = Moisture content of waste *i* (percent of water),
CS_i = Proportion of initial C that is stored for waste *i* (percent),
ICC_i = Initial C content of waste *i* (percent),
e = Natural logarithm, and
k = First-order decay rate for waste *i*, ($year^{-1}$).

For a given year *t*, the total stock of C in landfills ($TLFC_t$) is the sum of stocks across all four materials (grass, leaves, branches, food scraps). The annual flux of C in landfills (F_t) for year *t* is calculated in as the change in C stock compared to the preceding year according to Equation 6-3:

Equation 6-3: C Stock Annual Flux for Yard Trimmings and Food Scraps in Landfills

$$F_t = TLFC_t - TLFC_{(t-1)}$$

Thus, as seen in Equation 1, the C placed in a landfill in year *n* is tracked for each year *t* through the end of the inventory period. For example, disposal of food scraps in 1960 resulted in depositing about 1,135,000 metric tons of C in landfills. Of this amount, 16 percent (179,000 metric tons) is persistent; the remaining 84 percent (956,000 metric tons) is degradable. By 1965, more than half of the degradable portion (507,000 metric tons) decomposes, leaving a total of 628,000 metric tons (the persistent portion, plus the remainder of the degradable portion).

Continuing the example, by 2020, the total food scraps C originally disposed of in 1960 had declined to 179,000 metric tons (i.e., virtually all degradable C had decomposed). By summing the C remaining from 1960 with the C remaining from food scraps disposed of in subsequent years (1961 through 2020), the total landfill C from food scraps in 2020 was 49.6 million metric tons. This value is then added to the C stock from grass, leaves, and branches to calculate the total landfill C stock in 2019, yielding a value of 285.7 million metric tons (as shown in Table 6-123). In the same way total net flux is calculated for forest C and harvested wood products, the total net flux of landfill C for yard trimmings and food scraps for a given year (Table 6-121) is the difference in the landfill C stock for the following year (2021 C stock was forecast using 1990 to 2020 C stocks) and the stock in the current year. For example, the net change in 2020 shown in Table 6-121 (2.9 MMT C) is equal to the stock in 2021 (288.7 MMT C) minus the stock in 2020 (285.7 MMT C). The C stocks calculated through this procedure are shown in Table 6-123.

Table 6-122: Moisture Contents, C Storage Factors (Proportions of Initial C Sequestered), Initial C Contents, and Decay Rates for Yard Trimmings and Food Scraps in Landfills

Variable	Yard Trimmings			Food Scraps
	Grass	Leaves	Branches	
Moisture Content (% H_2O)	70	30	10	70
C Storage Factor, Proportion of Initial C Stored (%)	53	85	77	16
Initial C Content (%)	45	46	49	51
Decay Rate ($year^{-1}$)	0.313	0.179	0.015	0.151

Note: The decay rates are presented as weighted averages based on annual precipitation categories and population residing in each precipitation category.

Table 6-123: C Stocks in Yard Trimmings and Food Scraps in Landfills (MMT C)

Carbon Pool	1990	2005	2016	2017	2018	2019	2020	2021[a]
Yard Trimmings	**156.0**	**203.1**	**227.7**	**229.4**	**231.6**	**233.9**	**236.1**	**238.3**
Branches	14.6	18.1	20.3	20.5	20.7	20.9	21.1	21.3
Leaves	66.7	87.4	98.6	99.4	100.4	101.5	102.5	103.5
Grass	74.7	97.7	108.7	109.5	110.5	111.5	112.5	113.5
Food Scraps	**17.9**	**33.2**	**44.4**	**45.4**	**46.9**	**48.3**	**49.6**	**50.7**
Total Carbon Stocks	**173.9**	**236.3**	**272.0**	**274.8**	**278.5**	**282.2**	**285.7**	**289.1**

[a] 2021 C stock estimate was forecasted using 1990 to 2020 data.

Note: Totals may not sum due to independent rounding.

To develop the 2021 C stock estimate, estimates of yard trimming and food scrap carbon stocks were forecasted for 2021, based on data from 1990 through 2020. These forecasted values were used to calculate net changes in carbon stocks for 2020. Excel's FORECAST.ETS function was used to predict a 2021 value using historical data via an algorithm called "Exponential Triple Smoothing." This method determined the overall trend and provided appropriate carbon stock estimates for 2021.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2020. The same data source was used for the analysis, when available. When data were unavailable, missing values were estimated using linear interpolation or forecasting, as noted above.

Uncertainty

The uncertainty analysis for landfilled yard trimmings and food scraps includes an evaluation of the effects of uncertainty for the following data and factors: disposal in landfills per year (tons of C), initial C content, moisture content, decay rate, and proportion of C stored. The C storage landfill estimates are also a function of the composition of the yard trimmings (i.e., the proportions of grass, leaves and branches in the yard trimmings mixture). There are respective uncertainties associated with each of these factors.

A Monte Carlo (Approach 2) uncertainty analysis was applied to estimate the overall uncertainty of the sequestration estimate for 2020. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-124. Total yard trimmings and food scraps CO_2 flux in 2020 was estimated to be between -20.5 and -5.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 68 percent below to 56 percent above the 2020 flux estimate of -12.2 MMT CO_2 Eq.

Table 6-124: Approach 2 Quantitative Uncertainty Estimates for CO_2 Flux from Yard Trimmings and Food Scraps in Landfills (MMT CO_2 Eq. and Percent)

Source	Gas	2020 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a]			
			(MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Yard Trimmings and Food Scraps	CO_2	(12.2)	(20.5)	(5.4)	-68%	56%

[a] Range of flux estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Note: Parentheses indicate negative values or net C sequestration.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Source-specific quality control measures for *Landfilled Yard Trimmings and Food Scraps* included checking that input data were properly transposed within the spreadsheet, checking calculations were correct, and confirming that all activity data and calculations documentation was complete and updated to ensure data were properly handled through the inventory process.

Order of magnitude checks and checks of time-series consistency were performed to ensure data were updated correctly and any changes in emissions estimates were reasonable and reflected changes in activity data. An annual change trend analysis was also conducted to ensure the validity of the emissions estimates. Errors that were found during this process were corrected as necessary.

Recalculations Discussion

The current Inventory has been revised to reflect updated data from the most recent *Advancing Sustainable Materials Management: Facts and Figures* report. Recalculations based on these updates resulted in 2.8 percent change in the annual carbon stocks and sequestration values as compared to the previous inventory values. The largest changes occurred in the most recent years: a 3 percent increase in sequestration in 2016, a 40.3 percent increase in sequestration in 2017, a 37.5 percent increase in sequestration in 2018, and a 28.6 percent increase in sequestration in 2019. Large changes in yard trimmings can be attributed to updates to 2017 and 2018 yard trimmings and food scraps landfilled values reported in *Advancing Sustainable Materials Management: Facts and Figures 2018* (EPA 2020). A large increase in sequestration in 2019 can be attributed to updated generation values as well – 2019 landfill data were unavailable and were reported as 2018 values.

The bulk of the increase in sequestration is attributed to a change in food scrap measurement methodology in the *Advancing Sustainable Materials Management: Facts and Figures 2018* (EPA 2020). The revised methodology more fully captures flows of recovery of excess food and food waste for 2018 data. The 2018 food scraps recovery estimates include nine management pathways, three of which previously existed in the report (composting, combustion with energy recovery, and landfilling). The six new management pathways are:

- Animal feed
- Bio-based materials/biochemical processing
- Land application
- Donation
- Codigestion/anaerobic digestion
- Sewer/wastewater treatment

Food scrap generation estimates increased over 50 percent between 2017 and 2018, from 40.7 million tons to 63.1 million tons, due to the change in food generation measurement. Food scrap recovery estimates increased by nearly 800 percent (from 2,570 thousand tons in 2017 to 20,300 tons in 2018). Data on the six management pathways from 1990 to 2017 were not available.

Planned Improvements

EPA plans to evaluated data from recent peer-reviewed literature that may modify the default C storage factors, initial C contents, and decay rates for yard trimmings and food scraps in landfills. Based upon this evaluation, changes may be made to the default values.

EPA also plans to investigate updates to the decay rate estimates for food scraps, leaves, grass, and branches, as well as evaluate using decay rates that vary over time based on Census data changes over time. Currently the inventory calculations use 2010 U.S. Census data.

Other improvements include investigation into yard waste composition to determine if changes need to be made based on changes in residential practices, a review of available literature will be conducted to determine if there are changes in the allocation of yard trimmings. For example, leaving grass clippings in place is becoming a more common practice, thus reducing the percentage of grass clippings in yard trimmings disposed in landfills. In addition, agronomists may be consulted for determining the mass of grass per acre on residential lawns to provide an estimate of total grass generation for comparison with Inventory estimates.

Six new food waste management pathways were introduced in the 2018 *Advancing Sustainable Materials Management* report. Time series data all of these pathways are not provided prior to 2018 but EPA plans to investigate potential data sources and/or methods to apply data for the remaining time series.

Finally, EPA plans to review available data to ensure all types of landfilled yard trimmings and food scraps are being included in Inventory estimates, such as debris from road construction and commercial food waste not included in other chapter estimates.

6.11 Land Converted to Settlements (CRF Category 4E2)

Land Converted to Settlements includes all settlements in an Inventory year that had been in another land use(s) during the previous 20 years (USDA-NRCS 2015).[110] For example, cropland, grassland or forest land converted to settlements during the past 20 years would be reported in this category. Converted lands are retained in this category for 20 years as recommended by IPCC (2006). This Inventory includes all settlements in the conterminous United States and Hawaii, but does not include settlements in Alaska. Areas of drained organic soils on settlements in federal lands are also not included in this Inventory. Consequently, there is a discrepancy between the total amount of managed area for Land Converted to Settlements (see Section 6.1 Representation of the U.S. Land Base) and the settlements area included in the Inventory analysis.

Land use change can lead to large losses of carbon (C) to the atmosphere, particularly conversions from forest land (Houghton et al. 1983). Moreover, conversion of forest to another land use (i.e., deforestation) is one of the largest anthropogenic sources of emissions to the atmosphere globally (Schimel 1995), although this source may be declining globally according to a recent assessment (Tubiello et al. 2015).

IPCC (2006) recommends reporting changes in biomass, dead organic matter, and soil organic C stocks due to land use change. All soil organic C stock changes are estimated and reported for Land Converted to Settlements, but there is limited reporting of other pools in this Inventory. Loss of aboveground and belowground biomass, dead wood and litter C are reported for Forest Land Converted to Settlements, but not for other land use conversions to settlements.

Forest Land Converted to Settlements is the largest source of emissions from 1990 to 2020, accounting for approximately 75 percent of the average total loss of C among all of the land use conversions in Land Converted to Settlements. Losses of aboveground and belowground biomass, dead wood and litter C losses in 2020 are 36.7, 7.0, 6.4, and 9.3 MMT CO_2 Eq., respectively (10.0, 1.9, 1.7, and 2.5 MMT C). Mineral and organic soils also lost 16.2 and 2.4 MMT CO_2 Eq. in 2020 (4.4 and 0.6 MMT C). The total net flux is 77.9 MMT CO_2 Eq. in 2020 (21.2 MMT C), which is a 28 percent increase in CO_2 emissions compared to the emissions in the initial reporting year of 1990 (Table 6-125 and Table 6-126). The main driver of net emissions for this source category is the conversion of forest land to settlements, with large losses of biomass, deadwood and litter C.

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[110] NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 2001. This may have led to an underestimation of Land Converted to Settlements in the early part of the time series to the extent that some areas are converted to settlements from 1971 to 1978.

Table 6-125: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes for Land Converted to Settlements (MMT CO_2 Eq.)

	1990	2005	2016	2017	2018	2019	2020
Cropland Converted to Settlements	**3.4**	**9.8**	**6.0**	**6.0**	**5.9**	**5.9**	**5.9**
Mineral Soils	2.8	8.4	5.2	5.2	5.2	5.1	5.1
Organic Soils	0.6	1.3	0.8	0.8	0.8	0.8	0.8
Forest Land Converted to Settlements	**52.6**	**57.7**	**61.3**	**61.5**	**61.6**	**61.6**	**61.5**
Aboveground Live Biomass	31.7	34.2	36.5	36.6	36.7	36.7	36.7
Belowground Live Biomass	6.1	6.5	7.0	7.0	7.0	7.0	7.0
Dead Wood	5.5	5.9	6.4	6.4	6.4	6.4	6.4
Litter	8.0	8.7	9.3	9.3	9.3	9.3	9.3
Mineral Soils	1.1	2.0	1.9	1.9	1.9	1.9	1.9
Organic Soils	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Grassland Converted to Settlements	**5.2**	**16.3**	**11.3**	**11.3**	**11.3**	**11.3**	**11.2**
Mineral Soils	4.6	14.9	10.4	10.4	10.4	10.4	10.3
Organic Soils	0.6	1.4	0.9	0.9	0.9	0.9	0.9
Other Lands Converted to Settlements	**(0.4)**	**(1.4)**	**(1.2)**	**(1.2)**	**(1.2)**	**(1.2)**	**(1.2)**
Mineral Soils	(0.4)	(1.6)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)
Organic Soils	+	0.2	0.1	0.1	0.1	0.1	0.1
Wetlands Converted to Settlements	**+**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.3**
Mineral Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Organic Soils	+	0.4	0.3	0.3	0.3	0.3	0.3
Total Aboveground Biomass Flux	**31.7**	**34.2**	**36.5**	**36.6**	**36.7**	**36.7**	**36.7**
Total Belowground Biomass Flux	**6.1**	**6.5**	**7.0**	**7.0**	**7.0**	**7.0**	**7.0**
Total Dead Wood Flux	**5.5**	**5.9**	**6.4**	**6.4**	**6.4**	**6.4**	**6.4**
Total Litter Flux	**8.0**	**8.7**	**9.3**	**9.3**	**9.3**	**9.3**	**9.3**
Total Mineral Soil Flux	**8.1**	**23.8**	**16.3**	**16.2**	**16.2**	**16.2**	**16.2**
Total Organic Soil Flux	**1.4**	**3.6**	**2.4**	**2.4**	**2.4**	**2.4**	**2.4**
Total Net Flux	**60.8**	**82.8**	**77.8**	**77.9**	**78.0**	**77.9**	**77.9**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Table 6-126: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass C Stock Changes for Land Converted to Settlements (MMT C)

	1990	2005	2016	2017	2018	2019	2020
Cropland Converted to Settlements	**0.9**	**2.7**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**
Mineral Soils	0.8	2.3	1.4	1.4	1.4	1.4	1.4
Organic Soils	0.2	0.4	0.2	0.2	0.2	0.2	0.2
Forest Land Converted to Settlements	**14.3**	**15.7**	**16.7**	**16.8**	**16.8**	**16.8**	**16.8**
Aboveground Live Biomass	8.6	9.3	10.0	10.0	10.0	10.0	10.0
Belowground Live Biomass	1.7	1.8	1.9	1.9	1.9	1.9	1.9
Dead Wood	1.5	1.6	1.7	1.7	1.7	1.7	1.7
Litter	2.2	2.4	2.5	2.5	2.5	2.5	2.5
Mineral Soils	0.3	0.5	0.5	0.5	0.5	0.5	0.5
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Grassland Converted to Settlements	**1.4**	**4.4**	**3.1**	**3.1**	**3.1**	**3.1**	**3.1**
Mineral Soils	1.3	4.1	2.8	2.8	2.8	2.8	2.8
Organic Soils	0.2	0.4	0.2	0.2	0.2	0.2	0.2

Other Lands Converted to Settlements	**(0.1)**	**(0.4)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**	**(0.3)**
Mineral Soils	(0.1)	(0.4)	(0.4)	(0.4)	(0.4)	(0.3)	(0.3)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Settlements	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Total Aboveground Biomass Flux	**8.6**	**9.3**	**10.0**	**10.0**	**10.0**	**10.0**	**10.0**
Total Belowground Biomass Flux	**1.7**	**1.8**	**1.9**	**1.9**	**1.9**	**1.9**	**1.9**
Total Dead Wood Flux	**1.5**	**1.6**	**1.7**	**1.7**	**1.7**	**1.7**	**1.7**
Total Litter Flux	**2.2**	**2.4**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**
Total Mineral Soil Flux	**2.2**	**6.5**	**4.4**	**4.4**	**4.4**	**4.4**	**4.4**
Total Organic Soil Flux	**0.4**	**1.0**	**0.7**	**0.7**	**0.6**	**0.6**	**0.6**
Total Net Flux	**16.6**	**22.6**	**21.2**	**21.3**	**21.3**	**21.3**	**21.2**

+ Absolute value does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate C stock changes for Land Converted to Settlements, including (1) loss of aboveground and belowground biomass, dead wood and litter C with conversion of forest lands to settlements, as well as (2) the impact from all land use conversions to settlements on soil organic C stocks in mineral and organic soils.

Biomass, Dead Wood, and Litter Carbon Stock Changes

A Tier 2 method is applied to estimate biomass, dead wood, and litter C stock changes for *Forest* Land Converted to Settlements. Estimates are calculated in the same way as those in the *Forest Land Remaining Forest Land* category using data from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (USDA Forest Service 2020), however there is no country-specific data for settlements so the biomass, litter, and dead wood carbon stocks on these converted lands were assumed to be zero. The difference between the stocks is reported as the stock change under the assumption that the change occurred in the year of the conversion.

If FIA plots include data on individual trees, aboveground and belowground C density estimates are based on Woodall et al. (2011). Aboveground and belowground biomass estimates also include live understory, which is a minor component of biomass defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. For this Inventory, it was assumed that 10 percent of total understory C mass is belowground (Smith et al. 2006). Estimates of C density are based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003).

This inventory also includes estimates of change in dead organic matter for standing dead, deadwood and litter. If FIA plots include data on standing dead trees, standing dead tree C density is estimated following the basic method applied to live trees (Woodall et al. 2011) with additional modifications to account for decay and structural loss (Domke et al. 2011; Harmon et al. 2011). If FIA plots include data on downed dead wood, downed dead wood C density is estimated based on measurements of a subset of FIA plots for downed dead wood (Domke et al. 2013; Woodall and Monleon 2008). Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. To facilitate the downscaling of downed dead wood C estimates from the state-wide population estimates to individual plots, downed dead wood models specific to regions and forest types within each region are used. Litter C is the pool of organic C (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. A subset of FIA plots is measured for litter C. If FIA plots include litter material, a modeling approach using litter C measurements from FIA plots is used to estimate litter C density (Domke et al. 2016).

In order to ensure time-series consistency, the same methods are applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. See Annex 3.13 for more information about reference C density estimates for forest land and the compilation system used to estimate carbon stock changes from forest land.

Soil Carbon Stock Changes

Soil organic C stock changes are estimated for Land Converted to Settlements according to land-use histories recorded in the 2015 USDA NRI survey for non-federal lands (USDA-NRCS 2018). Land use and some management information were originally collected for each NRI survey location on a 5-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2015 (USDA-NRCS 2018).

NRI survey locations are classified as Land Converted to Settlements in a given year between 1990 and 2015 if the land use is settlements but had been classified as another use during the previous 20 years. NRI survey locations are classified according to land-use histories starting in 1979, and consequently the classifications are based on less than 20 years from 1990 to 1998. This may have led to an underestimation of Land Converted to Settlements in the early part of the time series to the extent that some areas are converted to settlement between 1971 and 1978. For federal lands, the land use history is derived from land cover changes in the National Land Cover Dataset (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015).

Mineral Soil Carbon Stock Changes

An IPCC Tier 2 method (Ogle et al. 2003) is applied to estimate C stock changes for Land Converted to Settlements on mineral soils from 1990 to 2015. Data on climate, soil types, land-use, and land management activity are used to classify land area and apply appropriate stock change factors (Ogle et al. 2003, 2006). Reference C stocks are estimated using the National Soil Survey Characterization Database (USDA-NRCS 1997) with cultivated cropland as the reference condition, rather than native vegetation as used in IPCC (2006). Soil measurements under agricultural management are much more common and easily identified in the National Soil Survey Characterization Database (USDA-NRCS 1997) than are soils under a native condition, and therefore cultivated cropland provide a more robust sample for estimating the reference condition. Country-specific C stock change factors are derived from published literature to determine the impact of management practices on soil organic C storage (Ogle et al. 2003, Ogle et al. 2006). However, there are insufficient data to estimate a set of land use, management, and input factors for settlements. Moreover, the 2015 NRI survey data (USDA-NRCS 2018) do not provide the information needed to assign different land use subcategories to settlements, such as turf grass and impervious surfaces, which is needed to apply the Tier 1 factors from the IPCC guidelines (2006). Therefore, the United States has adopted a land use factor of 0.7 to represent a net loss of soil organic C with conversion to settlements under the assumption that there are additional soil organic C losses with land clearing, excavation and other activities associated with development. More specific factor values can be derived in future Inventories as data become available. See Annex 3.12 for additional discussion of the Tier 2 methodology for mineral soils.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2015 so that changes reflect anthropogenic activity and not methodological adjustments. Soil organic C stock changes from 2016 to 2020 are estimated using a linear extrapolation method described in Box 6-4 of the Methodology section in *Cropland Remaining Cropland*. The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2015 emissions data, and is a standard data splicing method for estimating emissions at the end of a time series if activity data are not available (IPCC 2006). The Tier 2 method described previously will be applied to recalculate the 2016 to 2020 emissions in a future Inventory.

Organic Soil Carbon Stock Changes

Annual C emissions from drained organic soils in Land Converted to Settlements are estimated using the Tier 2 method provided in IPCC (2006). The Tier 2 method assumes that organic soils are losing C at a rate similar to croplands, and therefore uses the country-specific values for cropland (Ogle et al. 2003). To estimate CO_2

emissions from 1990 to 2015, the area of organic soils in Land Converted to Settlements is multiplied by the Tier 2 emission factor, which is 11.2 MT C per ha in cool temperate regions, 14.0 MT C per ha in warm temperate regions and 14.3 MT C per ha in subtropical regions (See Annex 3.12 for more information).

In order to ensure time-series consistency, the same methods are applied from 1990 to 2015, and a linear extrapolation method is used to approximate emissions for the remainder of the 2016 to 2020 time series (See Box 6-4 of the Methodology section in *Cropland Remaining Cropland*. The extrapolation is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2015 emissions data, and is a standard data splicing method for estimating emissions at the end of a time series if activity data are not available (IPCC 2006). Estimates will be recalculated in future Inventories when new NRI data are available.

Uncertainty

The uncertainty analysis for C losses with *Forest* Land Converted to Settlements is conducted in the same way as the uncertainty assessment for forest ecosystem C flux in the *Forest Land Remaining Forest Land* category. Sample and model-based error are combined using simple error propagation methods provided by the IPCC (2006), i.e., by taking the square root of the sum of the squares of the standard deviations of the uncertain quantities. For additional details, see the Uncertainty Analysis in Annex 3.13. The uncertainty analysis for mineral soil organic C stock changes and annual C emission estimates from drained organic soils in Land Converted to Settlements is estimated using a Monte Carlo approach, which is also described in the *Cropland Remaining Cropland* section.

Uncertainty estimates are presented in Table 6-127 for each subsource (i.e., biomass C, dead wood, litter, soil organic C in mineral soil and organic soils) and the method applied in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates from the Tier 2 and 3 approaches are combined using the simple error propagation methods provided by the IPCC (2006), i.e., as described in the previous paragraph. There are also additional uncertainties propagated through the analysis associated with the data splicing methods applied to estimate soil organic C stock changes from 2016 to 2020. The combined uncertainty for total C stocks in Land Converted to Settlements ranges from 34 percent below to 34 percent above the 2020 stock change estimate of 77.9 MMT CO_2 Eq.

Table 6-127: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass C Stock Changes occurring within Land Converted to Settlements (MMT CO_2 Eq. and Percent)

Source	2020 Flux Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Flux Estimate[a] (MMT CO_2 Eq.)		(%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cropland Converted to Settlements	**5.9**	**2.1**	**9.8**	**-65%**	**65%**
Mineral Soil C Stocks	5.1	1.3	8.9	-74%	74%
Organic Soil C Stocks	0.8	0.1	1.5	-86%	86%
Forest Land Converted to Settlements	**61.5**	**37.3**	**85.8**	**-39%**	**39%**
Aboveground Biomass C Stocks	36.7	13.9	59.5	-62%	62%
Belowground Biomass C Stocks	7.0	2.6	11.4	-62%	62%
Dead Wood	6.4	2.4	10.3	-62%	62%
Litter	9.3	3.5	15.1	-62%	62%
Mineral Soil C Stocks	1.9	1.3	2.5	-32%	32%
Organic Soil C Stocks	0.3	0.1	0.5	-72%	72%
Grassland Converted to Settlements	**11.2**	**6.1**	**16.4**	**-46%**	**46%**
Mineral Soil C Stocks	10.3	5.2	15.4	-49%	49%
Organic Soil C Stocks	0.9	0.1	1.7	-90%	90%
Other Lands Converted to Settlements	**(1.2)**	**(2.0)**	**(0.4)**	**-68%**	**68%**
Mineral Soil C Stocks	(1.3)	(2.0)	(0.5)	-61%	61%
Organic Soil C Stocks	0.1	(0.1)	0.3	-168%	168%
Wetlands Converted to Settlements	**0.3**	**(0.2)**	**0.9**	**-150%**	**150%**
Mineral Soil C Stocks	0.1	+	0.1	-103%	103%
Organic Soil C Stocks	0.3	(0.2)	0.8	-182%	182%

Total: Land Converted to Settlements	**77.9**	**51.4**	**104.4**	**-34%**	**34%**
Aboveground Biomass C Stocks	**36.7**	**13.9**	**59.5**	**-62%**	**62%**
Belowground Biomass C Stocks	**7.0**	**2.6**	**11.4**	**-62%**	**62%**
Dead Wood	**6.4**	**2.4**	**10.3**	**-62%**	**62%**
Litter	**9.3**	**3.5**	**15.1**	**-62%**	**62%**
Mineral Soil C Stocks	**16.2**	**9.7**	**22.6**	**-40%**	**40%**
Organic Soil C Stocks	**2.4**	**(6.2)**	**10.9**	**-361%**	**361%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values or net sequestration.

QA/QC and Verification

Quality control measures included checking input data, model scripts, and results to ensure data are properly handled throughout the inventory process. Inventory reporting forms and text are reviewed and revised as needed to correct transcription errors. No errors were found in this Inventory.

Recalculations Discussion

Recalculations are associated with new FIA data from 1990 to 2020 on biomass, dead wood and litter C stocks in *Forest* Land Converted to Settlements*,* and updated estimates for mineral and organic soils from 2016 to 2020 using the linear extrapolation method. As a result, Land Converted to Settlements has an estimated smaller C loss of 2.0 MMT CO_2 Eq. on average over the time series. This represents a 2.6 percent decrease in C stock changes for Land Converted to Settlements compared to the previous Inventory.

Planned Improvements

A planned improvement for the Land Converted to Settlements category is to develop an inventory of mineral soil organic C stock changes in Alaska and losses of C from drained organic soils in federal lands. This includes C stock changes for biomass, dead organic matter and soils. See Table 6-128 for the amount of managed land area in Land Converted to Settlements that is not included in the Inventory due to these omissions. The managed area that is not included in the Inventory ranges between 0 and about 600 thousand hectares depending on the year.

There are plans to improve classification of trees in settlements and to include transfer of biomass from forest land to those areas in this category. There are also plans to extend the Inventory to included C losses associated with drained organic soils in settlements occurring on federal lands.

New land representation data will also be compiled, and the emissions data will be recalculated for the latter years in the time series that are estimated using data splicing methods in this Inventory. These improvements will be made as funding and resources are available to expand the inventory for this source category.

Table 6-128: Area of Managed Land in *Settlements Remaining Settlements* that is not included in the current Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	LCS Managed Land Area (Section 6.1)	LCS Area Included in Inventory	LCS Area Not Included in Inventory
1990	2,861	2,861	0
1991	3,238	3,238	0
1992	3,592	3,592	0
1993	4,178	4,107	72
1994	4,777	4,630	147
1995	5,384	5,161	223
1996	5,927	5,658	269
1997	6,520	6,174	346
1998	7,065	6,650	416
1999	7,577	7,116	461
2000	8,095	7,568	528
2001	8,544	7,947	597
2002	8,886	8,284	602
2003	8,941	8,335	606
2004	8,957	8,345	612
2005	8,947	8,341	606
2006	8,959	8,352	607
2007	8,902	8,295	607
2008	8,722	8,111	610
2009	8,541	7,930	611
2010	8,335	7,725	611
2011	8,108	7,498	611
2012	7,918	7,298	620
2013	7,504	6,932	572
2014	7,087	6,586	501
2015	6,589	6,165	424
2016	ND	ND	ND
2017	ND	ND	ND
2018	ND	ND	ND
2019	ND	ND	ND
2020	ND	ND	ND

Note: NRI data are not available after 2015, and these years are designated as ND (No data).

6.12 Other Land Remaining Other Land (CRF Category 4F1)

Land use is constantly occurring, and areas under a number of differing land-use types remain in their respective land-use type each year, just as other land can remain as other land. While the magnitude of *Other Land Remaining Other Land* is known (see Table 6-4), research is ongoing to track C pools in this land use. Until such time that reliable and comprehensive estimates of C for *Other Land Remaining Other Land* can be produced, it is not possible to estimate CO_2, CH_4 or N_2O fluxes on *Other Land Remaining Other Land* at this time.

6.13 Land Converted to Other Land (CRF Category 4F2)

Land-use change is constantly occurring, and areas under a number of differing land-use types are converted to other land each year, just as other land is converted to other uses. While the magnitude of these area changes is known (see Table 6-4), research is ongoing to track C across *Other Land Remaining Other Land* and *Land Converted to Other Land*. Until such time that reliable and comprehensive estimates of C across these land-use and land-use change categories can be produced, it is not possible to separate CO_2, CH_4 or N_2O fluxes on *Land Converted to Other Land* from fluxes on *Other Land Remaining Other Land* at this time.