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 carbon stock changes from mineral soils, while carbon 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 (e.g., grassland converted to forestland).

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 carbon 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 carbon 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 carbon stocks and methane (CH_4) and nitrous oxide (N_2O) emissions from managed peatlands, aboveground and belowground biomass, dead organic matter, soil carbon 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 carbon 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. See Section 6.1 for additional information on wetlands included in this *Inventory*.

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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 of CO_2 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 carbon 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 carbon stocks in mineral and organic soils due to land use and management for all land use conversions to settlements, and the carbon stock changes in aboveground biomass, belowground biomass, dead wood, and litter are also included for the subcategory forest land converted to settlements.

In 2022, the Land Use, Land-Use Change, and Forestry (LULUCF) sector resulted in a net increase in carbon stocks (i.e., net CO_2 removals) of 921.8 MMT CO_2 Eq. This represents an offset of approximately 14.5 percent of total (i.e., gross) greenhouse gas emissions in 2022. Emissions of CH_4 and N_2O from LULUCF activities in 2022 were 58.4 and 9.1 MMT CO_2 Eq., respectively, and combined represent 1.1 percent of total greenhouse gas emissions.[3] In 2022, the overall net flux from LULUCF resulted in a removal of 854.3 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 2022 time series are shown in Figure 6-2.

Flooded land remaining flooded land was the largest source of non-CO_2 emissions from LULUCF in 2022, accounting for 65.5 percent of the LULUCF sector emissions. Non-CO_2 emissions from forest fires are the second largest source of LULUCF sector emissions; these emissions have increased 155.2 percent since 1990 and accounted for 21.9 percent of LULUCF emissions in 2022. Coastal wetlands remaining coastal wetlands and settlements remaining settlements soils accounted for 6.6 and 3.8 percent of non-CO_2 emissions from LULUCF in 2022, respectively, and the remaining sources account for less than one percent each.

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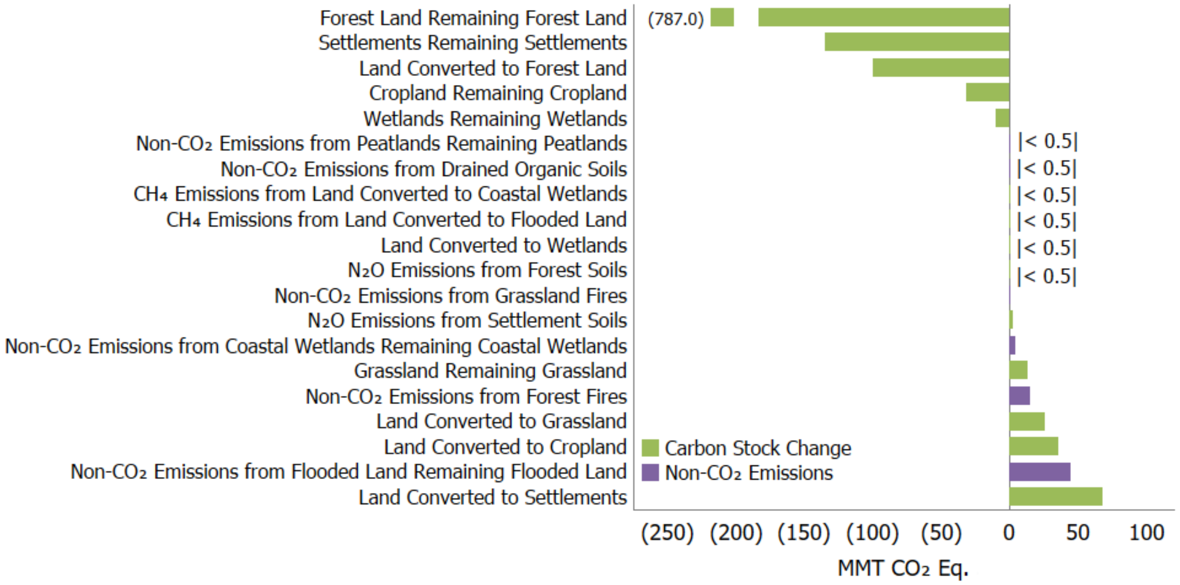
[2] LULUCF carbon stock change is the net carbon stock change from the following categories: forest land remaining forest land, land converted to forest land, cropland remaining cropland, land converted to cropland, grassland remaining grassland, land converted to grassland, wetlands remaining wetlands, 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 6-1: 2022 LULUCF Chapter Greenhouse Gas Sources and Sinks



Note: Parentheses in horizontal axis indicate net sequestration.

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

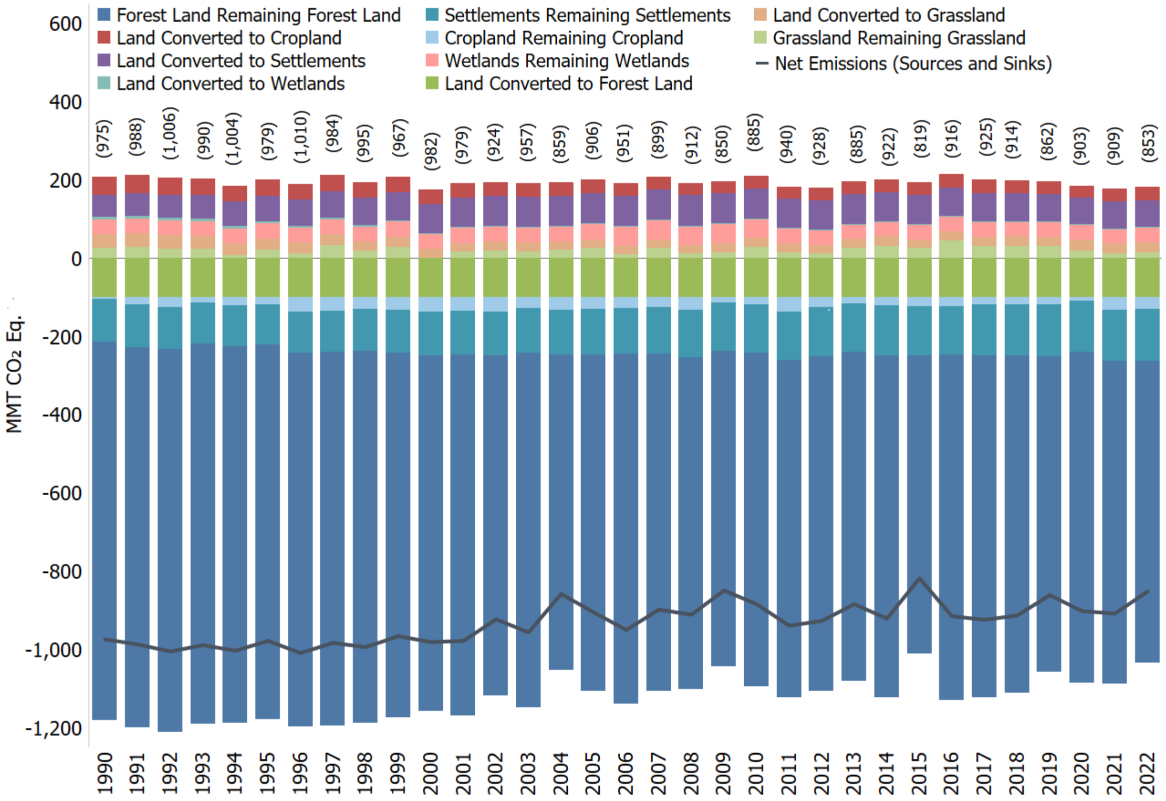


Table 6-1: Emissions and Removals (Net Flux) from Land Use, Land-Use Change, and Forestry (MMT CO_2 Eq.)

Land-Use Category	1990	2005	2018	2019	2020	2021	2022
Forest Land Remaining Forest Land	**(968.8)**	**(860.0)**	**(863.3)**	**(807.0)**	**(846.3)**	**(823.8)**	**(771.7)**
Changes in Forest Carbon Stocks[a]	(974.8)	(876.0)	(873.5)	(813.2)	(862.0)	(844.2)	(787.0)
Non-CO_2 Emissions from Forest Fires[b]	5.8	15.5	9.7	5.7	15.3	19.9	14.8
N_2O Emissions from Forest Soils[c]	0.1	0.4	0.4	0.4	0.4	0.4	0.4
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	**(100.2)**	**(100.2)**	**(100.4)**	**(100.3)**	**(100.3)**	**(100.3)**	**(100.3)**
Changes in Forest Carbon Stocks[e]	(100.2)	(100.2)	(100.4)	(100.3)	(100.3)	(100.3)	(100.3)
Cropland Remaining Cropland	**(5.0)**	**(31.6)**	**(17.8)**	**(19.4)**	**(8.8)**	**(32.0)**	**(31.7)**
Changes in Mineral and Organic Soil Carbon Stocks	(5.0)	(31.6)	(17.8)	(19.4)	(8.8)	(32.0)	(31.7)
Land Converted to Cropland	**45.4**	**34.5**	**31.9**	**31.4**	**29.3**	**34.9**	**35.1**
Changes in all Ecosystem Carbon Stocks[f]	45.4	34.5	31.9	31.4	29.3	34.9	35.1
Grassland Remaining Grassland	**24.6**	**24.9**	**29.7**	**28.9**	**17.1**	**11.5**	**14.0**
Changes in Mineral and Organic Soil Carbon Stocks	24.4	24.1	28.6	28.5	16.1	10.6	13.4
Non-CO_2 Emissions from Grassland Fires[g]	0.2	0.8	1.1	0.3	1.1	0.9	0.6
Land Converted to Grassland	**35.3**	**21.8**	**25.2**	**25.4**	**28.7**	**24.5**	**25.6**
Changes in all Ecosystem Carbon Stocks[f]	35.3	21.8	25.2	25.4	28.7	24.5	25.6
Wetlands Remaining Wetlands	**36.8**	**39.4**	**38.2**	**38.1**	**38.1**	**38.1**	**38.1**
Changes in Organic Soil Carbon Stocks in Peatlands	1.1	1.1	0.7	0.6	0.6	0.5	0.6
Non-CO_2 Emissions from Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Changes in Biomass, DOM, and Soil Carbon Stocks in Coastal Wetlands	(10.8)	(10.1)	(11.1)	(11.1)	(11.1)	(11.1)	(11.1)
CH_4 Emissions from Coastal Wetlands Remaining Coastal Wetlands	4.2	4.2	4.3	4.3	4.3	4.3	4.3
N_2O Emissions from Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.1	0.1	0.1
CH_4 Emissions from Flooded Land Remaining Flooded Land	42.3	44.0	44.2	44.2	44.2	44.2	44.2
Land Converted to Wetlands	**7.2**	**1.8**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**
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	0.3	0.3	0.2	0.2	0.2	0.2	0.2
Changes in Land Converted to Flooded Land	3.6	0.6	0.3	0.3	0.3	0.3	0.3
CH_4 Emissions from Land Converted to Flooded Land	2.9	0.4	0.2	0.2	0.2	0.2	0.2
Settlements Remaining Settlements	**(109.1)**	**(115.2)**	**(131.0)**	**(131.5)**	**(131.8)**	**(132.3)**	**(132.3)**
Changes in Organic Soil Carbon Stocks	9.9	10.1	14.4	14.6	15.1	15.4	15.4
Changes in Settlement Tree Carbon Stocks	(96.6)	(117.0)	(134.4)	(135.6)	(136.7)	(137.8)	(138.5)
N_2O Emissions from Settlement Soils[h]	2.1	3.1	2.4	2.5	2.5	2.5	2.5
Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills	(24.5)	(11.4)	(13.4)	(13.1)	(12.8)	(12.5)	(11.8)
Land Converted to Settlements	**57.2**	**77.1**	**71.4**	**70.2**	**68.8**	**68.2**	**68.2**
Changes in all Ecosystem Carbon Stocks[f]	57.2	77.1	71.4	70.2	68.8	68.2	68.2
LULUCF Emissions[i]	**57.9**	**68.9**	**62.8**	**58.0**	**68.4**	**72.9**	**67.5**
CH_4	53.1	58.6	55.6	52.5	59.3	62.2	58.4
N_2O	4.8	10.4	7.2	5.5	9.1	10.8	9.1
LULUCF Carbon Stock Change[j]	**(1,034.7)**	**(976.6)**	**(978.3)**	**(921.6)**	**(972.8)**	**(983.4)**	**(921.8)**

LULUCF Sector Net Total[k]	**(976.7)**	**(907.6)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.5)**	**(854.3)**

+ 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 carbon 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 nitrogen 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 carbon 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 LULUCF 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 carbon 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 carbon sequestration in the LULUCF sector decreased by approximately 10.9 percent between 1990 and 2022. This decrease was primarily due to a decline in the rate of net carbon accumulation in forest land*,* as well as an increase in emissions from land converted to settlements.[4] Specifically, there was a net carbon accumulation in settlements remaining settlements, which increased from 1990 to 2022, while the net carbon accumulation in forest land remaining forest land and land converted to wetlands slowed over this period. Net carbon accumulation remained steady from 1990 to 2022 in land converted to forest land, cropland remaining cropland, land converted to cropland, and wetlands remaining wetlands, while net carbon accumulation fluctuated in grassland remaining grassland.

Flooded land remaining flooded land was the largest source of CH_4 emissions from LULUCF in 2022, totaling 44.2 MMT CO_2 Eq. (1,579 kt of CH_4). Forest fires resulted in CH_4 emissions of 9.1 MMT CO_2 Eq. (325 kt of CH_4).

For N_2O emissions, forest fires were the largest source from LULUCF in 2022, totaling 5.7 MMT CO_2 Eq. (22 kt of N_2O). Nitrous oxide emissions from fertilizer application to settlement soils in 2022 totaled to 2.5 MMT CO_2 Eq. (10 kt of N_2O). This represents an increase of 22.8 percent since 1990. Additionally, the application of synthetic fertilizers to forest soils in 2022 resulted in N_2O emissions of 0.4 MMT CO_2 Eq. (2 kt of N_2O). Nitrous oxide emissions from fertilizer application to forest soils have increased by 431.9 percent since 1990, but still account for a relatively small portion of overall emissions.

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

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	2018	2019	2020	2021	2022
Carbon Stock Change (CO_2)[a]	**(1,034.7)**	**(976.6)**	**(978.3)**	**(921.6)**	**(972.8)**	**(983.4)**	**(921.8)**
Forest Land Remaining Forest Land	(974.8)	(876.0)	(873.5)	(813.2)	(862.0)	(844.2)	(787.0)
Land Converted to Forest Land	(100.2)	(100.2)	(100.4)	(100.3)	(100.3)	(100.3)	(100.3)
Cropland Remaining Cropland	(5.0)	(31.6)	(17.8)	(19.4)	(8.8)	(32.0)	(31.7)
Land Converted to Cropland	45.4	34.5	31.9	31.4	29.3	34.9	35.1
Grassland Remaining Grassland	24.4	24.1	28.6	28.5	16.1	10.6	13.4
Land Converted to Grassland	35.3	21.8	25.2	25.4	28.7	24.5	25.6
Wetlands Remaining Wetlands	(9.8)	(9.0)	(10.5)	(10.5)	(10.5)	(10.6)	(10.6)
Land Converted to Wetlands	4.1	1.1	0.3	0.3	0.3	0.3	0.3
Settlements Remaining Settlements	(111.2)	(118.3)	(133.5)	(134.0)	(134.3)	(134.8)	(134.8)
Land Converted to Settlements	57.2	77.1	71.4	70.2	68.8	68.2	68.2
CH_4	**53.1**	**58.6**	**55.6**	**52.5**	**59.3**	**62.2**	**58.4**
Forest Land Remaining Forest Land: Forest Fires[b]	3.4	9.2	6.0	3.4	9.8	12.7	9.1
Forest Land Remaining Forest Land: Drained Organic Soils[c]	+	+	+	+	+	+	+
Grassland Remaining Grassland: Grassland Fires[d]	0.1	0.4	0.6	0.2	0.6	0.5	0.3
Wetlands Remaining Wetlands: Flooded Land Remaining Flooded Land	42.3	44.0	44.2	44.2	44.2	44.2	44.2
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	4.2	4.2	4.3	4.3	4.3	4.3	4.3
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Land Converted to Wetlands: Land Converted to Flooded Lands	2.9	0.4	0.2	0.2	0.2	0.2	0.2
Land Converted to Wetlands: Land Converted to Coastal Wetlands	0.3	0.3	0.2	0.2	0.2	0.2	0.2
N_2O	**4.8**	**10.4**	**7.2**	**5.5**	**9.1**	**10.8**	**9.1**
Forest Land Remaining Forest Land: Forest Fires[b]	2.4	6.3	3.7	2.3	5.5	7.2	5.7
Forest Land Remaining Forest Land: Forest Soils[f]	0.1	0.4	0.4	0.4	0.4	0.4	0.4
Forest Land Remaining Forest Land: Drained Organic Soils[c]	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Grassland Remaining Grassland: Grassland Fires[d]	0.1	0.4	0.5	0.1	0.5	0.4	0.3
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Settlements Remaining Settlements: Settlement Soils[f]	2.1	3.1	2.4	2.5	2.5	2.5	2.5
LULUCF Carbon Stock Change[a]	**(1,034.7)**	**(976.6)**	**(978.3)**	**(921.6)**	**(972.8)**	**(983.4)**	**(921.8)**
LULUCF Emissions[g]	**57.9**	**68.9**	**62.8**	**58.0**	**68.4**	**72.9**	**67.5**
LULUCF Sector Net Total[h]	**(976.7)**	**(907.6)**	**(915.5)**	**(863.6)**	**(904.4)**	**(910.5)**	**(854.3)**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] LULUCF carbon stock change is the net carbon 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 nitrogen fertilizer additions on both forest land remaining forest land and land converted to forest land.

[f] Estimates include N_2O emissions from nitrogen 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 LULUCF 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	2018	2019	2020	2021	2022
Carbon Stock Change (CO_2)[a]	**(938,856)**	**(853,529)**	**(842,516)**	**(829,501)**	**(768,224)**	**(852,534)**	**(832,039)**
Forest Land Remaining Forest Land	(821,444)	(714,232)	(710,697)	(704,446)	(649,336)	(707,426)	(695,354)
Land Converted to Forest Land	(98,452)	(98,429)	(98,322)	(98,263)	(98,253)	(98,254)	(98,254)
Cropland Remaining Cropland	(23,176)	(29,001)	(22,293)	(16,597)	(14,544)	(23,335)	(18,940)
Land Converted to Cropland	54,792	54,651	56,597	56,327	56,280	56,725	56,511
Grassland Remaining Grassland	8,694	11,040	10,928	11,266	13,997	6,046	10,005
Land Converted to Grassland	(6,684)	(40,098)	(24,467)	(24,205)	(23,304)	(25,921)	(24,669)
Wetlands Remaining Wetlands	(7,372)	(6,601)	(7,953)	(7,990)	(8,031)	(8,059)	(8,095)
Land Converted to Wetlands	1884	820	339	341	349	250	256
Settlements Remaining Settlements	(109,567)	(116,642)	(127,510)	(126,961)	(126,469)	(133,610)	(134,514)
Land Converted to Settlements	62,469	84,965	80,860	81,026	81,087	81,050	81,014
CH_4	**1,911**	**2,190**	**2,145**	**2,048**	**2,032**	**2,336**	**2,356**
Forest Land Remaining Forest Land: Forest Fires[b]	116	390	342	245	228	534	554
Forest Land Remaining Forest Land: Drained Organic Soils[c]	1	1	1	1	1	1	1
Grassland Remaining Grassland: Grassland Fires[d]	3	13	12	12	12	12	12
Wetlands Remaining Wetlands: Flooded Land Remaining Flooded Land	1,592.8	1,617.0	1,620.7	1,620.8	1,620.9	1,622.7	1,622.8
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	149	151	153	153	153	154	154
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Land Converted to Wetlands: Land Converted to Flooded Lands	39	9	9	9	9	6	6
Land Converted to Wetlands: Land Converted to Coastal Wetlands	10	10	8	7	7	7	6
N_2O	**17**	**42**	**31**	**27**	**27**	**41**	**45**
Forest Land Remaining Forest Land: Forest Fires[b]	9	28	21	16	17	30	34
Forest Land Remaining Forest Land: Forest Soils[f]	+	2	2	2	2	2	2
Forest Land Remaining Forest Land: Drained Organic Soils[c]	+	+	+	+	+	+	+
Grassland Remaining Grassland:	+	1	1	1	1	1	1

Grassland Fires[d]							
Wetlands Remaining Wetlands: Coastal Wetlands Remaining Coastal Wetlands	+	1	+	1	1	1	1
Wetlands Remaining Wetlands: Peatlands Remaining Peatlands	+	+	+	+	+	+	+
Settlements Remaining Settlements: Settlement Soils[e]	7	10	7	7	8	8	8

+ Absolute value does not exceed 0.5 kt.

[a] LULUCF carbon stock change is the net carbon 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 nitrogen fertilizer additions on both forest land remaining forest land and land converted to forest land.

[f] Estimates include N_2O emissions from nitrogen fertilizer additions on both settlements remaining settlements and land converted to settlements.

Notes: Totals by gas 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 removals 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 2020) to ensure that the trend is accurate. Of the updates implemented for this *Inventory*, the most significant include (1) managed forest land in Hawaii and several U.S. Territories were included for the first time in the current *Inventory* which resulted in an increase in managed forest land area of approximate 1.3 M ha and associated increases in carbon stocks of 286 MMT C for the year 2023 in this *Inventory;* (2) updated methodological framework and accounting of carbon in structural components of trees across the United States for total tree cubic-foot volume, biomass, and carbon which led to an increase in estimated forest carbon stocks; and (3) incorporating new U.S. Department of Agriculture (USDA) National Resources Inventory (NRI) data through 2017, incorporating USDA-Natural Resources Conservation Service (NRCS) Conservation Effects Assessment Program (CEAP) survey data for 2013 to 2016, incorporating cover crop and tillage management information from the OpTIS remote-sensing data product from 2008 to 2020, in addition to other methodological updates for the estimation of croplands and grasslands described further in those respective category sections. Together, these and other updates increased total carbon sequestration by an average of 133.6 MMT CO_2 Eq. (15.5 percent) and decreased total non-CO_2 emissions by 2.2 MMT CO_2 Eq. (2.9 percent) across the time series, compared to the previous *Inventory* (i.e., 1990 to 2021). For more information on specific methodological updates, please see the Recalculations Discussion within the respective 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 for most categories. 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

Consistent with Article 13.7(a) of the Paris Agreement and Article 4.1(a) of the UNFCCC as well as relevant decisions under those agreements, 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 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 reporting guidelines for the reporting of inventories under the Paris Agreement and the UNFCCC.[5] The Parties' use of consistent methods to calculate emissions and removals for their inventories helps to ensure 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. Rather, this chapter presents emissions and removals in a common format consistent with how Parties are to report their national inventories under the Paris Agreement and the UNFCCC. The report itself, and this chapter, follow this common 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. This section of the *Inventory* has been developed in order to comply with this guidance. While the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) provide guidance for factoring out natural emissions and removals, the United States does not apply this guidance and estimates all emissions/removals on managed land regardless of whether the driver was natural.

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).

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

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] See Table 6-6 for an overview of the land area databases used to characterize land use in federal and non-federal lands in the conterminous United States, Alaska, and Hawaii.

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*, a distribution that has remained stable over the time series of the *Inventory* (Table 6-5). In 2022, the United States had a total of 281 million hectares of managed forest land (0.47 percent decrease compared to 1990). There are 160 million hectares of cropland (8.3 percent decrease compared to 1990), 339 million hectares of managed grassland (0.35 percent increase compared to 1990), 39 million hectares of managed wetlands (3 percent increase compared to 1990), 47 million hectares of settlements (41 percent increase compared to 1990), and 21 million hectares of managed other land (1.2 percent decrease compared to 1990) (Table 6-5).

Wetlands are not differentiated between managed and unmanaged with the exception of remote areas in Alaska, and so are classified and reported mostly as managed land within the coterminous United States.[10] In addition, carbon 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] Planned improvements are under development to estimate carbon stock changes and greenhouse gas emissions on all managed land and to 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 and economic 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

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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 https://www.fia.fs.usda.gov/tools-data/index.php.

[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.

[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 in the land representation, but emission/removal estimates only developed for those wetlands that are included under the flooded lands, coastal wetlands or peat extraction categories. Efforts are underway to better reflect wetland estimates in the future *Inventories*. 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 future *Inventories*.

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

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	2018	2019	2020	2021	2022
Managed Lands	**886,533**	**886,530**	**886,531**	**886,531**	**886,531**	**886,531**	**886,531**
Forest	282,375	281,806	280,971	280,440	281,067	281,071	281,041
Croplands	174,498	165,632	161,394	160,693	160,112	160,079	160,033
Grasslands	337,867	340,022	338,927	339,801	339,562	339,260	339,048
Settlements	33,427	40,172	45,971	46,312	46,641	46,960	47,185
Wetlands	37,456	38,310	38,495	38,551	38,430	38,478	38,566
Other	20,911	20,588	20,773	20,734	20,718	20,682	20,657
Unmanaged Lands	**49,708**	**49,711**	**49,710**	**49,710**	**49,710**	**49,710**	**49,710**
Forest	9,766	9,782	9,814	9,815	9,817	9,818	9,819
Croplands	0	0	0	0	0	0	0
Grasslands	25,090	25,154	25,268	25,266	25,265	25,264	25,262
Settlements	0	0	0	0	0	0	0
Wetlands	4,118	4,057	3,936	3,935	3,935	3,935	3,936
Other	10,734	10,718	10,693	10,693	10,693	10,693	10,693
Total Land Areas	**936,241**	**936,241**	**936,241**	**936,241**	**936,241**	**936,241**	**936,241**
Forest	292,140	291,588	290,784	290,255	290,883	290,889	290,861
Croplands	174,498	165,632	161,394	160,693	160,112	160,079	160,033
Grasslands	362,957	365,176	364,195	365,068	364,827	364,524	364,310
Settlements	33,427	40,172	45,971	46,312	46,641	46,960	47,185
Wetlands	41,574	42,366	42,430	42,486	42,365	42,413	42,502
Other	31,645	31,306	31,466	31,428	31,411	31,375	31,350

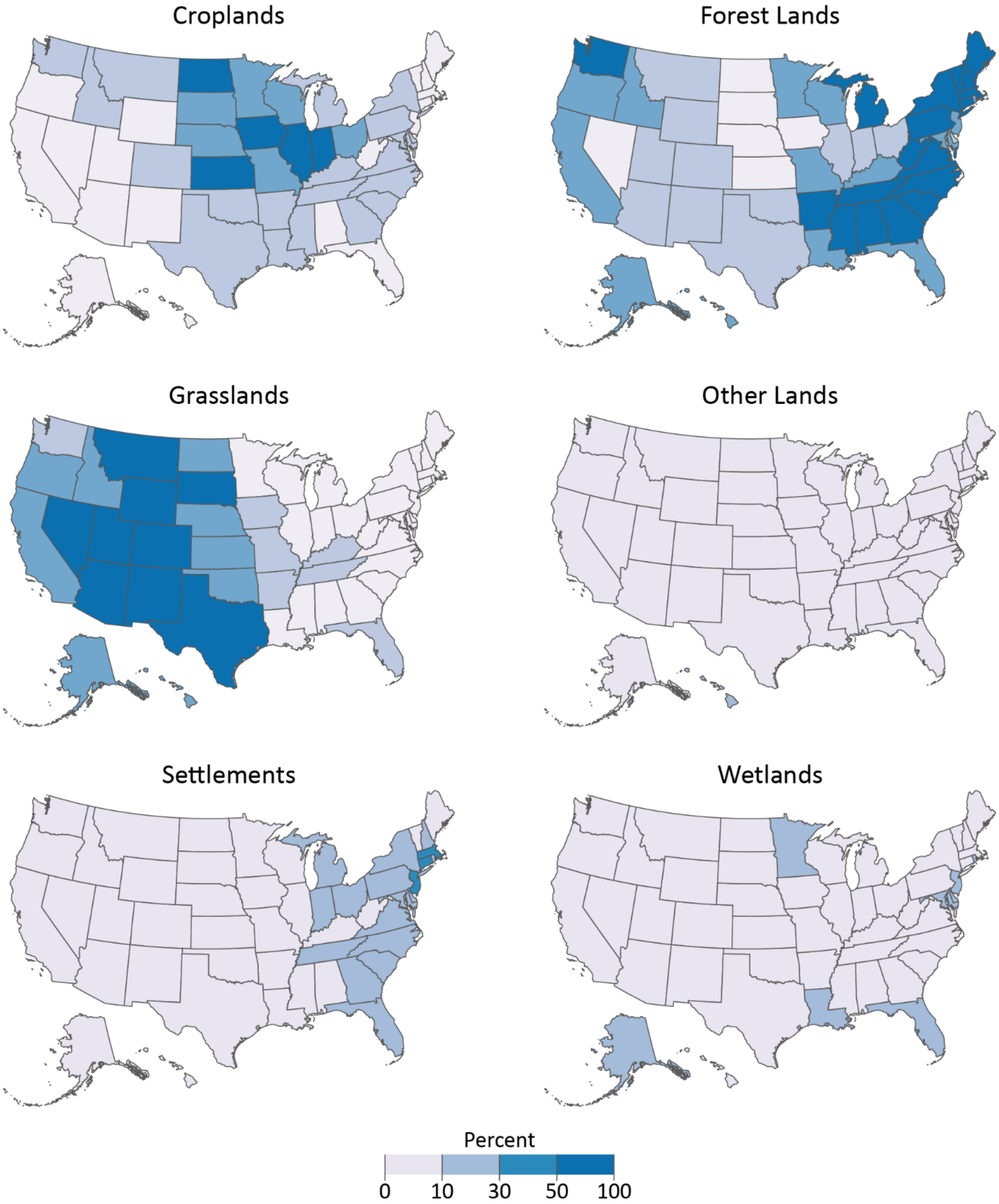
Table 6-5: Land Use and Land-Use Change for the U.S. Managed Land Base for All 50 States (Thousands of Hectares)

Land Use & Land-Use Change Categories	1990	2005	2018	2019	2020	2021	2022
Total Forest Land	**282,375**	**281,806**	**280,971**	**280,440**	**281,067**	**281,071**	**281,041**
FF	281,290	280,587	279,683	279,167	279,818	279,829	279,802
CF	208	137	101	88	77	77	76
GF	775	968	1,038	1,048	1,036	1,037	1,040
WF	15	23	21	18	16	15	15
SF	11	18	20	21	20	19	20
OF	77	73	108	98	99	94	89
Total Cropland	**174,498**	**165,632**	**161,394**	**160,693**	**160,112**	**160,079**	**160,033**
CC	162,273	150,417	149,721	149,503	149,823	150,591	151,276
FC	173	77	63	64	60	63	65
GC	11,673	14,623	11,231	10,758	9,914	9,132	8,418
WC	119	178	99	98	86	81	75
SC	75	102	107	105	101	97	94
OC	186	235	173	166	129	115	107
Total Grassland	**337,867**	**340,022**	**338,927**	**339,801**	**339,562**	**339,260**	**339,048**
GG	328,566	315,931	318,960	320,255	320,856	321,910	322,779
FG	572	1,663	4,184	4,202	4,177	4,162	3,894
CG	8,177	17,746	13,594	13,491	13,205	12,200	11,444
WG	168	466	181	172	159	143	134
SG	43	525	230	190	139	100	93
OG	341	3,692	1,778	1,491	1,026	746	705
Total Wetlands	**37,456**	**38,310**	**38,495**	**38,551**	**38,430**	**38,478**	**38,566**

WW	36,900	36,288	37,236	37,425	37,448	37,626	37,783
FW	37	71	96	85	83	78	76
CW	145	637	362	310	261	221	187
GW	326	1,169	564	501	415	342	314
SW	0	38	17	14	10	2	2
OW	47	107	220	216	212	210	204
Total Settlements	**33,427**	**40,172**	**45,971**	**46,312**	**46,641**	**46,960**	**47,185**
SS	30,562	31,445	40,769	41,615	42,466	43,189	43,748
FS	301	466	468	455	448	446	440
CS	1,231	3,604	1,917	1,726	1,528	1,366	1,228
GS	1,276	4,371	2,630	2,349	2,062	1,830	1,648
WS	4	59	30	25	18	14	14
OS	54	229	157	141	120	115	108
Total Other Land	**20,911**	**20,588**	**20,773**	**20,734**	**20,718**	**20,682**	**20,657**
OO	20,177	17,022	18,050	18,293	18,553	18,805	18,874
FO	51	77	98	101	101	108	111
CO	287	603	629	582	540	489	444
GO	371	2,764	1,772	1,541	1,309	1,068	1,018
WO	22	100	206	206	205	204	200
SO	2	21	17	11	10	10	10
Grand Total	**886,533**	**886,530**	**886,531**	**886,531**	**886,531**	**886,531**	**886,531**

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 U.S. Territories in future *Inventories*. In addition, carbon 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 2022



Methodology and Time-Series Consistency

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 transfer of land area between categories following land-use change 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 converted to cropland, cropland converted to forest land, and grassland converted 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 obtained 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, consistent with the IPCC guidelines (2006). 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, flooded lands (e.g., reservoirs) and peatlands where peat extraction occurs 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 carbon stocks.[15] 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,[16] while definitions of cropland, grassland, and settlements are based on the NRI.[17] 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 ten 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 ten 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 (Nelson et al. 2020).

- *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,[18] 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

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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] There are examples of managed land transitioning to unmanaged land in the United States. For example, in 2018, 100 hectares of managed grassland converted to unmanaged because data indicated that no further grazing occurred. Livestock data are collected annually by the Department of Agriculture, and no livestock had occurred in the area since the mid-1970s, and therefore there was no longer active management through livestock grazing. The area is also remote, at least 10 miles from roads and settlements, and therefore the land was no longer managed based on the implementation criteria.

[16] See https://www.fia.fs.usda.gov/library/field-guides-methods-proc/docs/2022/core_ver9-2_9_2022_SW_HW%20table.pdf, page 23.

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

[18] Currently, there is no data source to account for biomass carbon 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.

enrolled in conservation reserve programs (i.e., set-asides[19]) 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 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.[20] Savannas, deserts, and tundra are considered grassland. 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. In addition, all coastal wetlands are considered managed regardless of whether the water level is changed or if they 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). See Section 6.8 Wetlands Remaining Wetlands for more information.
- *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 ten 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), carbon stock changes and non-CO_2 emissions are not estimated for other lands because these areas are largely devoid of biomass, litter and soil carbon pools. However, carbon stock changes and non-CO_2 emissions should be estimated for land converted to other land during the first 20 years following conversion to account for legacy effects.

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[19] 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.

[20] 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.

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 carbon stock changes, N_2O, and CH_4 emissions on those lands. If NRI and FIA data are not available for an area, however, then the NLCD product is used to represent the land use. Sources of land use data included in the land representation in this *Inventory* are consistent with those included in the previous *Inventory.*

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 obtained 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 carbon stock changes in agricultural lands (except federal grasslands). The NRI survey was conducted every five 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 have 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 2017 from the NRI. The land use patterns are assumed to remain the same from 2018 through 2022 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 United States. The Forest Inventory and Analysis engages in a hierarchical system of sampling, with sampling categorized as Phases 1 through 3, in which sample points for each consecutive phase are subsets of the previous phase. Phase 1 refers to collection of remotely-sensed data (either aerial 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 carbon 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 ten 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 for 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 2019 through 2022; 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. Gaps exist in the land representation when the NRI and FIA datasets are combined, such as federal grasslands operated by Bureau of Land Management (BLM), USDA, and National Park Service, as well as Alaska.[21] 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, 2016, 2019, and 2021 in the conterminous United States (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015, Dewitz, 2023), and also for Alaska in 2001, 2011, and 2016 and Hawaii in 2001. Note that the 2021 NLCD product was not available at the time the land representation was begun for this *Inventory* so it was not included. 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

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[21] 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.

data in the time series, which is 2001 for Hawaii, 2019 for the conterminous United States and 2016 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 obtained 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.

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;[22]
- 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 carbon 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 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

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[22] 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.

that are protected from development if the regulations allow for extractive or recreational uses or suppression of natural disturbance (e.g., forest lands with active fire protection). 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 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.[23]

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).[24] 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 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

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

[24] Definitions are provided in the previous section.

specific land-use categories that are converted to forest land in the past, but rather a sum of all land converted to forest land.[25] 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 further 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 on the specific land-use changes in the past,[26] 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 each 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 less-precise estimates 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 adjustments 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. The FIA is used as the basis for both forest land area data as well as to estimate carbon stocks and fluxes on forest land in the conterminous United States and Alaska. The FIA does have survey plots in Alaska that are used to determine the carbon stock changes, and the associated area data for this region are harmonized with 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. In Hawaii and the U.S. Territories, FIA data are being collected; these data were used to compile area estimates and emissions and removals for forest land in 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. The NRI is used as the basis for both cropland area data as well as to estimate soil carbon stocks and fluxes on

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[25] 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*.

[26] 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*.

cropland. The NLCD is used to determine cropland area and soil carbon stock changes on federal lands in the conterminous United States and Hawaii. The NLCD is also used to determine croplands in Alaska, but carbon 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. The NRI is used as the basis for both grassland area data as well as to estimate soil carbon stocks and non-CO_2 greenhouse emissions on grassland. Grassland area and soil carbon stock changes are determined using the classification provided in the NLCD for federal land within the conterminous United States. The 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 carbon stock changes in these areas.
- *Wetlands*: The 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.[27]
- *Settlements*: The NRI captures non-federal settlement area in 49 states (excluding Alaska). If areas of forest land or grassland under ten 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 ten-acre (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.

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[27] 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.

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 obtained 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 obtained 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 quality assurance 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 obtained from the combined NRI, FIA, and NLCD data, a 4.8 percent difference. Much of this difference is associated with open water 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

The land representation estimates were recalculated from the previous *Inventory* with the following datasets: a) updated FIA data from 1990 to 2022 for the conterminous United States and Alaska, b) NRI data from 1990 to 2017 for the conterminous United States and Hawaii, and c) NLCD data for the conterminous United States from 2001 through 2019 and Alaska from 2001 through 2016. There were several changes in methods that resulted in small changes between this *Inventory* and the previous *Inventory*. First, pasture land was previously classified as cropland in the compilation of forest land conversion estimates using FIA data and is now classified as grassland to align with methods and definitions used to classify grasslands using NRI data. This led to a decrease in total managed cropland area and an increase in grassland area. Second, FIA data are now used to classify forest land and conversions to and from forest land in coastal southeast and southcentral Alaska which resulted in minor changes, primarily between forest land, wetlands, and grasslands, between this *Inventory* and the previous *Inventory*. Lastly, methods for classifying wetlands using FIA data were refined so that all water bodies are now classified as wetlands (previously some water bodies were classified as other lands) aligning with methods and definitions in the NRI. Collectively, these refinements in FIA methods to better align with methods for the other data sources (i.e., NRI and NLCD) resulted in changes throughout the entire representation of land (see "Approach for Combining Data Sources"). Specifically, managed wetland area decreased, on average over the time series, by 1.2 percent. Grassland and forest land increased by 0.1 percent and 0.04 percent, respectively. Settlement area decreased by 0.05 percent and cropland and managed other lands were essentially unchanged in the latest *Inventory*.

Planned Improvements

Research is underway to harmonize NRI and FIA sampling frames to improve consistency and facilitate estimation using multi-frame sampling. This includes development of a common land use classification schema between the two land inventories that can be used in the harmonization process. These steps will allow for population estimation exclusive of auxiliary information (e.g., NLCD). The multi-frame sample will also serve as reference data for the development of spatially explicit and spatially continuous map products for each year in the *Inventory* time series. Another key planned improvement for the *Inventory* is to fully incorporate area data by land-use type for

U.S. Territories. Although most of the managed land in the United States is included in the current land use data for the conterminous United States, Alaska, and Hawaii, a complete reporting of all lands in the United States, including U.S. Territories, is a key goal for the near future. An initial assessment of data sources for land use area data for U.S. Territories by land-use category are provided in Box 6-2. In addition, this *Inventory* includes forest land areas estimated for American Samoa, Guam, Hawaii, Northern Marianas Islands, U.S. Virgin Islands, and Puerto Rico using periodic inventories from the FIA program. These estimates are included in the forest land category, and the methods for compiling these area estimates and the associated carbon stocks and fluxes and integration of these estimates into the land representation will be refined to compensate for data limitations in the time series while also taking advantage of new data and data products. See 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 (NLCD), 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 dominant 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. 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 future Inventories is to reconcile the coastal wetlands data from the C-CAP product with the wetlands area data provided in the NRI, FIA and NLCD. Estimates from flooded lands are also included in this *Inventory*, but data are not directly used in the land representation analysis at this time; this is a planned improvement to include for future inventories. 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 (CRT Category 4A1)

Changes in Forest Carbon Stocks (CRT Category 4A1)

Delineation of Carbon Pools

For estimating carbon stocks or stock change (flux), carbon 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 as well as woody fragments with diameters of up to 7.5 cm.
- Soil organic carbon (SOC), including all organic material in soil to a depth of 1 meter but excluding the coarse roots of the belowground pools. Organic (e.g., peat and muck) soils have a minimum of 12 to 20 percent organic matter by mass and develop under poorly drained conditions of wetlands. All other soils are classified as mineral soil types and typically have relatively low amounts of organic matter.

In addition, there are two harvested wood pools included when estimating carbon 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 carbon 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, carbon is removed from the atmosphere and stored in living tree biomass. As trees die and otherwise deposit litter and debris on the forest floor, carbon 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 carbon 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 carbon to the atmosphere. Instead, harvesting transfers a portion of the carbon stored in wood to a "product pool." Once in a product pool, the carbon 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 carbon immediately, and these emissions are reported for information purposes in the Energy sector while the harvest (i.e., the associated reduction in forest carbon 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 carbon is released to the atmosphere. If wood products are disposed of in SWDS, the carbon 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 carbon stocks in the five carbon 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 carbon 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, Alaska, Puerto Rico, and the U.S. Virgin Islands, and periodic inventories are available for Hawaii and some of the other U.S. Territories. The methods for estimation and monitoring are continuously improved and these improvements are reflected in the carbon estimates (Domke et al. 2022; Westfall et al. 2023). First, in the conterminous 48 states and coastal southeast and southcentral Alaska, the total carbon stocks are estimated for each carbon storage pool at the individual NFI plot, next the annual net changes in carbon stocks for each pool at the population level 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 carbon 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 carbon stocks remaining on the NFI plot. The IPCC (2006) recommends estimating changes in carbon 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 carbon stock changes by these two categories continue to improve and in order to facilitate this delineation, a combination of estimation approaches was used to compile estimates in this *Inventory*. Methods for compiling carbon stocks and stock changes on forest land in interior Alaska are different from those used for estimation in the conterminous U.S. and coastal Alaska due to the recency of the operational FIA inventory in that region and differences in sampling protocols (see Annex 3.13 for more details). Finally, estimates of carbon stocks and stock changes on forest land in Hawaii and the U.S. Territories of American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands (hereafter referred to as the U.S. Territories) are included for the first time in this *Inventory*. The FIA program has conducted annual inventories in parts of Puerto Rico (Mainland, Vieques, Culebra) and the U.S. Virgin Islands and periodic inventories in Hawaii, American Samoa, Guam, Northern Mariana Islands, and Puerto Rico (Mona Island). These inventories in combination with published estimates of carbon stocks, stock changes, and IPCC (2019) default estimates were used to compile estimates of carbon stocks and stock changes on forest land for these regions (see Annex 3.13 for more details).

Forest Area in the United States

Approximately 32 percent of the managed 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 and periodic NFI plots included in the public FIA database as of September 2023 (which includes data collected through 2022 – note that the COVID 19 pandemic resulted in delays in data collection in many states) were used in this *Inventory*. The NFIs from the conterminous United States (USDA Forest Service 2023a, 2023b), Alaska, Hawaii, and the U.S. Territories 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 and periodic NFI data through 2022 for all states (USDA Forest Service 2023b; Nelson et al. 2020). The methods for compiling area estimates for Hawaii and the U.S. Territories in this section are different from those in Section 6.1 Representation of the U.S. Land Base because they do not rely on FIA data. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation (see Annex 3.13). This prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1 Representation of the U.S. Land Base. 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) of the USDA Natural Resources Conservation Service (Perry et al. 2005).

An estimated 67 percent (208 million hectares) of U.S. forests in Alaska, 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 in the conterminous United States, Alaska, and Hawaii, 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 United States have been more frequently or intensively surveyed than the forest lands removed from production because they do 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 conterminous United States and Alaska represented in this *Inventory* 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 carbon flux from forest land across the 1990 to 2022 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 carbon by altering the amount of carbon 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 carbon storage pools) may increase the eventual biomass density of the forest, thereby increasing the uptake and storage of carbon in the aboveground biomass pool.[28] Though harvesting forests removes much of the carbon in aboveground biomass (and possibly changes carbon density in other pools), on average, the estimated volume of annual net growth in aboveground tree biomass in the conterminous United States is essentially twice 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 carbon stocks and fluxes presented in this section.

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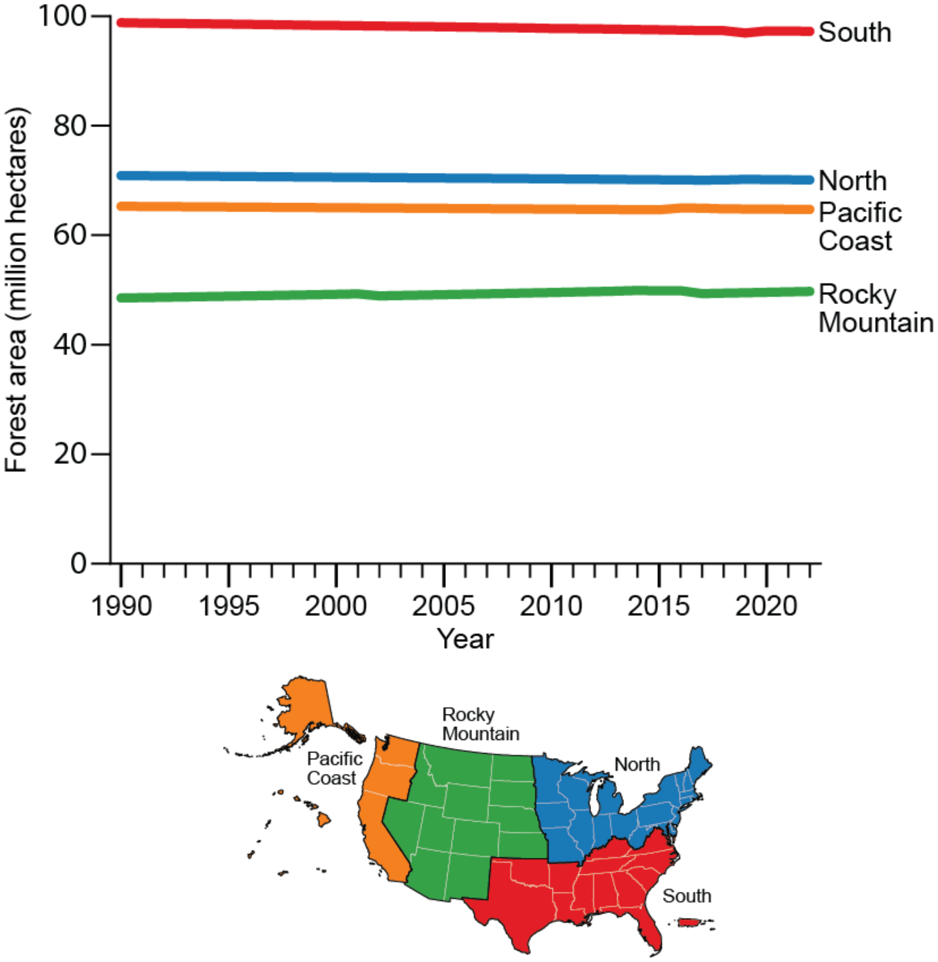
[28] The term "biomass density" refers to the mass of live vegetation per unit area. It is usually measured on a dry-weight basis. Species-specific carbon fractions are used to convert dry biomass to carbon (Westfall et al. 2023).

Figure 6-4: Changes in Forest Area by Region for Forest Land Remaining Forest Land in the conterminous United States and Alaska (1990-2022)



Forest Carbon Stocks and Stock Change

In the forest land remaining forest land category, 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 removal (i.e., net sequestration or accumulation) of carbon each year from 1990 through 2022. 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 carbon 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 carbon 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, substantial quantities of carbon in harvested wood are transferred to these long-term storage pools rather than being released rapidly to the atmosphere (Skog 2008). By maintaining current harvesting practices and regeneration activities on forest lands, along with continued input of harvested wood into the HWP pool, carbon stocks in the forest land remaining forest land category are likely to continue to increase in the near term, though possibly at a slower rate. Changes in carbon stocks in the forest ecosystem and harvested wood pools associated with forest land remaining forest land were estimated to result in net removal of 787.0 MMT CO_2 Eq. (214.6 MMT carbon) in 2022 (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 carbon in the Forest Ecosystem was 694.3 MMT CO_2 Eq. (189.3 MMT carbon) in 2022 (Table 6-8 and Table 6-9). The majority of this uptake in 2022, 491.7 MMT CO_2 Eq. (134.1 MMT carbon), was from aboveground biomass. Overall, estimates of average carbon density in forest ecosystems (including all pools) increased consistently over the time series with an average of approximately 208 MT carbon ha^{-1} from 1990 to 2022. This was calculated by dividing the forest land area estimates by forest ecosystem carbon 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 2022. The increasing forest ecosystem carbon density, when combined with relatively stable forest area, results in net carbon accumulation over time. However, due to an aging forest land base, increases in the frequency and severity of disturbances in forests in some regions, among other drivers of change, forest carbon density is increasing at a slower rate resulting in an overall decline in the sink strength of forest land remaining forest land in the United States. Aboveground live biomass is responsible for the majority of net carbon uptake among all forest ecosystem pools (Figure 6-5). These increases may be influenced in some regions by reductions in carbon 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 (e.g., 2022). The distribution of carbon in forest ecosystems in Alaska is substantially different from forests in the conterminous United States. In Alaska, more than nine percent of forest ecosystem carbon is stored in the litter carbon pool whereas in the conterminous United States, less than seven percent of the total ecosystem carbon stocks are in the litter pool. Much of the litter material in forest ecosystems is combusted during fire (IPCC 2006) leading to substantial carbon losses in this pool during severe fire years (Figure 6-5, Table A-217).

The estimated net accumulation of carbon in the HWP pool, i.e., the balance of additions from the transfer of harvested wood from the forest ecosystem and losses from the current decay of wood harvested in the past, was 92.8 MMT CO_2 Eq. (25.3 MMT carbon) in 2022 (Table 6-8, Table 6-9, Table A-210, and Table A-211). The majority of this uptake, 63.9 MMT CO_2 Eq. (17.4 MMT carbon), was from solidwood and paper in SWDS. Products in use accounted for an estimated 28.8 MMT CO_2 Eq. (7.9 MMT carbon) in 2022.

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	2018	2019	2020	2021	2022
Forest Ecosystem	**(851.0)**	**(770.0)**	**(779.6)**	**(726.2)**	**(765.2)**	**(749.5)**	**(694.3)**
Aboveground Biomass	(600.9)	(550.8)	(536.7)	(516.3)	(522.8)	(513.0)	(491.7)
Belowground Biomass	(116.8)	(107.5)	(105.4)	(102.3)	(102.2)	(100.9)	(96.9)
Dead Wood	(132.0)	(131.2)	(138.0)	(133.4)	(136.2)	(135.3)	(131.4)
Litter	(2.4)	20.5	(1.5)	26.5	(3.4)	(0.1)	26.4
Soil (Mineral)	2.0	(0.8)	1.3	(1.3)	(1.3)	(0.9)	(1.2)
Soil (Organic)	(1.6)	(1.0)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Drained Organic Soil[a]	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Harvested Wood	**(123.8)**	**(106.0)**	**(93.9)**	**(86.9)**	**(96.8)**	**(94.7)**	**(92.8)**
Products in Use	(54.8)	(42.6)	(28.8)	(22.6)	(32.3)	(30.4)	(28.8)
SWDS	(69.0)	(63.4)	(65.1)	(64.3)	(64.5)	(64.3)	(63.9)
Total Net Flux	**(974.8)**	**(876.0)**	**(873.5)**	**(813.2)**	**(862.0)**	**(844.2)**	**(787.0)**

[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 CO_2 emissions from drained organic soils. Also, Table 6-28 and Table 6-29 for non-CO_2 emissions from drainage of organic soils from both forest land remaining forest land and land converted to forest land.

Notes: Managed forest land area for Hawaii and the U.S. Territories was compiled using FIA data in this section which is different from how area estimates for those lands were compiled in Section 6.1 Representation of the U.S. Land Base. This results in small differences (less than 0.5 million hectares) in the forest land area estimates in this Section and Section 6.1. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used 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 6.2 Forest Land Remaining Forest Land (CRT Category 4A1). The forest ecosystem carbon stock changes do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 Settlements Remaining Settlements (CRT Category 4E1) for estimates of carbon stock change from settlement trees). Forest ecosystem carbon stocks on managed forest land in interior Alaska, Hawaii, and the U.S. Territories were compiled using the gain-loss method as described in Annex 3.13. Parentheses indicate net carbon uptake (i.e., a net removal of carbon from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest carbon pool and the atmosphere. Harvested wood estimates are based on results from annual surveys (see Annex 3.13, Table A-197) and models. Totals may not sum due to independent rounding.

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

Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Forest Ecosystem	**(232.1)**	**(210.0)**	**(212.6)**	**(198.1)**	**(208.7)**	**(204.4)**	**(189.3)**
Aboveground Biomass	(163.9)	(150.2)	(146.4)	(140.8)	(142.6)	(139.9)	(134.1)
Belowground Biomass	(31.9)	(29.3)	(28.8)	(27.9)	(27.9)	(27.5)	(26.4)
Dead Wood	(36.0)	(35.8)	(37.6)	(36.4)	(37.1)	(36.9)	(35.8)
Litter	(0.7)	5.6	(0.4)	7.2	(0.9)	(0.0)	7.2
Soil (Mineral)	0.5	(0.2)	0.4	(0.4)	(0.3)	(0.2)	(0.3)
Soil (Organic)	(0.4)	(0.3)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
Drained Organic Soil[a]	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Harvested Wood	**(33.8)**	**(28.9)**	**(25.6)**	**(23.7)**	**(26.4)**	**(25.8)**	**(25.3)**
Products in Use	(14.9)	(11.6)	(7.8)	(6.2)	(8.8)	(8.3)	(7.9)
SWDS	(18.8)	(17.3)	(17.8)	(17.5)	(17.6)	(17.5)	(17.4)
Total Net Flux	**(265.8)**	**(238.9)**	**(238.2)**	**(221.8)**	**(235.1)**	**(230.2)**	**(214.6)**

[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 carbon flux from drained organic soils. Also, see Table 6-28 and Table 6-29 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: Managed forest land area for Hawaii and the U.S. Territories was compiled using FIA data in this section which is different from how area estimates for those lands were compiled 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. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used 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 6.2 Forest Land Remaining Forest Land (CRT Category 4A1). The forest ecosystem carbon stock changes do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 Settlements Remaining Settlements (CRT Category 4E1) for estimates of carbon stock change from settlement trees). Forest ecosystem carbon stocks on managed forest land in Alaska, Hawaii, and the U.S. Territories were compiled using the gain-loss method as described in Annex 3.13. Parentheses indicate net carbon uptake (i.e., a net removal of carbon from the atmosphere). Total net flux is an estimate of the actual net flux between the total forest carbon 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 carbon storage pools are presented in Table 6-10. Together, the estimated aboveground biomass and soil carbon pools account for a large proportion of total forest ecosystem carbon 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 include estimates of managed forest land in Hawaii and the U.S. Territories compiled using FIA estimates in this section while the area estimates for managed forest land in Hawaii and the U.S. Territories in Section 6.1 were compiled using different methods. Differences also exist because forest land area estimates are based on the latest NFI data through 2022, and woodland areas previously included as forest land have been separated and included in the grassland categories in this *Inventory*.[29]

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

	1990	2005	2019	2020	2021	2022	2023
Forest Area (1,000 ha)	***283,500***	***282,521***	***281,137***	***281,779***	***281,780***	***281,752***	***281,725***
Carbon Pools (MMT C)							
Forest Ecosystem	**55,142**	**58,536**	**61,519**	**61,717**	**61,926**	**62,130**	**62,320**
Aboveground Biomass	12,739	15,122	17,199	17,340	17,483	17,622	17,757
Belowground Biomass	2,255	2,718	3,124	3,151	3,179	3,207	3,233
Dead Wood	1,977	2,521	3,038	3,074	3,111	3,148	3,184
Litter	3,789	3,794	3,775	3,767	3,768	3,768	3,761
Soil (Mineral)	28,407	28,401	28,400	28,400	28,401	28,401	28,401
Soil (Organic)	5,976	5,981	5,983	5,983	5,983	5,983	5,983
Harvested Wood	**1,895**	**2,353**	**2,671**	**2,694**	**2,721**	**2,747**	**2,772**
Products in Use	1,249	1,447	1,523	1,530	1,538	1,547	1,555
SWDS	646	906	1,147	1,165	1,182	1,200	1,217
Total C Stock	**57,037**	**60,890**	**64,189**	**64,411**	**64,647**	**64,877**	**65,092**

Notes: Managed forest land area for Hawaii and the U.S. Territories was compiled using FIA data in this section which is different from how area estimates for those lands were compiled 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. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1 Representation of the U.S. Land Base (CRT Category 4.1). 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 (CRT Category 4A1). The forest ecosystem carbon stocks do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see Section 6.10 Settlements Remaining Settlements (CRT Category 4E1) for estimates of carbon stock change from settlement trees). Forest ecosystem carbon stocks on managed forest land in Alaska, Hawaii, and the U.S. Territories 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 2022 requires estimates of carbon stocks for 2022 and 2023.

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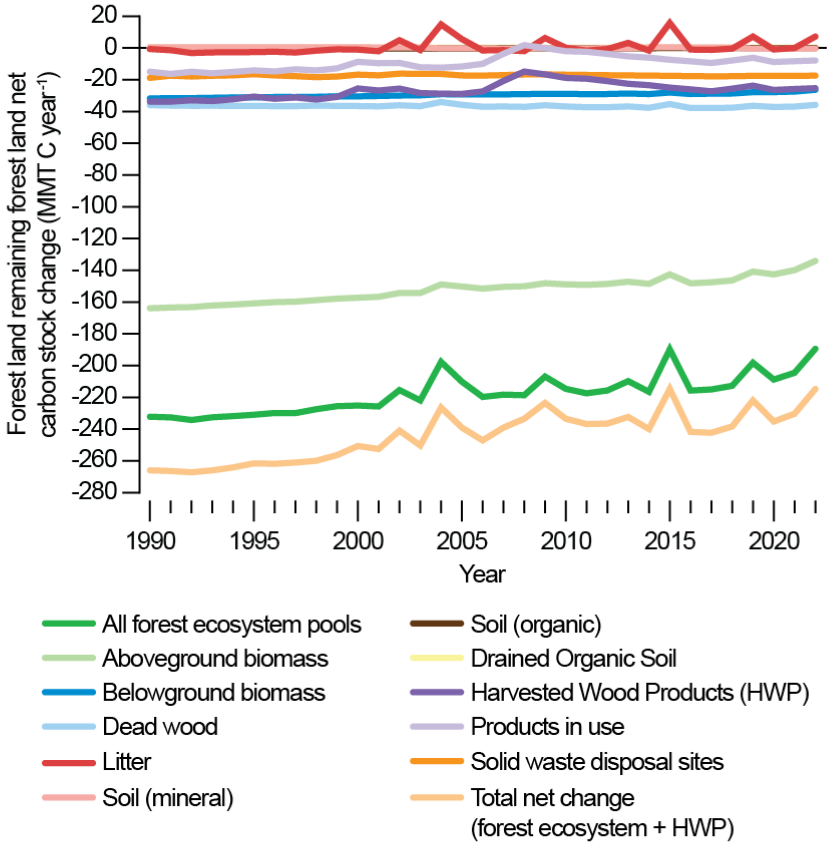
[29] See Annex 3.13, Table A-213 for annual differences between the forest area reported in Section 6.1 Representation of the U.S. Land Base and Section 6.2 Forest Land Remaining Forest Land.

Figure 6-5: Estimated Net Annual Changes in Carbon Stocks for All Carbon Pools in Forest Land Remaining Forest Land in the Conterminous United States and Alaska (1990-2022)



Box 6-3: CO_2 Emissions from Forest Fires

As stated previously, the forest inventory approach implicitly includes all carbon losses due to disturbances such as forest fires, because only carbon remaining in the forest is estimated. Net carbon stock change is estimated by subtracting consecutive carbon stock estimates. A forest fire disturbance removes carbon from the forest. The inventory data from the NFI on which net carbon stock estimates are based already reflect this carbon loss. Therefore, estimates of net annual changes in carbon stocks for U.S. forest land already includes CO_2 emissions from forest fires occurring in the conterminous states (48 states), Hawaii, Puerto Rico, and Guam 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 the UNFCCC.

Emissions estimates are developed using IPCC (2019) 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 United States for 2022 are 129.2 MMT CO_2 per year (Table 6-11). This estimate is an embedded component of the net annual forest carbon stock change estimates provided previously (i.e., Table 6-9), but this separate approach to estimating 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 carbon stock change estimates provided above.

Table 6-11: Estimates of CO$_2$ (MMT per Year) Emissions[a] from Forest Fires in the Conterminous 48 States, Hawaii, Puerto Rico, Guam, and Alaska

	1990	2005	2018	2019	2020	2021	2022
CO$_2$ emitted from fires on forest land in the Conterminous 48 States, Hawaii, Puerto Rico, and Guam (MMT yr^{-1})	11.9	28.6	77.5	19.1	124.0	156.7	71.8
CO$_2$ emitted from fires on managed forest land in Alaska (MM Tyr^{-1})	43.2	113.5	7.1	34	0.4	6.8	57.4
Total CO$_2$ emitted (MMTyr^{-1})	**55.1**	**142.2**	**84.6**	**53**	**124.4**	**163.5**	**129.2**

[a] These emissions have already been included in the estimates of net annual changes in carbon 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 the *2006 IPCC Guidelines for National Inventories*. Forest ecosystem carbon stocks and net annual carbon stock change were determined according to the stock-difference method for the conterminous United States and coastal southeast and southcentral Alaska, which involved applying carbon estimation factors to annual forest inventories across time to obtain carbon stocks and then subtracting between the years to obtain the stock change. The gain-loss method was used to estimate carbon stocks and net annual carbon stock changes in interior Alaska, Hawaii, and the U.S. Territories. The approaches for estimating carbon stocks and stock changes on forest land remaining forest land are described in Annex 3.13. All annual and periodic NFI plots available in the public FIA database (USDA Forest Service 2023b) 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 *Inventory* 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 from 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, managed forest land area estimates for Hawaii and the U.S. Territories were compiled using FIA data in this section which is different from how estimates for these lands were compiled 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 conterminous United States and coastal Alaska 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 to t_1 was then projected to 2022. This projection approach requires simulating changes in the age-class distribution resulting from forest aging and disturbance events and then applying carbon density estimates for each age class to obtain population estimates for the nation. In cases where there are t_1 estimates in the last year (e.g., 2022) of the NFI no projections are necessary for those plots.

To implement the gain-loss approach in interior Alaska, forest land conditions in Alaska were observed on NFI plots from 2014 to 2022. 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 2022. First, carbon stocks for each forest ecosystem carbon pool were predicted for the year 2016 for all NFI plot locations (each plot 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 for each 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 2022.

To implement the gain-loss approach in Hawaii and the U.S. Territories, a combination of Tier 1 and Tier 2 methods were applied. All forest land conditions were observed on annual and periodic NFI plots from 2001 to 2019 (see Annex 3.13 for specific inventories included for each Island). Plot-level data from the NFI were harmonized with data describing ecological zone (FAO 2010), soil attributes (Johnson and Kern 2003, Deenik and McClellan, 2007, IPCC 2019), and dead wood and litter carbon stocks (Oswalt et al. 2008, IPCC 2019). Only estimates of carbon stocks in live trees were consistently available in the NFI for Hawaii and the U.S. Territories for each inventory. These estimates were used to obtain average annual carbon stock change estimates for above and belowground live trees which were applied to each forest plot to capture growth, harvest removals, and mortality. The carbon stocks and annual stock change estimates were compared with country-specific estimates (Oswalt et al. 2008; Selmants et al. 2017), and IPCC (2019) default estimates to ensure they were consistent with other sources. There were limited data available on disturbances and management activities on NFI plots over the times series so Tier 1 methods were applied for dead wood and litter. It was assumed that the average transfer rate into dead wood and litter pools is equivalent to the average transfer rate out of the dead organic matter pool so there are no net carbon stock changes included for these pools in the time series (IPCC 2006). Similarly, given data limitations on forest soils and changes on NFI plots over the time series, a Tier 1 approach was also used for soil carbon with country-specific estimates (Johnson and Kern 2003) and IPCC (2019) defaults used to estimate soil carbon stocks with no net carbon stock change reported.

To estimate carbon 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 carbon in forest ecosystems within the conterminous United States and Alaska and harvested wood products for all of the United States is provided below. See Annex 3.13 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 2022. 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. This approach enables the attribution of forest carbon accumulation by forest growth, land-use change, and natural disturbances such as fire. Development will continue on a system that attributes changes in forest carbon to disturbances and delineates land converted to forest land from forest land remaining forest land. As part of this development, carbon pool science will continue and will be expanded to improve the estimates of carbon 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 carbon stock transfers associated with afforestation and deforestation (Woodall et al. 2015b). Both modules are developed from land use area statistics and carbon stock change or carbon 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 2023a, 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; Westfall et al. 2022; USDA Forest Service 2023d, 2023a). 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 or seven-panel design, with 20 percent or 14.3 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 ten 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 and periodic inventory datasets by state and U.S. Territory. 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 2023d). Forest carbon 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 carbon storage pools identified by IPCC (2006) as described above. All estimates for the conterminous United States and Alaska 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 2023b, 2023c). Carbon conversion factors were applied at the disaggregated level of each inventory plot and then appropriately expanded to population estimates. Only live (and in some cases) standing dead wood estimates are available in the annual and periodic FIA inventories in Hawaii and the U.S. Territories. For this reason, a combination of approaches was used to obtain estimates for all carbon pools for the time series in these locations.

Carbon in Biomass

Live tree carbon 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. Over the last decade, the USDA Forest Service’s FIA program and collaborators from universities and industry have been developing a new national methodology for the prediction of individual-tree volume, biomass, and carbon content. The resulting methodology is referred to as the National-Scale Volume and Biomass (NSVB) framework. The previous methodology used was the Component Ratio Method (CRM) framework (Woodall et al. 2010). While CRM was nationally consistent, tree biomass was still based on the volume predicted by regional models and tree carbon was assumed to be 50-percent of biomass, regardless of species. Hence, the need for NSVB, a nationally consistent methodology for compatible predictions of tree volume, biomass, and carbon content (Westfall et al. In press).

The NSVB covers timber tree species in the conterminous United States and coastal Alaska. All other trees (i.e., trees that are woodland species and trees within Pacific and Caribbean Islands) use regional models for volume and biomass, with updated carbon fractions (when available). While NSVB did not directly update models for trees that are considered woodland species or trees within the Pacific (USDA Forest Service 2022a, b) and Caribbean Islands (collectively referred to hereafter as “non-NSVB trees”), volume, biomass, and carbon estimates for these trees have also changed. For non-NSVB trees, the standardization of tree defects and how variables are reported (i.e., whether models for total-stem or merchantable-bole volumes are available) may be reflected as differences in volume estimates. Additionally, biomass estimates for non-NSVB trees are based on regional biomass models and no longer are adjusted as they were under the CRM. Finally, updates to carbon fractions (when available) and calculation of aboveground biomass are reflected in aboveground and belowground biomass carbon estimates (see Recalculations section and Annex 3.13 for more details).

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 ten percent of total understory carbon mass is belowground (Smith et al. 2006). Estimates of carbon density were based on information in Birdsey (1996) and tree biomass estimates from the FIADB. Understory biomass represented over one percent of carbon in biomass, but its contribution rarely exceeded two percent of the total carbon stocks or stock changes across all forest ecosystem carbon pools each year.

Carbon in Dead Organic Matter

Dead organic matter is calculated as three separate pools—standing dead trees, downed dead wood, and litter—with carbon stocks estimated from sample data or from models as described below. The standing dead tree carbon pool includes aboveground and belowground (coarse root) biomass for trees of at least 2.54 cm dbh. Calculations followed the basic methods applied to live trees (Westfall et al. 2023) with additional modifications to account for decay and structural loss (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 carbon 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 carbon is the pool of organic carbon (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 carbon. A modeling approach, using litter carbon measurements from FIA plots (Domke et al. 2016), was used to estimate litter carbon for every FIA plot used in the estimation framework. These estimates are now available in the FIADB (USDA Forest Service 2023b).

Carbon in Forest Soil

Soil carbon is the largest terrestrial carbon sink with much of that carbon 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 carbon on forest land from the FIA program and the International Soil Carbon Monitoring Network were used to develop and implement a model framework that enabled the prediction of mineral and organic (i.e., undrained organic soils) soil carbon to a depth of 100 cm from empirical measurements collected on sample plots at a depth of 20 cm and included site-, stand-, and climate-specific variables that yield predictions of soil carbon stocks specific to forest land in the United States (Domke et al. 2017). These estimates are now available in the FIADB (USDA Forest Service 2023b). This 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 carbon 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 carbon is reported to a depth of 30 cm in Section 6.3 Land Converted to Forest Land. Estimates of carbon stock changes from organic soils shown in Table 6-8 and Table 6-9 include the emissions from drained organic forest soils, and 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 carbon 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 the 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 carbon 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, carbon in exported wood was estimated as if it remains in the United States, and carbon 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 carbon 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 informational 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 forests are 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 USDC Bureau of the Census, among 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; AF&PA 2023; FAO 2023). 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 carbon in wood and paper products in use in the United States,

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

(2A) annual change of carbon 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 carbon 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) Carbon in imports of wood, pulp, and paper to the United States,

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

(5) Carbon 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 estimation 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 carbon conversion factors, were used to determine the HWP uncertainty using IPCC Approach 2. See Annex 3.13 for additional information. The 2022 net annual change for forest carbon stocks was estimated to be between –866.5 and –708.3 MMT CO_2 Eq. around a central estimate of –787.0 MMT CO_2 Eq. at a 95 percent confidence level. This includes a range of –769.6 to –618.9 MMT CO_2 Eq. around a central estimate of –694.3 MMT CO_2 Eq. for forest ecosystems and –118.0 to -70.0 MMT CO_2 Eq. around a central estimate of -92.8 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 Carbon Stocks (MMT CO_2 Eq. and Percent)

Source	Gas	2022 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	(694.3)	(769.6)	(618.9)	-10.9%	+10.9%
Harvested Wood Products[b]	CO_2	(92.8)	(118.0)	(70.0)	-27.2%	+24.6%
Total Forest	**CO_2**	**(787.0)**	**(866.5)**	**(708.3)**	**-10.1%**	**10.0%**

[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

The FIA program has conducted consistent forest surveys based on extensive statistically-based sampling of most of the forest land in the conterminous U.S., 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 carbon stock estimates. Field sampling protocols, summary data, and detailed inventory databases are archived and are publicly available (USDA Forest Service 2023d).

General quality control procedures were used in performing calculations to estimate carbon stocks based on survey data. For example, the carbon 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 2023b). Agreement between the carbon datasets and the original inventories is important to verify accuracy of the data used.

Additional verification analyses are currently underway to compare forest carbon stock change estimates developed using the NSVB model to estimates stemming from other forest biomass models as well as remote sensing imagery.

Estimates of the HWP variables and the HWP contribution under the production estimation approach use data from USDC Bureau of the Census and USDA Forest Service surveys of production and trade, among 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; AF&PA 2023; FAO 2023). Factors to convert wood and paper to units of carbon are based on estimates by industry and U.S. Forest Service published sources (see Annex 3.13). The WOODCARB II model uses estimation methods suggested by IPCC (2006). Estimates of annual carbon 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 carbon in houses standing in 2001 needs to match an independent estimate of carbon 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 carbon in products in use in the United States and, to a lesser degree, reduce uncertainty in estimates of annual change in carbon 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

There were several methodological improvements implemented in the current *Inventory* which have resulted in substantial changes when compared to the previous (1990 through 2021) *Inventory*.

First, there were new FIA data included for several states, in some cases, multiple years of new data in this *Inventory* resulting from delays that occurred due to the global pandemic. Delays still exist in some states so it is possible that multiple years of data may be available in the years ahead leading to small changes in forest ecosystem carbon stocks and stock changes throughout the time series. These changes are most notable in the conterminous United States (Table 6-14) and coastal southeast and southcentral Alaska (Table 6-15). In coastal Alaska, remeasurement data from the FIA program facilitated the use of the compilation system used in most of the conterminous United States, improving consistency and facilitating the disaggregation of forest land conversions in this region for the first time. This transition in compilation methodology resulted in a 10.6 percent increase in forest land area (449,287 ha) in coastal Alaska which contributed, in part, to increases in forest ecosystem carbon stocks across all pools (Table 6-15).

This *Inventory* also implemented new methods for estimating standing live and dead aboveground biomass carbon in the FIA program (Westfall et al. 2023). These new methods, leveraging the newly developed national-scale volume and biomass framework (NSVB), represent nearly a decade of research and development in the FIA program. The new methods: 1) greatly simplify predictions of aboveground biomass because only five model specifications are used nationally instead of dozens of species- and species-group specific models used in each region and/or state, 2) eliminate administrative boundaries (e.g., regions or states) in favor of ecologically-based regions (i.e., ecodivisons) to capture variation in tree size and volume (or biomass) within species or species groups, 3) models are based on tree measurements from in-situ data which also facilitates more accurate quantification of model uncertainty, 4) result in consistent model behavior for all tree species and sizes, and 5) use species-specific carbon fractions for biomass to carbon conversions compared to the previous method which assumed a default 50 percent biomass to carbon fraction.

The implementation of the NSVB models resulted in an increase in estimates of aboveground biomass carbon stocks on forest land in the United States of approximately 11 percent (1,761.9 MMT C) in the current *Inventory* for the year 2022 relative to the previous *Inventory* estimate for the year 2022 (Table 6-13) and accounted for 34 percent of the total increase in estimates of forest carbon stocks in this *Inventory* relative to the previous *Inventory* for the same year (Table 6-13). These increases can largely be attributed to more accurate characterization of top and limb biomass in the new models (Westfall et al. 2023). This also led to small increases in estimates of belowground biomass carbon stocks since that model is based on a ratio of aboveground biomass. There were also increases of more than 11 percent (321 MMT C) in estimates of dead wood carbon stocks due to the implementation of the new NSVB models in the FIA program for standing dead trees (Table 6-13), which accounted for 6.2 percent of the increases in estimates of forest ecosystem carbon stocks in this *Inventory* relative to the previous *Inventory* for the same year.

The litter and soil model framework used in this *Inventory* and implemented across the entire time series was formally adopted in the FIA program this year and predictions compiled using this framework are now available in the public FIA database (USDA Forest Service 2023b). As part of the formal adoption of these methods in the FIA program, all variables and associated datasets used in the models were evaluated. New climate normals for the time period 1991 to 2020 were included in both the litter and soil models using PRISM data for the conterminous

United States and climate normals for 1981 to 2010 (the only period available) were included for the first time in coastal Alaska. Collectively, these updates and improvements resulted in carbon stock estimates that were 10.1 percent larger (3,150.7 MMT C) in this *Inventory* relative to the previous *Inventory* for mineral and organic soil in the United States and overall accounted for approximately 48 percent of the total increases in forest carbon stock in the current *Inventory* for the year 2022 when compared to the previous *Inventory* for the same year (Table 6-13, Table 6-14). In coastal Alaska, there were comparable increases in predictions in the *Inventory* relative to previous *Inventories*. These increases can be attributed to increases in estimates of forest land area in coastal Alaska as well as the incorporation of climate data in the litter and soil models. Estimates of litter carbon stocks also decreased slightly on forest land remaining forest land relative to the previous Inventory (Table 6-13) due to the implementation of the NSVB models where the litter model relies on estimates of aboveground biomass as a model parameter. Finally, new data on wildfire in Interior Alaska in the latest *Inventory* also contributed to updated estimates in the time series for this area of forest land where there were decreases in the estimates of all but the organic soil carbon pools (Table 6-16). Collectively these updates and improvements resulted in a 2.3 percent decrease (119.1 MMT C) in estimates of litter carbon stocks on forest land in the United States

Managed forest land in Hawaii and several U.S. Territories were included for the first time in the current *Inventory* which resulted in an increase in managed forest land area of approximate 1.3 M ha and associated increases in carbon stocks of 286 MMT C for the year 2023 in this *Inventory*. While the inclusion of these forest land areas represents a relatively small increase in forest area and forest ecosystem carbon stocks overall, their inclusion represents an important improvement toward completeness in this *Inventory*.

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

	2022 Estimate, Previous *Inventory*	**2022 Estimate, Current *Inventory***	**2023 Estimate, Current *Inventory***
Forest Area (1000 ha)	***279,800***	***281,752***	***281,725***
Carbon Pools (MMT C)			
Forest	**56,951**	**62,130**	**62,320**
Aboveground Biomass	15,861	17,622	17,757
Belowground Biomass	3,143	3,207	3,233
Dead Wood	2,827	3,148	3,184
Litter	3,888	3,768	3,761
Soil (Mineral)	25,916	28,401	28,401
Soil (Organic)	5,317	5,983	5,983
Harvested Wood	**2,749**	**2,747**	**2,772**
Products in Use	1,549	1,547	1,555
SWDS	1,200	1,200	1,217
Total Stock	**59,701**	**64,877**	**65,092**

Note: Totals may not sum due to independent rounding.

Table 6-14: Recalculations of Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land (MMT C) in the Conterminous United States

	2022 Estimate, Previous *Inventory*	**2022 Estimate, Current *Inventory***	**2023 Estimate, Current *Inventory***
Forest Area (1000 ha)	***249,821***	***250,036***	***249,999***
Carbon Pools (MMT C)			
Forest	**46,575**	**51,195**	**51,391**
Aboveground Biomass	14,947	16,641	16,773
Belowground Biomass	2,959	3,006	3,032
Dead Wood	2,558	2,883	2,920
Litter	2,474	2,383	2,384
Soil (Mineral)	23,086	25,467	25,467

Soil (Organic)	550	815	815

Note: Totals may not sum due to independent rounding.

Table 6-15: Recalculations of Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land (MMT C) in Coastal Southeast and Southcentral Alaska

	2022 Estimate, Previous *Inventory*	2022 Estimate, Current *Inventory*	2023 Estimate, Current *Inventory*
Forest Area (1000 ha)	***4,222***	***4,671***	***4,681***
Carbon Pools (MMT C)			
Forest	**1,235**	**1,458**	**1,460**
Aboveground Biomass	362	421	423
Belowground Biomass	76	85	85
Dead Wood	94	107	107
Litter	129	130	130
Soil (Mineral)	411	470	470
Soil (Organic)	163	245	245

Note: Totals may not sum due to independent rounding.

Table 6-16: Recalculations of Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land (MMT C) in Interior Alaska

	2022 Estimate, Previous *Inventory*	2022 Estimate, Current *Inventory*	2023 Estimate, Current *Inventory*
Forest Area (1000 ha)	***25,758***	***25,758***	***25,758***
Carbon Pools (MMT C)			
Forest	**9,142**	**9,192**	**9,183**
Aboveground Biomass	551	485	484
Belowground Biomass	107	92	92
Dead Wood	176	154	153
Litter	1,285	1,248	1,240
Soil (Mineral)	2,419	2,308	2,308
Soil (Organic)	4,604	4,905	4,905

Note: Totals may not sum due to independent rounding.

Table 6-17: Recalculations of Forest Area (1,000 ha) and Carbon Stocks in Forest Land Remaining Forest Land (MMT C) in Hawaii and United States Territories

	2022 Estimate, Previous *Inventory*	2022 Estimate, Current *Inventory*	2023 Estimate, Current *Inventory*
Forest Area (1000 ha)	***NE***	***1,287***	***1,287***
Carbon Pools (MMT C)			
Forest	**NE**	**285**	**286**
Aboveground Biomass	NE	76	77
Belowground Biomass	NE	23	24
Dead Wood	NE	4	4
Litter	NE	7	7
Soil (Mineral)	NE	156	156
Soil (Organic)	NE	19	19

NE (Not Estimated)
Note: Totals may not sum due to independent rounding.

The new FIA data and methodological improvements described throughout this text and specifically in this section on recalculations of estimates of forest ecosystem carbon stocks extend to forest ecosystem carbon stock changes in the current *Inventory*. In total, estimates for the forest land remaining forest land sink increased 21.4 percent (sink estimates increased by 40.8 MMT C). On average across the time-series, these recalculations resulted in a 21.7 percent increase in estimates of the forest sink across the time series (sink estimates increased on average, 43.4 MMT C over the time series) relative to the previous *Inventory* (Table 6-18).

Changes in estimates of forest ecosystem carbon stock changes accounted for most of the increases between this *Inventory* and the previous *Inventory* (Table 6-18) and of those, new data and improvements in methods in the conterminous United States accounted for 97 percent (-41.8 MMT C) increases in estimates of forest ecosystem carbon stock changes in the current Inventory relative to the same year in the previous Inventory (Table 6-19). Estimates of carbon stock changes in the aboveground biomass pool increased by 25.2 percent in the current Inventory relative to the same year in the previous Inventory and accounted for 65.2 percent (-27.2 MMT C) of the increase in estimates from this *Inventory* (Table 6-19). These changes can be directly attributed to the implementation of the NSVB models in the FIA program. These increases extend to the belowground biomass pool where the increases in estimates of aboveground biomass resulted in increases in the estimates of belowground biomass by 23.8 percent (-5.1 MMT C). These increases accounted for 12.2 percent of the total increase in carbon stock changes in the forest ecosystem pools in this *Inventory*. There were also substantial increases in dead wood carbon stock changes which can also be attributed to the implementation of the NSVB models for standing dead trees (Westfall et al. In press). There was a 34.4 percent increase (-9.5 MMT C) in estimates of dead wood carbon stock changes between this Inventory and the same year in the previous Inventory. This increase in the estimates of dead wood accounts for 22.8 percent of the total increases in estimates of forest ecosystem carbon stock changes in this Inventory relative to the same year in the previous *Inventory* (Table 6-19).

There were also small differences in the estimates of carbon stock changes for the litter and the soil carbon pools in the conterminous United States, coastal and Interior Alaska (Table 6-19, Table 6-20, Table 6-21). These changes were all relatively small when compared to changes in live and standing dead biomass.

The inclusion of forest land in Hawaii and several U.S. Territories also contributed to increases in the estimates of carbon stock changes in the current Inventory. Collectively, these areas contributed -1.3 MMT C to the forest land remaining forest land carbon sink in the year 2022 in the current *Inventory* (Table 6-22).

Finally, new data included in the HWP time series resulted in a minor decrease (< 1 percent) in carbon stocks in the HWP pools (Table 6-13) and an associated decrease of 7.9 percent (2.2 MMT C) in estimates of carbon stock changes (Table 6-18). These decreases are the result of decreases in estimates of carbon stock changes for products in use (19.4 percent) in the current *Inventory* relative to the same year in the previous *Inventory* (Table 6-18). With the easing of the global pandemic and the return of consumers to the marketplace, there was a rebound in the purchase and accumulation of solid wood products. Alternatively, paper products in use have been declining in recent years, which could be the result of greater digitization across society. These trends are expected to continue in 2023.

Table 6-18: Recalculations of Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land and Harvested Wood Pools (MMT C)

Carbon Pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Forest	**(161.6)**	**(204.4)**	**(189.3)**
Aboveground Biomass	(111.6)	(139.9)	(134.1)
Belowground Biomass	(22.1)	(27.5)	(26.4)
Dead Wood	(27.6)	(36.9)	(35.8)
Litter	0.5	(0.0)	7.2
Soil (Mineral)	(1.1)	(0.2)	(0.3)
Soil (Organic)	0.0	(0.0)	(0.0)
Drained organic soil	0.2	0.2	0.2
Harvested Wood	**(28.0)**	**(25.8)**	**(25.3)**
Products in Use	(10.3)	(8.3)	(7.9)
SWDS	(17.7)	(17.5)	(17.4)

Total Net Flux	**(189.6)**	**(230.2)**	**(214.6)**

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

Table 6-19: Recalculations of Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land (MMT C) in the Conterminous United States

Carbon Pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Forest	**(158.5)**	**(200.3)**	**(195.9)**
Aboveground Biomass	(108.1)	(135.3)	(132.1)
Belowground Biomass	(21.3)	(26.4)	(25.8)
Dead Wood	(27.7)	(37.2)	(36.8)
Litter	(0.5)	(1.0)	(0.8)
Soil (Mineral)	(1.1)	(0.2)	(0.3)
Soil (Organic)	0.0	(0.1)	(0.1)

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

Table 6-20: Recalculations of Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land (MMT C) in Coastal Alaska

Carbon Pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Forest	**(2.0)**	**(1.9)**	**(1.9)**
Aboveground Biomass	(1.3)	(1.4)	(1.4)
Belowground Biomass	(0.3)	(0.3)	(0.3)
Dead Wood	(0.3)	(0.1)	(0.1)
Litter	0.0	(0.1)	(0.1)
Soil (Mineral)	0.0	0.0	0.0
Soil (Organic)	0.0	0.0	0.0

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

Table 6-21: Recalculations of Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land (MMT C) in Interior Alaska

Carbon Pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Forest	**(1.2)**	**(1.1)**	**9.6**
Aboveground Biomass	(2.1)	(2.1)	0.4
Belowground Biomass	(0.5)	(0.5)	0.0
Dead Wood	0.4	0.4	1.1
Litter	1.0	1.0	8.0
Soil (Mineral)	0.0	0.0	0.0
Soil (Organic)	0.0	0.0	0.0

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

Table 6-22: Recalculations of Net Carbon Flux from Forest Ecosystem Pools in Forest Land Remaining Forest Land (MMT C) in Hawaii and United States Territories

Carbon Pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Forest	**NE**	**(1.4)**	**(1.3)**
Aboveground Biomass	NE	(1.0)	(1.0)
Belowground Biomass	NE	(0.3)	(0.3)
Dead Wood	NE	(0.0)	0.0

Litter	NE	0.0	(0.0)
Soil (Mineral)	NE	(0.0)	0.0
Soil (Organic)	NE	0.0	0.0

NE (Not Estimated)

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

Planned Improvements

Reliable estimates of forest carbon 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 carbon pool estimation, coordination with other land-use categories, and periodic and annual inventory data incorporation.

While this *Inventory* submission includes carbon change by forest land remaining forest land and land converted to forest land and carbon stock changes for all IPCC pools in these two categories, there are many improvements that are still necessary. The estimation approach used for the conterminous United States 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*, including coastal Alaska, research is underway to leverage all FIA data (periodic and annual inventories) 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 streamlined 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 periodic and annual NFI (USDA Forest Service 2023b). 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 was used to estimate uncertainty associated with carbon stock changes in the forest land remaining forest land category in this report. There is research underway investigating more robust approaches to estimate 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 carbon pool (Smith et al. 2022) will be updated similar to the litter (Domke et al. 2016) and soil carbon pools (Domke et al. 2017). With the implementation of the new models for volume, biomass, and carbon estimation for live and standing dead trees, the methods for litter and soil carbon estimation used in this *Inventory* and recent *Inventories* have been adopted in the FIA program so there is now alignment and consistency between litter and soil carbon estimates in this *Inventory* and the FIA database. Finally, components of other pools, such as carbon 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 carbon 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 carbon estimates as new state surveys become available (USDA Forest Service 2023b). With the exception of Wyoming (which will have sufficient remeasurements in the years ahead), all other states in the conterminous United States and coastal Alaska now have sufficient annual NFI data to consistently estimate carbon stocks and stock changes for the future using the state-level compilation system. The FIA program continues to install permanent plots in interior 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. Estimates of carbon stocks and stock changes for Hawaii and the U.S. Territories were included in this *Inventory* using Tier 1 and Tier 2 methods. The methods used to include all managed forest land in the conterminous United States will be used in future Inventories for Hawaii and U.S. Territories as additional forest carbon 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 (i.e., disturbance or land-use changes) detection and attribution across the entire reporting period and all managed forest land in the United States. Leveraging this auxiliary information will aid the efforts to improve estimates for interior Alaska, Hawaii, and the U.S. Territories, as well as the entire inventory system. In addition to fully inventorying all managed forest land in the United States, the more intensive sampling (i.e., more samples) of fine woody debris, litter, and SOC on a subset of FIA plots continues and will substantially improve spatial and temporal resolution of carbon pools (Westfall et al. 2013) as this information becomes available. Increased sample intensity of some carbon 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 (2019). In 2022, emissions from this source were estimated to be 9.1 MMT CO_2 Eq. of CH_4 and 5.7 MMT CO_2 Eq. of N_2O (Table 6-23; kt units provided in Table 6-24). The estimates of non-CO_2 emissions from forest fires include the conterminous 48 states, Hawaii, Puerto Rico, Guam and managed forest land in Alaska (Ogle et al. 2018) because the fire data in use with the current methods identifies fires on these areas within the interval 1990 through 2022.

Table 6-23: Non-CO_2 Emissions from Forest Fires (MMT CO_2 Eq.)[a]

Gas	1990	2005	2018	2019	2020	2021	2022
CH_4	3.4	9.2	6.0	3.4	9.8	12.7	9.1
N_2O	2.4	6.3	3.7	2.3	5.5	7.2	5.7
Total	**5.8**	**15.4**	**9.7**	**5.7**	**15.3**	**19.9**	**14.8**

[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 6-24: Non-CO_2 Emissions from Forest Fires (kt)[a]

Gas	1990	2005	2018	2019	2020	2021	2022
CH_4	122	328	213	120	349	452	327
N_2O	9	24	14	9	21	27	22
CO	3179	8447	4648	3054	7266	9598	7593
NO_x	49	124	93	51	123	160	121

[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 (2019) methodology, which represent updates of the IPCC (2006) guidance on reporting fire emissions. For the conterminous states and Alaska, estimates were developed with U.S.-specific data and models on area burned, fuel, consumption, and emissions as provided through the Wildland Fire Emissions Inventory System calculator (WFEIS, French et al. 2011, 2014). However, these fire emissions models did not extend to include Hawaii, Puerto Rico, or Guam, so forest fire estimates for these areas relied on Tier 1 emissions factors (IPCC 2019). Spatial definitions of wildland burned areas were the starting point for all estimates, from WFEIS or Tier 1. The three burned area datasets in use are the Monitoring Trends in Burn Severity (MTBS, Eidenshink et al. 2007), MODIS burned area mapping (MODIS MCD64A1 V6.1, Giglio et al. 2018), and Wildland Fire Interagency Geospatial Service (WFIGS) fire perimeters (WFIGS 2023). The MTBS data available for this report (MTBS 2023) included fires from 1990 through 2021 for all states and Puerto Rico (the exception was Alaska 2021 where emissions calculations were not available). The MODIS-based records include 2001 through 2022 for the 48 conterminous states plus Alaska. The WFIGS-based records for 2020 through 2022 included all states plus Puerto Rico and Guam. 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 (Larkin et al. 2014; IPCC 2019). See the emissions from forest fires section in Annex 3.13 for further details on all fire-related emissions calculations for forests. Consistent use of available data sources, data processing, and calculation methods were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

Uncertainty

Uncertainty estimates for non-CO_2 emissions from forest fires are based on a Monte Carlo (IPCC Approach 2) approach to propagate variability among the alternate WFEIS annual estimates per state. Uncertainty in parts of the WFEIS system are not currently quantified. Among potential sources for future analysis are burned areas from MTBS, WFIGS, or MODIS, the fuels models or the Consume model (Prichard et al. 2014). 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 6-25.

Table 6-25: Quantitative Uncertainty Estimates of Non-CO_2 Emissions from Forest Fires (MMT CO_2 Eq. and Percent)[a]

Source	Gas	2022 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	9.1	6.2	12.1	-32%	+32%
Non-CO_2 Emissions from Forest Fires	N_2O	5.7	3.6	7.8	-36%	+37%

[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 2022) *Inventory* to compile estimates of non-CO_2 emissions from forest fires represent a slight change relative to the previous (1990 through 2021) *Inventory*. The basic components of calculating forest fire emissions (IPCC 2019) remain unchanged, but the WFEIS-based estimates now include MTBS, WFIGS, and MODIS based burns (depending on year). The MTBS and WFIGS based estimates are now calculated per burn event (i.e., separately for each forest fire), which improves precision for scaling or allocating emissions such as to managed versus unmanaged lands in Alaska.

An additional source of change leading to recalculations are recent and ongoing updates to the MTBS fire records (i.e., including both most-recent as well as possible updates to past years' fires). The WFEIS calculations now use version 6.1 of the MODIS burned area model and updated versions of the Fuel Characteristic Classification System (FCCS) fuel layer and the Consume model (see WFEIS 2023) for additional details on updates. The addition of forest fire emissions for Hawaii, Puerto Rico, and Guam had little effect on the magnitude of overall emissions.

Estimates of non-CO_2 emissions from forest fires (e.g., Table 6-24) are lower for most years over the time series 1990-2021 in comparison with the previous Inventory (EPA 2023), with an average decrease of 12 percent across all years. For, 2021 the estimate decreased from 24.4 to 19.9 MMT CO_2 Eq. (an 18.7 percent decrease). Changes over the time series are expected because the entire interval is recalculated each year in response to modifications in the fire datasets that can affect all years. For example, MTBS updates burn perimeters for all years as data resolution changes. This year, the WFEIS calculator updated a fuel dataset as well as the Consume model (noted above). The addition of estimates for Hawaii, Puerto Rico, and Guam had negligible effect on the estimates.

Planned Improvements

Continuing improvements are planned for developing better fire and site-specific estimates for forest fires, for example, improving on the Tier-1 factors currently employed for Hawaii, Puerto Rico, and Guam. Additional focus will be on addressing three aspects of reporting: best use of WFEIS, better resolution of uncertainty as discussed above, and identification of burned areas that are not currently captured by the burn records in use.

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 off-site locations. 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[30] in 2022 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 2022 were 0.4 MMT CO_2 Eq. (1.5 kt) and have increased by 455 percent from 1990 to 2022. Total forest soil N_2O emissions are summarized in Table 6-26.

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[30] 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.

Table 6-26: 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	2018	2019	2020	2021	2022
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	0.2	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	0.1	0.4	0.4	0.4	0.4	0.4	0.4
Total							
MMT CO_2 Eq.	**0.1**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
kt N_2O	**0.3**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**

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

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 2022, 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 stands (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 2022, 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 2022.

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 carbon 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 nitrogen fertilizer. All forest soils are treated equivalently under this methodology. Furthermore, only applications of synthetic nitrogen fertilizers to forest are captured in this *Inventory*, so applications of organic nitrogen fertilizers are not estimated. However, the total quantity of organic nitrogen inputs to soils in the United States is included in the *Inventory* within the agricultural soil management source category (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[31] of uncertainty at ±50 percent, and area receiving fertilizer is assigned a ±20 percent according to expert knowledge (Binkley 2004). IPCC (2006) 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 6-27. Direct N_2O fluxes from soils in 2022 are estimated to be between 0.1 and 1.0 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 2022. Indirect N_2O emissions in 2022 are 0.1 MMT CO_2 Eq. and have a range are between 0.01 and 0.3 MMT CO_2 Eq., which is 86 percent below to 238 percent above the emission estimate for 2022.

Table 6-27: 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	2022 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	1.0	-59%	+211%
Indirect N_2O Fluxes from Soils	N_2O	0.1	+	0.3	-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 current *Inventory*.

CO_2, CH_4, and N_2O Emissions from Drained Organic Soils[32]

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*

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

[32] Estimates of 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 carbon stock changes on forest lands in a complete and comprehensive manner.

(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 content. 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 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 2022 are estimated as 0.1 MMT CO_2 Eq. per year (Table 6-28; kt units provided in Table 6-29).

The Tier 1 methodology provides methods to estimate emissions of 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 6-28: Non-CO_2 Emissions from Drained Organic Forest Soils[a,b] (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
CH_4	+	+	+	+	+	+	+
N_2O	0.1	0.1	0.1	0.1	0. 1	0.1	0.1
Total	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**

+ 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 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 carbon stock changes on forest lands in a complete and comprehensive manner.

Note: Totals may not sum due to independent rounding.

Table 6-29: Non-CO_2 Emissions from Drained Organic Forest Soils[a,b] (kt)

Source	1990	2005	2018	2019	2020	2021	2022
CH_4	1	1	1	1	1	1	1
N_2O	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.

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[a] This table includes estimates from forest land remaining forest land and land converted to forest land.

[b] Estimates of 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 carbon 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 6-30).

Table 6-30: 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 carbon 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 (DOC) 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 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 conducted 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 conducted 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 2022. 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 6-31). 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 number of significant digits in the resulting estimates, relative to past values. The total non-CO_2 emissions in 2022 from drained organic soils on forest land remaining forest land and land converted to forest land were estimated to be between zero and 0.150 MMT CO_2 Eq. around a central estimate of 0.068 MMT CO_2 Eq. at a 95 percent confidence level.

Table 6-31: Quantitative Uncertainty Estimates for Non-CO_2 Emissions on Drained Organic Forest Soils (MMT CO_2 Eq. and Percent)[a]

Source	2022 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**	**-107%**	**+121%**

+ 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 carbon from drainage waters may be double counted if soil carbon stock and change is based on sampling and this carbon 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 current *Inventory*.

Planned Improvements

Additional data will be compiled to update estimates of forest areas on drained organic soils as new reports and geospatial products become available. For example, current and recent past estimates are based on drained organic soils identified in a limited number of the conterminous states; if forests on drained organic soils are identified in additional areas including Alaska, Hawaii, Puerto Rico, or Guam, they will be included in future *Inventories*.

6.3 Land Converted to Forest Land (CRT Category 4A2)

The carbon 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.[33] 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 carbon 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[34]

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.

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[33] 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.

[34] The estimates reported in this section only include the 48 conterminous states in the United States. Land use conversions to forest land in Alaska are currently included in the Forest Land Remaining Forest Land section because currently there is insufficient data to separate the changes and estimates for Hawaii were not included because there is insufficient NFI data to support inclusion at this time. Also, it is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1 Representation of the U.S. Land Base (CRT Category 4.1). 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 6.3 Land Converted to Forest Land.

Over the 20-year conversion period used in the land converted to forest land category, the conversion of grassland to forest land resulted in the largest source of carbon transfer and uptake, accounting for approximately 38 percent of the uptake annually. Estimated carbon uptake has remained relatively stable over the time series across all conversion categories (see Table 6-24). The net flux of carbon from all forest pool stock changes in 2022 was -100.3 MMT CO_2 Eq. (-27.4 MMT C) (see Table 6-24 and Table 6-25).

Mineral soil carbon stocks increased 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 carbon. In contrast, grassland converted to forest land leads to a loss of soil carbon across the time series, which negates some of the gain in soil carbon with the other land-use conversions. Managed pasture to forest land is the most common conversion. This conversion leads to a loss of soil carbon because pastures are mostly improved in the

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United States with fertilization and/or irrigation, which enhances carbon input to soils relative to typical forest management activities.

Table 6-32: Net CO_2 Flux from Forest Carbon Pools in Land Converted to Forest Land by Land Use Change Category (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Forest Land	**(17.6)**	**(17.5)**	**(17.3)**	**(17.3)**	**(17.2)**	**(17.2)**	**(17.2)**
Aboveground Biomass	(10.2)	(10.1)	(10.0)	(10.0)	(10.0)	(10.0)	(10.0)
Belowground Biomass	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)	(1.7)
Dead Wood	(2.2)	(2.2)	(2.2)	(2.2)	(2.2)	(2.2)	(2.2)
Litter	(3.3)	(3.2)	(3.2)	(3.2)	(3.2)	(3.2)	(3.2)
Mineral Soil	(0.2)	(0.2)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)
Grassland Converted to Forest Land	**(36.7)**	**(36.9)**	**(37.2)**	**(37.2)**	**(37.2)**	**(37.2)**	**(37.2)**
Aboveground Biomass	(22.5)	(22.7)	(22.8)	(22.8)	(22.8)	(22.8)	(22.8)
Belowground Biomass	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)
Dead Wood	(4.0)	(4.1)	(4.1)	(4.1)	(4.1)	(4.1)	(4.1)
Litter	(7.6)	(7.7)	(7.7)	(7.7)	(7.7)	(7.7)	(7.7)
Mineral Soil	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Other Land Converted to Forest Land	**(5.2)**	**(5.3)**	**(5.5)**	**(5.5)**	**(5.5)**	**(5.5)**	**(5.5)**
Aboveground Biomass	(2.2)	(2.2)	(2.3)	(2.3)	(2.3)	(2.3)	(2.3)
Belowground Biomass	(0.3)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
Dead Wood	(0.7)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)	(0.8)
Litter	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)
Mineral Soil	(0.7)	(0.8)	(1.0)	(0.9)	(0.9)	(0.9)	(0.9)
Settlements Converted to Forest Land	**(31.9)**	**(31.6)**	**(31.4)**	**(31.4)**	**(31.4)**	**(31.4)**	**(31.4)**
Aboveground Biomass	(19.8)	(19.6)	(19.5)	(19.4)	(19.4)	(19.4)	(19.4)
Belowground Biomass	(3.4)	(3.3)	(3.3)	(3.3)	(3.3)	(3.3)	(3.3)
Dead Wood	(3.8)	(3.8)	(3.8)	(3.8)	(3.8)	(3.8)	(3.8)
Litter	(4.9)	(4.8)	(4.8)	(4.8)	(4.8)	(4.8)	(4.8)
Mineral Soil	(0.0)	(0.03)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Wetlands Converted to Forest Land	**(8.8)**	**(8.9)**	**(8.9)**	**(8.9)**	**(8.9)**	**(8.9)**	**(8.9)**
Aboveground Biomass	(4.9)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)	(5.0)

Belowground Biomass	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)
Dead Wood	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)	(1.2)
Litter	(1.8)	(1.8)	(1.8)	(1.8)	(1.8)	(1.8)	(1.8)
Mineral Soil	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Aboveground Biomass Flux	**(59.7)**	**(59.6)**	**(59.6)**	**(59.6)**	**(59.6)**	**(59.6)**	**(59.6)**
Total Belowground Biomass Flux	**(9.0)**	**(9.0)**	**(9.0)**	**(9.0)**	**(9.0)**	**(9.0)**	**(9.0)**
Total Dead Wood Flux	**(12.0)**	**(12.0)**	**(12.1)**	**(12.1)**	**(12.1)**	**(12.1)**	**(12.1)**
Total Litter Flux	**(18.8)**	**(18.8)**	**(18.8)**	**(18.8)**	**(18.8)**	**(18.8)**	**(18.8)**
Total Mineral Soil Flux	**(0.8)**	**(0.8)**	**(1.0)**	**(0.9)**	**(0.9)**	**(0.9)**	**(0.9)**
Total Flux	**(100.2)**	**(100.2)**	**(100.4)**	**(100.3)**	**(100.3)**	**(100.3)**	**(100.3)**

Notes: Totals may not sum due to independent rounding. Parentheses indicate net uptake. Forest ecosystem carbon stock changes from land conversion in interior Alaska, Hawaii, and the U.S. Territories are currently included in the forest land remaining forest land section because there is insufficient data to separate the changes at this time. It is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1 Representation of the U.S. Land Base. 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. The forest ecosystem carbon stock changes from land conversion do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see 6.10 Settlements Remaining Settlements (CRT Category 4E1) for estimates of carbon 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 of the Forest Land Remaining Forest Land section of the *Inventory*.

Table 6-33: Net Carbon Flux from Forest Carbon Pools in Land Converted to Forest Land by Land Use Change Category (MMT C)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Forest Land	**(4.8)**	**(4.8)**	**(4.7)**	**(4.7)**	**(4.7)**	**(4.7)**	**(4.7)**
Aboveground Biomass	(2.8)	(2.8)	(2.7)	(2.7)	(2.7)	(2.7)	(2.7)
Belowground Biomass	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)
Dead Wood	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)
Litter	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)
Mineral Soil	(0.1)	(0.1)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
Grassland Converted to Forest Land	**(10.0)**	**(10.1)**	**(10.2)**	**(10.2)**	**(10.2)**	**(10.2)**	**(10.1)**
Aboveground Biomass	(6.1)	(6.2)	(6.2)	(6.2)	(6.2)	(6.2)	(6.2)
Belowground Biomass	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)	(0.7)
Dead Wood	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)	(1.1)
Litter	(2.1)	(2.1)	(2.1)	(2.1)	(2.1)	(2.1)	(2.1)
Mineral Soil	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Other Land Converted to Forest Land	**(1.4)**	**(1.4)**	**(1.5)**	**(1.5)**	**(1.5)**	**(1.5)**	**(1.5)**
Aboveground Biomass	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)	(0.6)
Belowground Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Wood	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Litter	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Mineral Soil	(0.2)	(0.2)	(0.3)	(0.2)	(0.3)	(0.3)	(0.3)
Settlements Converted to Forest Land	**(8.7)**	**(8.6)**	**(8.6)**	**(8.6)**	**(8.6)**	**(8.6)**	**(8.6)**
Aboveground Biomass	(5.4)	(5.4)	(5.3)	(5.3)	(5.3)	(5.3)	(5.3)
Belowground Biomass	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)	(0.9)
Dead Wood	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)

Litter	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)	(1.3)
Mineral Soil	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)
Wetlands Converted to Forest Land	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**
Aboveground Biomass	(1.3)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)	(1.4)
Belowground Biomass	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Dead Wood	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)	(0.3)
Litter	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)	(0.5)
Mineral Soil	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Aboveground Biomass Flux	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**	**(16.3)**
Total Belowground Biomass Flux	**(2.5)**	**(2.5)**	**(2.5)**	**(2.4)**	**(2.4)**	**(2.4)**	**(2.4)**
Total Dead Wood Flux	**(3.3)**	**(3.3)**	**(3.3)**	**(3.3)**	**(3.3)**	**(3.3)**	**(3.3)**
Total Litter Flux	**(5.1)**	**(5.1)**	**(5.1)**	**(5.1)**	**(5.1)**	**(5.1)**	**(5.1)**
Total Mineral Soil Flux	**(0.2)**	**(0.2)**	**(0.3)**	**(0.2)**	**(0.2)**	**(0.3)**	**(0.2)**
Total Flux	**(27.3)**	**(27.3)**	**(27.4)**	**(27.4)**	**(27.4)**	**(27.4)**	**(27.4)**

+ Absolute value does not exceed 0.05 MMT C.

Notes: Totals may not sum due to independent rounding. Parentheses indicate net uptake. Forest ecosystem carbon stock changes from land conversion in interior Alaska, Hawaii, and the U.S. Territories are currently included in the forest land remaining forest land section because there is not sufficient data to separate the changes at this time. It is not possible to separate forest land remaining forest land from land converted to forest land in Wyoming because of the split annual cycle method used for population estimation, this prevents harmonization of forest land in Wyoming with the NRI/NLCD method used in Section 6.1 Representation of the U.S. Land Base. 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. The forest ecosystem carbon stock changes from land conversion do not include trees on non-forest land (e.g., agroforestry systems and settlement areas—see 6.10 Settlements Remaining Settlements (CRT Category 4E1) for estimates of carbon 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 6-9 and Table 6-10 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 carbon pools for land converted to forest land. National Forest Inventory data and IPCC (2006) defaults for reference carbon stocks were used to compile separate estimates for the five carbon 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 2023b, 2023c). Carbon conversion factors were applied at the individual plot and then appropriately expanded to state population estimates, which are summed to provide the national estimate. To ensure consistency in the land converted to forest land category where carbon 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 carbon stock values were applied in the year of conversion on individual plots to estimate the C stocks removed due to land-use conversion from croplands and grasslands. There is no biomass loss data or IPCC (2006) defaults to include transfers, losses, or gains of carbon in the year of the conversion for other land use (i.e., other lands, settlements, wetlands) conversions to forest land so these were incorporated for these conversion categories. All annual NFI plots included in the public FIA database as of September 2023 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 2022. This projection approach requires simulating changes in the age-class distribution resulting from forest aging and disturbance events and then applying carbon density estimates for each age class to obtain population estimates for the nation.

Carbon in Biomass

Live tree carbon 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, aboveground tree carbon was based on Westfall et al. (2023). The component ratio method (CRM) which is a function of volume, species, and diameter was used to compile estimates for woodland species where diameter measurements are taken at root collar and to compile belowground biomass carbon for all tree species (Woodall et al. (2011a). An additional component of foliage, which was not explicitly included in Woodall et al. (2011a), was added to each woodland 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 carbon mass is belowground (Smith et al. 2006). Estimates of carbon density were based on information in Birdsey (1996) and biomass estimates from Jenkins et al. (2003). Understory biomass represented over one percent of carbon 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. As previously discussed, 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 carbon stocks estimated from sample data or from models. The standing dead tree carbon pool includes aboveground and belowground (coarse root) biomass for trees of at least 2.54 cm dbh. Calculations followed the basic method applied to live trees (Westfall et al. 2023, Woodall et al. 2011a) with additional modifications to account for decay and structural loss (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 carbon 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 carbon is the pool of organic carbon (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 carbon. A modeling approach, using litter carbon measurements from FIA plots (Domke et al. 2016) was used to estimate litter carbon for every FIA plot used in the estimation framework. Dead organic matter carbon stock estimates are included for all land-use conversions to forest land.

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) and the 2017 National Resources Inventory (NRI) (USDA-NRCS 2020. The areas have been modified in the NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (NLCD; Yang et al. 2018) are harmonized with the NRI data. This process ensures that the land use areas are consistent across all land-use categories (see Section 6.1, Representation of the U.S. Land Base for more information). 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). See Annex 3.12 for more information about this method.

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. Mineral soil organic C stock changes from 2021 to 2022 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 2020 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 2021 to 2022 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 carbon 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 carbon 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 to propagate errors with estimation of mineral soils carbon stock changes for land-use conversions, and is described in the cropland remaining cropland section.

Uncertainty estimates are presented in Table 6-34 for each land conversion category and carbon pool. Uncertainty estimates were obtained using a combination of sample-based and model-based approaches for all non-soil carbon 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 carbon stocks in land converted to forest land ranged from 11 percent below to 11 percent above the 2022 carbon stock change estimate of –100.3 MMT CO_2 Eq.

Table 6-34: Quantitative Uncertainty Estimates for Forest Carbon Pool Stock Changes (MMT CO_2 Eq. per Year) in 2022 from Land Converted to Forest Land by Land Use Change

Land Use/Carbon Pool	2022 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	(17.2)	(25.8)	(8.7)	-50%	50%
Aboveground Biomass	(10.0)	(18.4)	(1.7)	-83%	83%
Belowground Biomass	(1.7)	(2.7)	(0.7)	-61%	61%
Dead Wood	(2.2)	(3.4)	(1.0)	-56%	56%

Litter	(3.2)	(4.3)	(2.1)	-34%	34%
Non-federal Mineral Soils	(0.1)	(0.3)	0.0	-142%	142%
Federal Mineral Soils	(0.0)	(0.1)	0.1	-8,796%	8,796%
Grassland Converted to Forest Land	(37.2)	(39.6)	(34.8)	-6%	6%
Aboveground Biomass	(22.8)	(24.2)	(21.5)	-6%	6%
Belowground Biomass	(2.7)	(3.0)	(2.5)	-10%	10%
Dead Wood	(4.1)	(4.3)	(4.0)	-3%	3%
Litter	(7.7)	(8.3)	(7.2)	-7%	7%
Non-federal Mineral Soils	0.2	(0.1)	0.5	-142%	142%
Federal Mineral Soils	0.0	(0.1)	0.1	-1,310%	1,310%
Other Lands Converted to Forest Land	(5.5)	(7.8)	(3.2)	-42%	42%
Aboveground Biomass	(2.3)	(4.4)	(0.2)	-92%	92%
Belowground Biomass	(0.4)	(0.8)	0.1	-121%	121%
Dead Wood	(0.8)	(1.3)	(0.2)	-74%	74%
Litter	(1.2)	(1.8)	(0.6)	-53%	53%
Non-federal Mineral Soils	(0.9)	(1.4)	(0.5)	-49%	49%
Federal Mineral Soils	(0.0)	(0.2)	0.1	-666%	666%
Settlements Converted to Forest Land	(31.4)	(37.9)	(24.9)	-21%	21%
Aboveground Biomass	(19.4)	(25.6)	(13.3)	-32%	32%
Belowground Biomass	(3.3)	(4.6)	(2.0)	-40%	40%
Dead Wood	(3.8)	(4.9)	(2.6)	-31%	31%
Litter	(4.8)	(5.7)	(3.9)	-19%	19%
Non-federal Mineral Soils	(0.1)	(0.1)	(0.0)	-32%	32%
Federal Mineral Soils	(0.0)	(0.0)	0.0	-193%	193%
Wetlands Converted to Forest Land	(8.9)	(9.1)	(8.8)	-2%	2%
Aboveground Biomass	(5.0)	(5.2)	(4.9)	-3%	3%
Belowground Biomass	(0.9)	(0.9)	(0.9)	-3%	3%
Dead Wood	(1.2)	(1.3)	(1.2)	-4%	4%
Litter	(1.8)	(1.9)	(1.7)	-3%	3%
Non-federal Mineral Soils	0.0	0.0	0.0	0%	0%
Federal Mineral Soils	0.0	0.0	0.0	0%	0%
Total: Aboveground Biomass	(59.6)	(70.3)	(48.9)	-18%	18%
Total: Belowground Biomass	(9.0)	(10.7)	(7.2)	-19%	19%
Total: Dead Wood	(12.1)	(13.8)	(10.3)	-15%	15%
Total: Litter	(18.8)	(20.4)	(17.2)	-9%	8%
Total: Mineral Soils	(0.9)	(1.3)	(0.5)	-42%	42%
Total: Lands Converted to Forest Lands	(100.3)	(111.4)	(89.2)	-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 carbon stocks removed from croplands and grasslands in the year of conversion on individual plots and the Tier 2 method for estimating mineral soil carbon stock changes (Ogle et al. 2003, 2006; IPCC 2006). All annual NFI plots included in the public FIA database as of September 2023 were used in this *Inventory*. This is the fourth year that remeasurement data from the annual NFI were available throughout the conterminous United States (with the exception of Wyoming) and coastal southeast and southcentral Alaska to estimate land-use conversion. The availability of remeasurement data from the annual NFI allowed for consistent plot-level estimation of carbon 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 carbon stock changes increased by approximately 2 percent in 2022 between the previous *Inventory* (1990 through 2021) and the current *Inventory* (Table 6-35). While the overall change is relatively small, changes by conversion categories were substantial between this *Inventory* and the previous *Inventory*. These changes can be attributed to six methodological improvements implemented this year. First, managed pastureland was previously classified as cropland and is now classified as grassland to align with NRI definitions and classifications. This resulted in a substantial structural decrease in the cropland converted to forest land category area and associated carbon stock changes and a substantial structural increase in the grassland converted to forest land area and associated carbon stock changes. Second, in this *Inventory* all NFI plots with evidence of water are classified as wetlands to align with definitions and classifications in the NRI. In the previous *Inventory*, some NFI plots with evidence of water were classified as other land. This methodological improvement resulted in increases in the wetlands converted to forest land category and decreases in the other land converted to forest land category. Third, estimates of carbon stocks and stock changes on managed forest land in coastal Alaska are now compiled in the same ways as the conterminous United States allowing for estimates of land conversions. This led to small increases in the area and associated carbon stock change estimates in the land converted to forest land category. Fourth, the implementation of new methods for estimating aboveground biomass carbon in live and standing dead trees resulted in changes across all land use conversion categories in the aboveground and belowground biomass, dead wood, and litter pools. Fifth, new climate normals (1990 through 2020) were incorporated in the litter model resulting in additional changes in that pool. Finally, there were new NFI data incorporated into the latest *Inventory* which contributed to changes when compared with the previous *Inventory*.

Table 6-35: Recalculations of the Net Carbon Flux from Forest Carbon Pools in Land Converted to Forest Land by Land Use Change Category (MMT C)

Conversion category and Carbon pool (MMT C)	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Cropland Converted to Forest Land	**(10.3)**	**(4.7)**	**(4.7)**
Aboveground Biomass	(6.0)	(2.7)	(2.7)
Belowground Biomass	(1.2)	(0.5)	(0.5)
Dead Wood	(1.3)	(0.6)	(0.6)
Litter	(1.8)	(0.9)	(0.9)
Mineral Soil	(0.1)	(0.0)	(0.0)
Grassland Converted to Forest Land	**(3.4)**	**(10.2)**	**(10.1)**
Aboveground Biomass	(1.7)	(6.2)	(6.2)
Belowground Biomass	(0.3)	(0.7)	(0.7)
Dead Wood	(0.3)	(1.1)	(1.1)
Litter	(1.1)	(2.1)	(2.1)
Mineral Soil	0.1	0.1	0.1
Other Land Converted to Forest Land	**(2.9)**	**(1.5)**	**(1.5)**
Aboveground Biomass	(1.3)	(0.6)	(0.6)
Belowground Biomass	(0.2)	(0.1)	(0.1)
Dead Wood	(0.4)	(0.2)	(0.2)
Litter	(0.7)	(0.3)	(0.3)

Mineral Soil	(0.3)	(0.3)	(0.3)
Settlements Converted to Forest Land	**(9.3)**	**(8.6)**	**(8.6)**
Aboveground Biomass	(5.7)	(5.3)	(5.3)
Belowground Biomass	(1.1)	(0.9)	(0.9)
Dead Wood	(1.1)	(1.0)	(1.0)
Litter	(1.5)	(1.3)	(1.3)
Mineral soil	(0.0)	(0.0)	(0.0)
Wetlands Converted to Forest Land	**(0.9)**	**(2.4)**	**(2.4)**
Aboveground Biomass	(0.4)	(1.4)	(1.4)
Belowground Biomass	(0.1)	(0.2)	(0.2)
Dead Wood	(0.1)	(0.3)	(0.3)
Litter	(0.4)	(0.5)	(0.5)
Mineral Soil	0.0	0.0	0.0
Total Aboveground Biomass Flux	**(15.0)**	**(16.3)**	**(16.3)**
Total Belowground Biomass Flux	**(2.8)**	**(2.4)**	**(2.4)**
Total Dead Wood Flux	**(3.2)**	**(3.3)**	**(3.3)**
Total Litter Flux	**(5.5)**	**(5.1)**	**(5.1)**
Total SOC (Mineral) Flux	**(0.3)**	**(0.3)**	**(0.2)**
Total Flux	**(26.8)**	**(27.4)**	**(27.4)**

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 carbon 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 carbon 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 carbon to depths of 20, 30, and 100 cm in the forest land category using in situ measurements from the FIA 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. Second, 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 (CRT Category 4B1)

Carbon in cropland ecosystems occurs in biomass, dead organic matter, and soils. However, carbon 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 carbon 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, carbon is found in organic and inorganic forms of carbon, but soil organic carbon is the main source and sink for atmospheric CO_2. IPCC (2006) recommends reporting changes in soil organic carbon stocks due to agricultural land use and management activities for mineral and organic soils.[35]

Well-drained mineral soils typically contain from 1 to 6 percent organic carbon by weight, whereas mineral soils with high water tables for substantial periods of a year may contain significantly more carbon (NRCS 1999). Conversion of mineral soils from their native state to agricultural land uses can cause up to half of the soil organic carbon to be lost to the atmosphere due to enhanced microbial decomposition. The rate and ultimate magnitude of carbon 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 net carbon 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 carbon inputs (e.g., decayed plant matter, roots, and organic amendments such as manure and crop residues) and carbon 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 carbon 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.[36] Due to the depth and richness of the organic layers, carbon 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 carbon 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 2020) 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)[37] (i.e., considered set-aside cropland).

There are two discrepancies between the current land representation (see Section 6.1) and the area data that have been used in the *Inventory* for cropland remaining cropland. First, croplands in Alaska are not included in the *Inventory*, and second, some miscellaneous croplands that occur throughout the United States are also not included in the *Inventory* due to limited understanding of greenhouse gas emissions from these management systems (e.g., aquaculture). These differences lead to discrepancies between the managed area in cropland remaining cropland and the cropland area included in the *Inventory* analysis (Table 6-39). Improvements are underway to incorporate croplands in Alaska and miscellaneous croplands as part of future *Inventories* (see Planned Improvements section).

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[35] 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*.

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

[37] 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.

Land use and land management of mineral soils are the largest contributor to total net carbon stock change, especially in the early part of the time series (see Table 6-36 and Table 6-37). In 2022, mineral soils are estimated to sequester 62.0 MMT CO_2 Eq. (16.9 MMT C). This level of carbon storage in mineral soils represents a more than 58 percent increase since the initial reporting year of 1990. Carbon dioxide emissions from organic soils are 30.3 MMT CO_2 Eq. (8.3 MMT C) in 2022, which is an 11 percent decrease in losses of soil carbon compared to 1990. In total, United States agricultural soils in cropland remaining cropland sequestered approximately 31.7 MMT CO_2 Eq. (8.6 MMT C) in 2022.

Table 6-36: Net CO_2 Flux from Soil Carbon Stock Changes in Cropland Remaining Cropland (MMT CO_2 Eq.)

Soil Type	1990	2005	2018	2019	2020	2021	2022
Mineral Soils	(39.2)	(61.8)	(47.1)	(48.5)	(38.2)	(62.2)	(62.0)
Organic Soils	34.2	30.2	29.3	29.1	29.4	30.2	30.3
Total Net Flux	**(5.0)**	**(31.6)**	**(17.8)**	**(19.4)**	**(8.8)**	**(32.0)**	**(31.7)**

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

Table 6-37: Net CO_2 Flux from Soil Carbon Stock Changes in Cropland Remaining Cropland (MMT C)

Soil Type	1990	2005	2018	2019	2020	2021	2022
Mineral Soils	(10.7)	(16.9)	(12.9)	(13.2)	(10.4)	(17.0)	(16.9)
Organic Soils	9.3	8.2	8.0	7.9	8.0	8.2	8.3
Total Net Flux	**(1.4)**	**(8.6)**	**(4.9)**	**(5.3)**	**(2.4)**	**(8.7)**	**(8.6)**

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

Soil organic carbon 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 (Ogle et al. 2023). The mineral soil carbon stock changes between 1990 and 2022 range from 38.2 to 69.6 MMT CO_2 Eq. per year, with a mean of 55.9 MMT CO_2 Eq. Soil organic carbon losses from drainage of organic soils are relatively stable across the time series with a mean emission of 30.2 MMT CO_2 Eq. per year.

The spatial variability in the 2020 annual soil organic carbon stock changes[38] are displayed in Figure 6-6 and Figure 6-7 for mineral and organic soils, respectively. Isolated areas with high rates of carbon accumulation occur throughout the agricultural land base in the United States, but there are more concentrated areas, such as the Maryland, Delaware, and Virginia where there have been relatively high adoption rates of cover crop management. The regions with the highest rates of emissions from drainage of organic soils occur in the Southeastern Coastal Region (particularly Florida and Louisiana), Northeast and upper Midwest 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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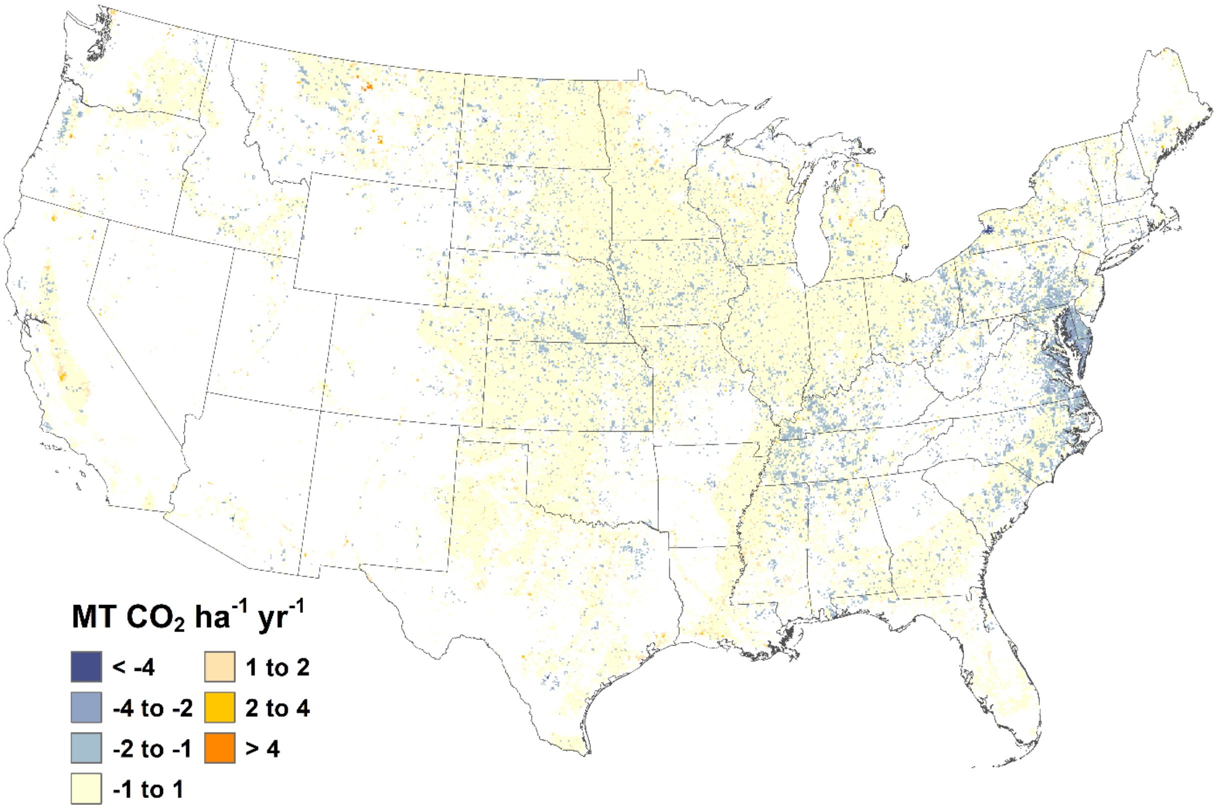
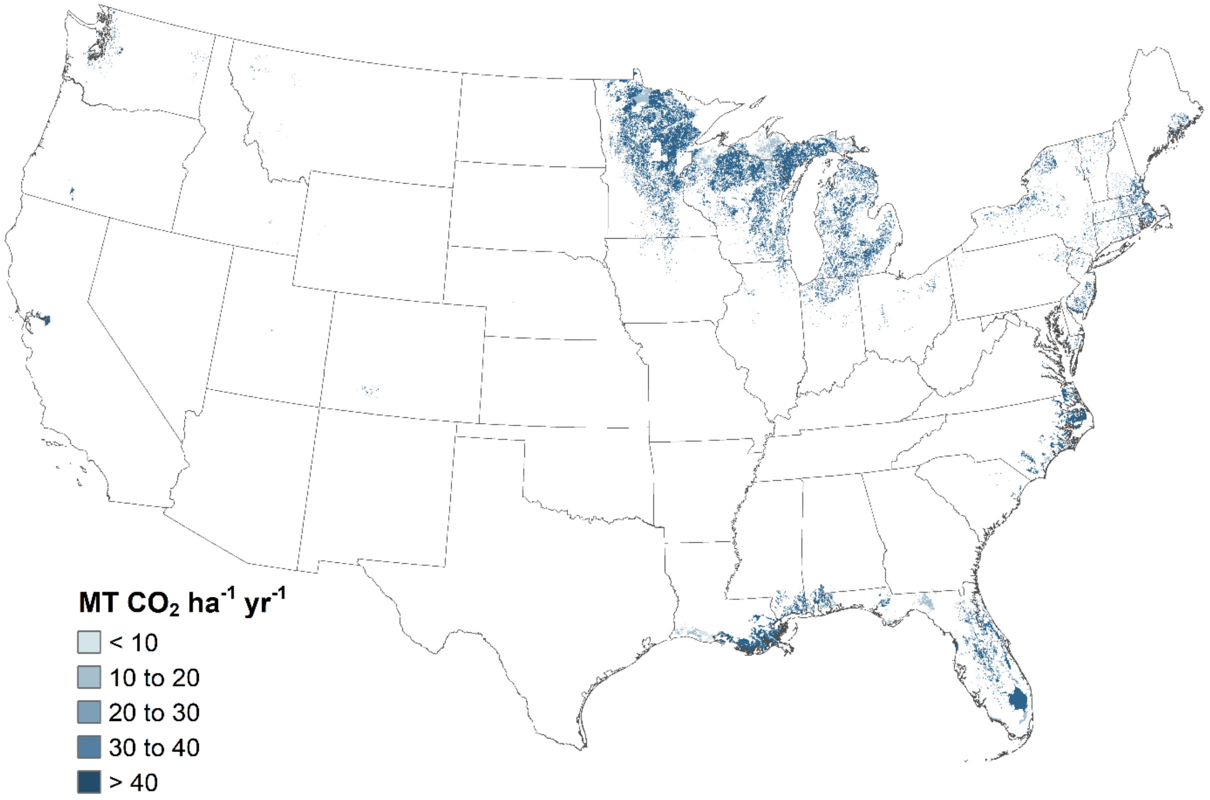
[38] Only national-scale emissions are estimated for 2021 to 2022 in this *Inventory* using the surrogate data method, and therefore the fine-scale emission patterns in this map are based on *Inventory* data from 2020.

Figure 6-6: Total Net Annual Soil Carbon Stock Changes for Mineral Soils under Agricultural Management within States, 2020, Cropland Remaining Cropland



Note: Only national-scale soil organic carbon stock changes are estimated for 2021 to 2022 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 2020. Negative values represent a net increase in soil organic carbon stocks, and positive values represent a net decrease in soil organic carbon stocks.

Figure 6-7: Total Net Annual Soil Carbon Stock Changes for Organic Soils under Agricultural Management within States, 2020, Cropland Remaining Cropland



Note: Only national-scale soil organic carbon stock changes are estimated for 2021 to 2022 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 2020.

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate changes in soil organic carbon 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[39] due to changes in mineral soil organic carbon stocks are estimated using a Tier 3 method for the majority of annual crops (Ogle et al. 2010, 2023). 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

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

estimate carbon stock changes across most of the time series, a surrogate data method has been applied to estimate stock changes in the last two 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 carbon 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 through 2017 (USDA-NRCS 2020), and the cropping histories were extended through 2020 using the USDA-NASS Crop Data Layer Product (CDL) (USDA-NASS 2021). The areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (Yang et al. 2018) are harmonized with the NRI data. This process ensures that the land-use areas are consistent across all land- use categories (see Section 6.1 Representation of the U.S. Land Base for more information).

The NRI is a statistically-based sample and includes approximately 604,000 survey locations in agricultural land for the conterminous United States and Hawaii. There are 364,333 survey locations that are included in the Tier 3 method, and another 239,757 locations included in the Tier 2 method. Each survey location is associated with a weight that allows scaling of carbon stock changes from NRI survey locations to the entire country (i.e., each weight 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 2017 (USDA-NRCS 2020). For 2018 to 2020, the time series is extended with the crop data provided in USDA-NASS CDL (USDA-NASS 2021), by overlaying NRI survey locations on the CDL in a geographic information system and extracting the crop types to extend the cropping histories. NRI survey locations are classified as cropland remaining cropland in a given year between 1990 and 2020 if the land use has been cropland for a continuous time period of at least 20 years. The 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.

Soil Carbon Stock Changes for Mineral Soils

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate organic carbon 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, dry beans, grass hay, grass-clover hay, lentils, oats, onions, peanuts, peas, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco, tomatoes, and wheat, but is not applied to estimate organic carbon stock changes from other crops or rotations with other crops. The model-based approach uses the DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011) to estimate soil organic carbon stock changes, soil nitrous oxide (N_2O) emissions from agricultural soil management, and methane (CH_4) emissions from rice cultivation. Carbon and nitrogen 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 carbon and N_2O) in a single inventory analysis ensures that there is a consistent treatment of the processes and interactions between carbon and nitrogen 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 carbon stock changes on federal croplands. Mineral soil organic carbon 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 carbon 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 carbon stock changes from 2021 to 2022 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 2020 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,[40] and weather data from the PRISM Climate Group (PRISM 2022). See Box 6-4 for more information about the surrogate data method. Stock change estimates for 2021 to 2022 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 carbon 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 (ARMA) errors (Brockwell and Davis 2016) is used to estimate the relationship between the surrogate data and the modeled 1990 to 2020 emissions data that has been compiled using the inventory methods described in this section. The model to extend the time series is given by

$$\mathrm{Y} = \mathrm{X}\beta + \varepsilon,$$

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 2020 using standard statistical techniques, and these estimates are used to predict the missing emissions data for 2021 to 2022.

A critical issue with the 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 2020), 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 carbon stocks and stock changes are estimated to a 30 cm depth using the DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011), which simulates cycling of carbon, nitrogen, and other nutrients in cropland, grassland, forest, and savanna ecosystems. The DayCent model utilizes the soil carbon modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et

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

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[41] (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 (2022), and soil attributes from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2020). 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).

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

A Tier 3 model-based approach is used to estimate soil organic carbon stock changes for the majority of agricultural land with mineral soils. This approach results in a more complete and accurate estimation of soil organic carbon 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 carbon 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 carbon dynamics at about 364,000 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 carbon stocks that assumes a step-change from one equilibrium level of the carbon stock to another equilibrium level. In contrast, the Tier 3 approach simulates a continuum of carbon 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 carbon dynamics (and CO_2 emissions and uptake) on a daily time step based on carbon emissions and removals from plant production and decomposition processes. These changes in soil organic carbon 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 2017 USDA NRI survey (USDA-NRCS 2020). 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

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[41] 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 2020. 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.

management activities, and is used to inform the inventory analysis about tillage practices, mineral fertilization, manure amendments, cover crop management, as well as planting and harvest dates (USDA-NRCS 2022; USDA-NRCS 2018; USDA-NRCS 2012). CEAP data are collected at a subset of NRI survey locations, and currently provide management information from approximately 2002 to 2006 and 2013 to 2016. These data are combined with other datasets in an imputation analysis. This imputation analysis is comprised of three steps: a) determine the trends in management activity across the time series by combining information from several datasets (discussed below); b) use Gradient Boosting (Friedman 2001) to determine the likely management practice at a given NRI survey location; and c) assign management practices from the CEAP survey to the specific NRI locations using a predictive mean matching method for certain variables that are adapted to reflect the trending information (Little 1988; van Buuren 2012). Gradient boosting is a machine learning technique used in regression and classification tasks, among others. It combines predictions from multiple weak prediction models and outperforms many complicated machine learning algorithms. It makes the best predictions at specific NRI survey locations or at state or region level models. The predictive mean matching method identifies the most similar management activity recorded in the CEAP surveys that match the prediction from the gradient boosting algorithm. The 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 gradient boosting. There are six complete imputations of the management activity data using these methods.

To determine trends in mineral fertilization and manure amendments, 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 data collection known as the Agricultural Resource Management Surveys (ARMS) (USDA-ERS 2020). Additional data on fertilization practices are compiled through other sources particularly the National Agricultural Statistics Service (USDA-NASS 1992, 1999, 2004). To determine the trends in tillage management, CEAP data are combined with Conservation Technology Information Center data between 1989 and 2004 (CTIC 2004) and OpTIS Data Product[42] for 2008 to 2020 (Hagen et al. 2020). The CTIC data are adjusted for long-term adoption of no-till agriculture (Towery 2001). For cover crops, CEAP data are combined with information from USDA Census of Agriculture (USDA-NASS 2012, 2017) and the OpTIS data (Hagen et al. 2020). It is assumed that cover crop management was minimal prior to 1990 and the rates increased linearly over the decade to the levels of cover crop management in the CEAP survey.

Uncertainty in the carbon 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 carbon and nitrogen dynamics in the DayCent model algorithms and associated parameterization; and sampling uncertainty associated with the statistical design of the NRI survey. Uncertainty is estimated with two variance components (Ogle et al. 2010). The first variance component quantifies the uncertainty in management activity data, model structure and parameterization. To assess this uncertainty, carbon and nitrogen 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 derived from fitting a linear mixed-effect model (Ogle et al. 2007, 2010, 2023). The data are combined in a Monte Carlo stochastic simulation with 1,000 iterations for 1990 through 2020. For each iteration, there is a random selection of management data from the imputation product (select one of the six imputations), and random selection of parameter values and random effects for the linear mixed-effect model (i.e., structural uncertainty estimator). The second variance component quantifies uncertainty in scaling from the NRI survey to the entire land base, and is computed with the NRI replicate weights using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components 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. Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2020 using the DayCent model. Further

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[42] OpTIS data on tillage and cover crop practices provided by Regrow Agriculture, Inc.

elaboration on the methodology and data used to estimate carbon 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 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes from 2021 to 2022 are approximated with a linear extrapolation of emission patterns from 1990 to 2020. 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). The time series of activity data will be updated in a future inventory, and emissions from 2021 to 2022 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 carbon 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 2017 NRI survey (USDA-NRCS 2020). 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. Activity data used exclusively in the Tier 2 method are wetland restoration for Conservation Reserve Program land from Euliss and Gleason (2002). Climate zones in the United States are determined from the IPCC climate map (IPCC 2006), and then assigned to NRI survey locations.

Reference carbon 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 carbon stock change factors are derived from published literature to determine the impact of management practices on soil organic carbon 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 of this practice. Instead, factors from IPCC (2006) are used to estimate the effect of those activities.

Uncertainty in soil carbon stock changes is estimated with two variance components (Ogle et al., 2010). The first variance component quantifies the uncertainty in management activity data and carbon stock change factors. To assess this uncertainty, changes in soil organic carbon stocks for mineral soils are estimated 1,000 times for 1990 through 2020 using a Monte Carlo stochastic simulation approach and probability distribution functions for the country-specific stock change factors, reference carbon stocks, and land use activity data (Ogle et al. 2003; Ogle et al. 2006). The second variance component quantifies uncertainty in scaling from the NRI survey to the entire land base, and is computed with the NRI replicate weights using a standard variance estimator for a two-stage sample design (Särndal *et al.* 1992). The two variance components 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. 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 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes for the remainder of the time series are approximated with a linear extrapolation of emission patterns from 1990 to 2020.

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 2021 to 2022 will be recalculated (see Planned Improvements section).

Soil Carbon Stock Changes for Organic Soils

Annual carbon emissions from drained organic soils in cropland remaining cropland are estimated using the Tier 2 method provided in IPCC (2006), with country-specific carbon loss rates (Ogle et al. 2003) rather than default IPCC rates. As with mineral soils, uncertainty is estimated with two variance components (Ogle et al., 2010). The first variance component quantifies the uncertainty in management activity data and emission factors. A Monte Carlo stochastic simulation with 1,000 iterations is used to quantify this uncertainty with probability distribution functions for the country-specific organic soil emission factors and land use activity data. The second variance component quantifies uncertainty in scaling from the NRI survey to the entire land base, and is computed with the NRI replicate weights using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). The two variance components 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. 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 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes for the remainder of the time series are approximated with a linear extrapolation of emission patterns from 1990 to 2020. 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 2021 to 2022 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 carbon stocks associated with cropland remaining cropland (including both mineral and organic soils). Uncertainty estimates are presented in Table 6-38 for each subsource (mineral and organic soil carbon 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 from two variance components (Ogle et al. 2010). For the first component, a Monte Carlo approach is used to address uncertainties in management activity data as well as model parameterization and structure or emissions factors for the Tier 3 and Tier 2 methods, respectively (Ogle et al. 2010, 2023). The second variance component is quantifying uncertainty in scaling from the NRI survey to the entire land base, and is computed using a standard variance estimator for a two-stage sample design (Särndal *et al.* 1992). The two variance components 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 (see Annex 3.12 for further discussion). For 2021 to 2022, additional uncertainty is propagated through a Monte Carlo analysis that is associated with the surrogate data method (see Box 6-3). Soil organic carbon 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 carbon stocks in cropland remaining cropland ranges from 212 percent below to 212 percent above the 2022 stock change estimate of -31.7 MMT CO_2 Eq. The large relative uncertainty around the 2022 stock change estimate is mostly due to variation in soil organic carbon 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 Soil Carbon Stock Changes occurring within Cropland Remaining Cropland (MMT CO_2 Eq. and Percent)

Source	2022 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
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 3 Inventory Methodology	(58.8)	(123.6)	5.9	-110%	+110%
Mineral Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	(3.2)	(8.4)	2.0	-162%	+162%
Organic Soil C Stocks: Cropland Remaining Cropland, Tier 2 Inventory Methodology	30.3	12.7	47.9	-58%	+58%
Combined Uncertainty for Flux associated with Agricultural Soil Carbon Stock Change in Cropland Remaining Cropland	**(31.7)**	**(99.0)**	**35.6**	**-212%**	**+212%**

[a] Range of C stock change estimates is 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 carbon stock changes. However, woody biomass carbon stock changes are likely minor in perennial crops, with relatively small amounts of woody crops such as orchards and nut plantations. There will be removal and replanting of tree crops each year, but the net effect on biomass carbon 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 carbon 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 69 long-term experiment sites and 145 NRI soil monitoring network sites, with 1406 observations across all of the sites (see Annex 3.12 for more information). Quality control uncovered several errors in the Tier 2 method following the initial analysis, such as no estimation for some NRI survey locations (i.e., federal lands and Hawaii), double counting some NRI survey locations with aggregation to the national scale, and errors in the estimation of the two variance components associated with the uncertainty analysis. The errors have been corrected following the diagnosis of the quality control issues.

Recalculations Discussion

Several improvements have been implemented in this *Inventory* leading to the need for recalculations. These improvements included a) incorporating new USDA-NRCS NRI data through 2017; b) extending the time series for crop histories through 2020 using USDA-NASS CDL data; c) incorporating USDA-NRCS CEAP survey data for 2013 to 2016; d) incorporating cover crop and tillage management information from the OpTIS remote-sensing data product from 2008 to 2020; e) modifying the statistical imputation method for the management activity data associated with about tillage practices, mineral fertilization, manure amendments, cover crop management, and planting and harvest dates using gradient boosting instead of an artificial neural network; f) updating time series of synthetic nitrogen fertilizer sales data, PRP nitrogen and manure nitrogen available for application to soils; g) constraining synthetic nitrogen fertilization and manure nitrogen applications in the Tier 3 method at the state scale rather than the national scale; h) re-calibrating the soil carbon module in the DayCent model using Bayesian methods; and i) expanding the crops in the Tier 3 method to include dry beans, lentils, onions, peas and tomatoes, which shifted some NRI survey locations from the Tier 2 to the Tier 3 method. The combined impact from these improvements resulted in an average annual increase in soil C stocks of 4.2 MMT CO_2 Eq., or 26 percent, from 1990 to 2021 relative to the previous *Inventory*.

Planned Improvements

A key improvement is conducting an analysis of carbon stock changes in Alaska for cropland. The improvement will be conducted using the Tier 2 method for mineral and organic soils that is described earlier in this section. The analysis will initially focus on land-use change, which typically has a larger impact on soil organic carbon stock changes than management practices, but will be further refined over time to incorporate management data. The improvement will resolve most of the differences between the managed land base for cropland remaining cropland and amount of area currently included in cropland remaining cropland (see Table 6-39).

Table 6-39: Comparison of Managed Land Area in Cropland Remaining Cropland and Area in the Current Cropland Remaining Cropland Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	**Managed Land**	***Inventory***	**Difference**
1990	162,273	162,247	26
1991	161,840	161,814	26
1992	161,343	161,317	26
1993	159,577	159,551	26
1994	157,890	157,864	26
1995	157,277	157,251	26
1996	156,639	156,613	26
1997	156,018	155,992	26
1998	152,335	152,309	26
1999	151,432	151,406	26
2000	151,257	151,231	26
2001	150,734	150,708	26
2002	150,426	150,400	26
2003	151,055	151,029	26
2004	150,787	150,761	26
2005	150,417	150,391	26
2006	149,908	149,882	26
2007	150,117	150,091	26
2008	149,718	149,692	26
2009	149,660	149,634	26
2010	149,222	149,196	26
2011	148,626	148,600	26
2012	148,297	148,271	26
2013	148,660	148,633	26
2014	149,141	149,115	26
2015	148,525	148,499	26
2016	148,436	148,410	26
2017	148,331	148,305	26

2018	149,720	149,694	26
2019	149,503	149,477	26
2020	149,822	149,796	26
2021	150,591	*	*
2022	151,276	*	*

Activity data on land use have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

There are several other planned improvements underway related to the plant production module in DayCent. 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 uncertainty, particularly the submodules that are used to approximate the cycling of nitrogen through the plant-soil system, which will also have impacts on carbon cycling in the model simulations.

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 carbon inputs to the soil that are associated with residue burning. In addition, 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.

Another improvement is to estimate biomass carbon stock changes in agroforestry systems and perennial tree crops. Methods combining survey data and remote sensing imagery are under development to determine the extent of land with agroforestry and perennial tree crops. In addition, a meta-analysis is being conducted to derive country-specific factors for biomass C stock changes in agroforestry systems. Although the influence of perennial tree crop biomass is expected to be minor, carbon stock changes may be significantly impacted by the affect of agroforestry practices.

Many of these improvements are expected to be completed for the next (1990 through 2023) *Inventory* (i.e., 2025 submission), pending prioritization of resources.

6.5 Land Converted to Cropland (CRT Category 4B2)

Land converted to cropland includes all current cropland in an inventory year that had been in another land use(s) during the previous 20 years (IPCC 2006), 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).

Land use change can lead to large losses of carbon 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 (Tubiello et al. 2015).

The *2006 IPCC Guidelines* recommend reporting changes in biomass, dead organic matter and soil organic carbon stocks with land use change. All soil organic carbon stock changes are estimated and reported for land converted to cropland, but reporting of carbon stock changes for aboveground and belowground biomass, dead wood, and litter pools is limited to forest land converted to cropland and grassland converted to cropland for woodland conversions (i.e., woodland conversion to cropland).[43]

Grassland converted to cropland is the largest source of emissions from 1990 to 2000, while forest land converted to cropland is the largest source of emissions from 2001 to 2022. This shift is largely due to reduced losses of carbon from mineral soils after 2001. The high losses of carbon from forest land converted to cropland is due to reductions in biomass and dead organic matter carbon following conversion from forests (Table 6-40 and Table 6-41). The net change in total carbon stocks for 2022 led to CO_2 emissions to the atmosphere of 35.1 MMT CO_2 Eq. (9.6 MMT C), including 12.1 MMT CO_2 Eq. (3.3 MMT C) from aboveground biomass carbon losses, 2.0 MMT CO_2 Eq. (0.6 MMT C) from belowground biomass carbon losses, 2.3 MMT CO_2 Eq. (0.6 MMT C) from dead wood carbon losses, 3.4 MMT CO_2 Eq. (0.9 MMT C) from litter carbon losses, 12.6 MMT CO_2 Eq. (3.4 MMT C) from mineral soils and 2.7 MMT CO_2 Eq. (0.7 MMT C) from drainage and cultivation of organic soils. The overall net loss of carbon has declined by 23 percent from 1990 to 2022.

Table 6-40: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes in Land Converted to Cropland by Land-Use Change Category (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
Grassland Converted to Cropland	**27.3**	**17.2**	**13.7**	**13.0**	**10.6**	**16.1**	**16.3**
Aboveground Live Biomass	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	24.6	13.7	10.7	10.1	8.0	13.5	13.6
Organic Soils	2.4	3.3	2.7	2.7	2.4	2.4	2.4
Forest Land Converted to Cropland	**19.2**	**19.2**	**19.7**	**19.7**	**19.7**	**19.6**	**19.6**
Aboveground Live Biomass	11.4	11.6	11.9	11.9	11.9	11.9	11.9
Belowground Live Biomass	1.9	2.0	2.0	2.0	2.0	2.0	2.0
Dead Wood	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Litter	3.2	3.3	3.3	3.4	3.4	3.4	3.4
Mineral Soils	0.4	0.2	0.1	0.1	0.1	0.1	0.1
Organic Soils	0.1	+	+	+	+	+	+
Other Lands Converted to Cropland	**(1.8)**	**(2.5)**	**(1.6)**	**(1.6)**	**(1.2)**	**(1.1)**	**(1.1)**
Mineral Soils	(1.9)	(2.6)	(1.7)	(1.6)	(1.2)	(1.1)	(1.1)
Organic Soils	0.1	0.1	+	+	+	+	+
Settlements Converted to Cropland	**(0.0)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**
Mineral Soils	(0.1)	(0.1)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Cropland	**0.7**	**0.7**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Mineral Soils	0.2	0.2	0.2	0.2	0.2	0.1	0.2
Organic Soils	0.5	0.5	0.2	0.2	0.2	0.2	0.2
Aboveground Live Biomass	**11.6**	**11.7**	**12.0**	**12.0**	**12.1**	**12.1**	**12.1**
Belowground Live Biomass	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**
Dead Wood	**2.2**	**2.2**	**2.3**	**2.3**	**2.3**	**2.3**	**2.3**
Litter	**3.3**	**3.3**	**3.4**	**3.4**	**3.4**	**3.4**	**3.4**
Total Mineral Soil Flux	**23.2**	**11.3**	**9.2**	**8.6**	**6.9**	**12.5**	**12.6**
Total Organic Soil Flux	**3.2**	**3.9**	**3.0**	**3.0**	**2.6**	**2.6**	**2.7**
Total Net Flux	**45.4**	**34.5**	**31.9**	**31.4**	**29.3**	**34.9**	**35.1**

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[43] Changes in biomass carbon stocks are estimated for forest land converted to cropland and grassland converted to cropland for woodland conversions. There is a planned improvement to include the effect of other land use conversions, in addition to herbaceous grassland conversions to cropland in a future *Inventory*. Note: changes in dead organic matter are assumed negligible for other land use conversions to cropland, except forest land and woodland conversions.

+ 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 6-41: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes in Land Converted to Cropland (MMT C)

	1990	2005	2018	2019	2020	2021	2022
Grassland Converted to Cropland	**7.4**	**4.7**	**3.7**	**3.6**	**2.9**	**4.4**	**4.4**
Aboveground Live Biomass	+	+	+	+	+	+	+
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	6.7	3.7	2.9	2.8	2.2	3.7	3.7
Organic Soils	0.7	0.9	0.7	0.7	0.6	0.6	0.7
Forest Land Converted to Cropland	**5.2**	**5.2**	**5.4**	**5.4**	**5.4**	**5.4**	**5.4**
Aboveground Live Biomass	3.1	3.2	3.2	3.3	3.3	3.3	3.3
Belowground Live Biomass	0.5	0.5	0.5	0.6	0.6	0.6	0.6
Dead Wood	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Litter	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Mineral Soils	0.1	+	+	+	+	+	+
Organic Soils	+	+	+	+	+	+	+
Other Lands Converted to Cropland	**(0.5)**	**(0.7)**	**(0.4)**	**(0.4)**	**(0.3)**	**(0.3)**	**(0.3)**
Mineral Soils	(0.5)	(0.7)	(0.5)	(0.4)	(0.3)	(0.3)	(0.3)
Organic Soils	+	+	+	+	+	+	+
Settlements Converted to Cropland	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Cropland	**0.2**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Mineral Soils	0.1	0.1	+	+	+	+	+
Organic Soils	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Aboveground Live Biomass	**3.2**	**3.2**	**3.3**	**3.3**	**3.3**	**3.3**	**3.3**
Belowground Live Biomass	**0.5**	**0.5**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Dead Wood	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Litter	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**
Total Mineral Soil Flux	**6.3**	**3.1**	**2.5**	**2.4**	**1.9**	**3.4**	**3.4**
Total Organic Soil Flux	**0.9**	**1.1**	**0.8**	**0.8**	**0.7**	**0.7**	**0.7**
Total Net Flux	**12.4**	**9.4**	**8.7**	**8.6**	**8.0**	**9.5**	**9.6**

+ 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 carbon stock changes for land converted to cropland, including (1) loss of aboveground and belowground biomass, dead wood and litter carbon 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 carbon stocks.

Biomass, Dead Wood and Litter Carbon Stock Changes

A Tier 2 method is applied to estimate biomass, dead wood, and litter carbon 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 2023). However, there is no country-specific data for cropland biomass, so only a default biomass estimate

(IPCC 2006) for croplands was used to estimate carbon stock changes (litter and dead wood carbon stocks were assumed to be zero since no reference carbon 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. Details for each of the carbon attributes described below are available in Domke et al. (2022) and Westfall et al. (2023). If FIA plots include data on individual trees, aboveground and belowground carbon density estimates are based on Woodall et al. (2011) and Westfall et al. (2023). 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 carbon mass is belowground (Smith et al. 2006). Estimates of carbon 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 carbon density is estimated following the basic method applied to live trees (Woodall et al. 2011; Westfall et al. 2023) with additional modifications for woodland species 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 carbon 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 carbon 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 carbon is the pool of organic carbon (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 carbon. If FIA plots include litter material, a modeling approach using litter carbon measurements from FIA plots is used to estimate litter carbon density (Domke et al. 2016). See Annex 3.13 for more information about reference carbon 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 2017 USDA NRI survey for non-federal lands (USDA-NRCS 2020). Land use and some management information (e.g., crop type, soil attributes, and irrigation) had been collected for each NRI point on a five-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, which are currently available through 2017 (USDA-NRCS 2020), and the time series for cropping histories was extended through 2020 using the USDA-NASS Crop Data Layer Product (CDL) (USDA-NASS 2021) and National Land Cover Dataset (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015). The areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (NLCD; Yang et al. 2018) are harmonized with the NRI data. This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 Representation of the U.S. Land Base for more information).

NRI survey locations are classified as land converted to cropland in a given year between 1990 and 2020 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 NLCD (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Soil Carbon Stock Changes for Mineral Soils

An IPCC Tier 3 model-based approach using the DayCent ecosystem model (Ogle et al. 2010, 2023) is applied to estimate carbon stock changes from 1990 to 2020 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, dry beans, grass hay, grass-clover hay, lentils, oats, onions, peanuts, peas, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tobacco, tomatoes, and wheat. Soil organic carbon stock changes on the remaining mineral soils are estimated with the IPCC Tier 2 method (Ogle et al. 2003, 2006), 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.[44]

For the years 2021 to 2022, a surrogate data method is used to estimate soil organic carbon 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 2020 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,[45] and weather data from the PRISM Climate Group (PRISM 2022). See Box 6-4 in the Methodology section of Cropland Remaining Cropland for more information about the surrogate data method. Stock change estimates for 2021 to 2022 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 carbon stocks and stock changes are estimated using the DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011). The DayCent model utilizes the soil carbon 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 2020). Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2020. 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 Tier 3 method is applied from 1990 to 2020 so that changes reflect anthropogenic activity and not methodological adjustments. Soil organic carbon stock changes from 2021 to 2022 are approximated using a linear extrapolation of emission patterns from 1990 to 2020. 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 2020 to 2022 will be recalculated.

Tier 2 Approach. For the mineral soils not included in the Tier 3 analysis, soil organic carbon 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 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes are approximated for the remainder of the 2021 to 2022 time series with a linear extrapolation of emission patterns from 1990 to 2020. 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 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 2021 to 2022 will be recalculated.

Soil Carbon Stock Changes for Organic Soils

Annual carbon emissions from drained organic soils in land converted to cropland are estimated using the Tier 2 method provided in IPCC (2006), with country-specific carbon loss rates (Ogle et al. 2003) as described in the

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[44] 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 2018).

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

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 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes for the remainder of the time series (i.e., 2021 to 2022) are approximated with a linear extrapolation of emission patterns from 1990 to 2020. 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 for 2021 to 2022 will be recalculated in a future *Inventory* when new activity data are incorporated into the analysis.

Uncertainty

The uncertainty analyses for biomass, dead wood and litter carbon losses with forest land converted to cropland and grassland converted to cropland for woodland conversions are conducted in the same way as the uncertainty assessment for forest ecosystem carbon 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 soil organic carbon stock changes using the Tier 3 and Tier 2 methodologies are quantified from two variance components (Ogle et al. 2010), as described in cropland remaining cropland. For 2021 to 2022, 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 6-42 for each sub-source (i.e., biomass carbon stocks, dead wood carbon stocks, litter carbon stocks, soil organic carbon 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 carbon stock changes for biomass, dead organic matter and soils are combined using the simple error propagation methods provided by the IPCC (2006). The combined uncertainty for total carbon stock changes in land converted to cropland ranged from 93 percent below to 93 percent above the 2022 stock change estimate of 35.1 MMT CO_2 Eq. The large relative uncertainty in the 2022 estimate is mostly due to variation in soil organic carbon stock changes that is not explained by the surrogate data method, leading to high prediction error with this splicing method.

Table 6-42: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass Carbon Stock Changes occurring within Land Converted to Cropland (MMT CO_2 Eq. and Percent)

Source	2022 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	**16.3**	**(12.1)**	**44.7**	**-174%**	**174%**
Aboveground Live Biomass	0.1	+	0.3	-128%	124%
Belowground Live Biomass	+	+	+	-100%	56%
Dead Wood	+	+	0.1	-100%	173%
Litter	+	+	0.1	-100%	147%
Mineral Soil C Stocks: Tier 3	11.0	(17.2)	39.3	-256%	256%
Mineral Soil C Stocks: Tier 2	2.6	0.6	4.5	-77%	77%
Organic Soil C Stocks: Tier 2	2.4	0.5	4.4	-79%	79%
Forest Land Converted to Cropland	**19.6**	**3.4**	**35.8**	**-82%**	**82%**
Aboveground Live Biomass	11.9	(3.2)	27.1	-127%	127%
Belowground Live Biomass	2.0	(0.6)	4.6	-127%	127%
Dead Wood	2.2	(0.6)	5.1	-128%	127%

Litter	3.4	(0.9)	7.6	-127%	128%
Mineral Soil C Stocks: Tier 2	0.1	+	0.2	-107%	107%
Organic Soil C Stocks: Tier 2	+	+	0.1	-429%	429%
Other Lands Converted to Cropland	**(1.1)**	**(2.1)**	+	**-99%**	**99%**
Mineral Soil C Stocks: Tier 2	(1.1)	(2.1)	+	-99%	99%
Organic Soil C Stocks: Tier 2	+	+	+	0%	0%
Settlements Converted to Cropland	**(0.1)**	**(0.3)**	+	**-97%**	**97%**
Mineral Soil C Stocks: Tier 2	(0.2)	(0.3)	(0.1)	-71%	71%
Organic Soil C Stocks: Tier 2	+	+	0.1	-103%	103%
Wetlands Converted to Croplands	**0.4**	**(0.1)**	**0.8**	**-115%**	**115%**
Mineral Soil C Stocks: Tier 2	0.2	+	0.3	-124%	124%
Organic Soil C Stocks: Tier 2	0.2	(0.2)	0.6	-173%	173%
Total: Land Converted to Cropland	**35.1**	**2.4**	**67.8**	**-93%**	**93%**
Aboveground Live Biomass	**12.1**	**(3.1)**	**27.2**	**-126%**	**126%**
Belowground Live Biomass	**2.0**	**(0.5)**	**4.6**	**-126%**	**126%**
Dead Wood	**2.3**	**(0.6)**	**5.1**	**-126%**	**125%**
Litter	**3.4**	**(0.9)**	**7.7**	**-126%**	**126%**
Mineral Soil C Stocks: Tier 3	**11.0**	**(17.2)**	**39.3**	**-256%**	**256%**
Mineral Soil C Stocks: Tier 2	**1.6**	**(0.7)**	**3.8**	**-144%**	**144%**
Organic Soil C Stocks: Tier 2	**2.7**	**0.7**	**4.7**	**-73%**	**73%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates is 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 carbon stock changes. Biomass carbon 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 carbon 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 carbon 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

Several improvements have been implemented in this *Inventory* leading to the need for recalculations. These improvements included a) incorporating new USDA-NRCS NRI data through 2017; b) extending the time series for crop histories through 2020 using USDA-NASS CDL data; c) incorporating USDA-NRCS CEAP survey data for 2013 to 2016; d) incorporating cover crop and tillage management information from the OpTIS remote-sensing data product from 2008 to 2020; e) modifying the statistical imputation method for the management activity data associated with about tillage practices, mineral fertilization, manure amendments, cover crop management, planting and harvest dates using gradient boosting instead of an artificial neural network; f) updating time series of synthetic nitrogen fertilizer sales data, PRP nitrogen and manure nitrogen available for application to soils; g) constraining synthetic nitrogen fertilization and manure nitrogen applications in the Tier 3 method at the state scale rather than the national scale; h) re-calibrating the soil carbon module in the DayCent model using Bayesian methods; i) expanding the crops in the Tier 3 method to include dry beans, lentils, onions, peas and tomatoes, which shifted some NRI survey locations from the Tier 2 to the Tier 3 method, and j) updated FIA data from 1990 to 2022 on biomass, dead wood and litter carbon stocks associated with forest land converted to cropland. Finally, see further updates in Section 6.2 Forest Land Remaining Forest Land, describing updates to the estimates for aboveground volume and biomass which impacted lands converted to cropland estimates. As a result, land converted to cropland has an estimated smaller carbon loss of 20.7 MMT CO_2 Eq. on average over the time series. This represents a 37 percent average decrease in carbon stock change losses for land converted to cropland compared to the previous *Inventory*, and is mainly due to less loss of carbon associated with forest land converted to cropland.

Planned Improvements

A key improvement is to estimate the biomass carbon stock changes for other land use changes beyond only forest land converted to cropland and grassland converted to cropland for woodland conversion, which is included in the current *Inventory*. Additional planned improvements are discussed in the Planned Improvements section of Cropland Remaining Cropland.

6.6 Grassland Remaining Grassland (CRT Category 4C1)

Carbon in grassland ecosystems occurs in biomass, dead organic matter, and soils. Soils are the largest pool of carbon in grasslands, and have the greatest potential for longer-term storage or release of carbon. Biomass and dead organic matter carbon pools are relatively ephemeral compared to the soil carbon pool, with the exception of carbon 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 carbon stocks with land use and management. Carbon stock changes for aboveground and belowground biomass, dead wood and litter pools are reported for woodlands (i.e., a subcategory of grasslands[46]), and may be extended to include agroforestry management associated with grasslands in the future. For soil organic carbon, 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.[47]

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 inter-seeding of legumes. Woodlands are also considered grassland and are areas of continuous tree cover that do not meet the definition of forest land (see Section 6.1 Representation of the U.S. Land Base for more information about the criteria for forest land).

There is a discrepancy between the current land representation (see Section 6.1) and the area data that have been used in the inventory for grassland remaining grassland. Specifically, grasslands in Alaska are not included in the *Inventory*, and this land base is approximately 50 million hectares. This difference leads to a discrepancy between the managed area in grassland remaining grassland in the land representation and the grassland area included in the emissions and removals estimation for the grassland remaining grassland land-use category (Table 6-46). Improvements are underway to incorporate grasslands in Alaska as part of future *Inventories* (see Planned Improvements section).

For grassland remaining grassland, there has been considerable variation in carbon stocks between 1990 and 2022. These changes are driven by variability in weather patterns and associated interaction with land management

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[46] Woodlands are considered grasslands in the U.S. land representation because they do not meet the definition of forest land.

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

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 carbon stocks for 2022 led to net CO_2 emissions to the atmosphere of 13.4 MMT CO_2 Eq. (3.6 MMT C), including -1.3 MMT CO_2 Eq. (-0.4 MMT C) from net gains of aboveground biomass C, -0.2 MMT CO_2 Eq. (-0.1 MMT C) from net gains in belowground biomass carbon, 2.8 MMT CO_2 Eq. (0.8 MMT C) from net losses in dead wood carbon, less than 0.05 MMT CO_2 Eq. (less than 0.05 MMT C) from net gains in litter C, 6.5 MMT CO_2 Eq. (1.8 MMT C) from net losses in mineral soil organic carbon, and 5.5 MMT CO_2 Eq. (1.5 MMT C) from losses of carbon due to drainage and cultivation of organic soils (Table 6-43 and Table 6-44). Losses of carbon are 45.2 percent lower in 2022 compared to 1990, but as noted previously, stock changes are highly variable from 1990 to 2022, with an average annual change of 19.9 MMT CO_2 Eq. (5.4 MMT C).

Table 6-43: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes in Grassland Remaining Grassland (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
Aboveground Live Biomass	(2.7)	(2.1)	(1.4)	(1.4)	(1.4)	(1.4)	(1.3)
Belowground Live Biomass	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)	(0.2)
Dead Wood	3.2	3.1	2.9	2.9	2.9	2.9	2.8
Litter	(0.4)	(0.2)	+	+	+	+	+
Mineral Soils	18.6	18.6	22.0	22.0	9.3	3.8	6.5
Organic Soils	6.1	5.1	5.3	5.3	5.5	5.5	5.5
Total Net Flux	**24.4**	**24.1**	**28.6**	**28.5**	**16.1**	**10.6**	**13.4**

+ 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 6-44: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes in Grassland Remaining Grassland (MMT C)

	1990	2005	2018	2019	2020	2021	2022
Aboveground Live Biomass	(0.7)	(0.6)	(0.4)	(0.4)	(0.4)	(0.4)	(0.4)
Belowground Live Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Wood	0.9	0.8	0.8	0.8	0.8	0.8	0.8
Litter	(0.1)	(0.1)	+	+	+	+	+
Mineral Soils	5.1	5.1	6.0	6.0	2.5	1.0	1.8
Organic Soils	1.7	1.4	1.4	1.4	1.5	1.5	1.5
Total Net Flux	**6.6**	**6.6**	**7.8**	**7.8**	**4.4**	**2.9**	**3.6**

+ 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 carbon stock changes for 2020[48] 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 carbon in isolated areas that mostly occurred in pastures of the upper Midwest and eastern United States; losses occurred primarily in the northwestern region. For organic soils, the regions with the highest rates of emissions coincide with the largest concentrations of organic soils that occur in managed grassland, including the Southeastern Coastal Region (particularly Florida), areas surrounding the Great Lakes in the upper Midwest and Northeast, and a few isolated areas along the Pacific Coast.

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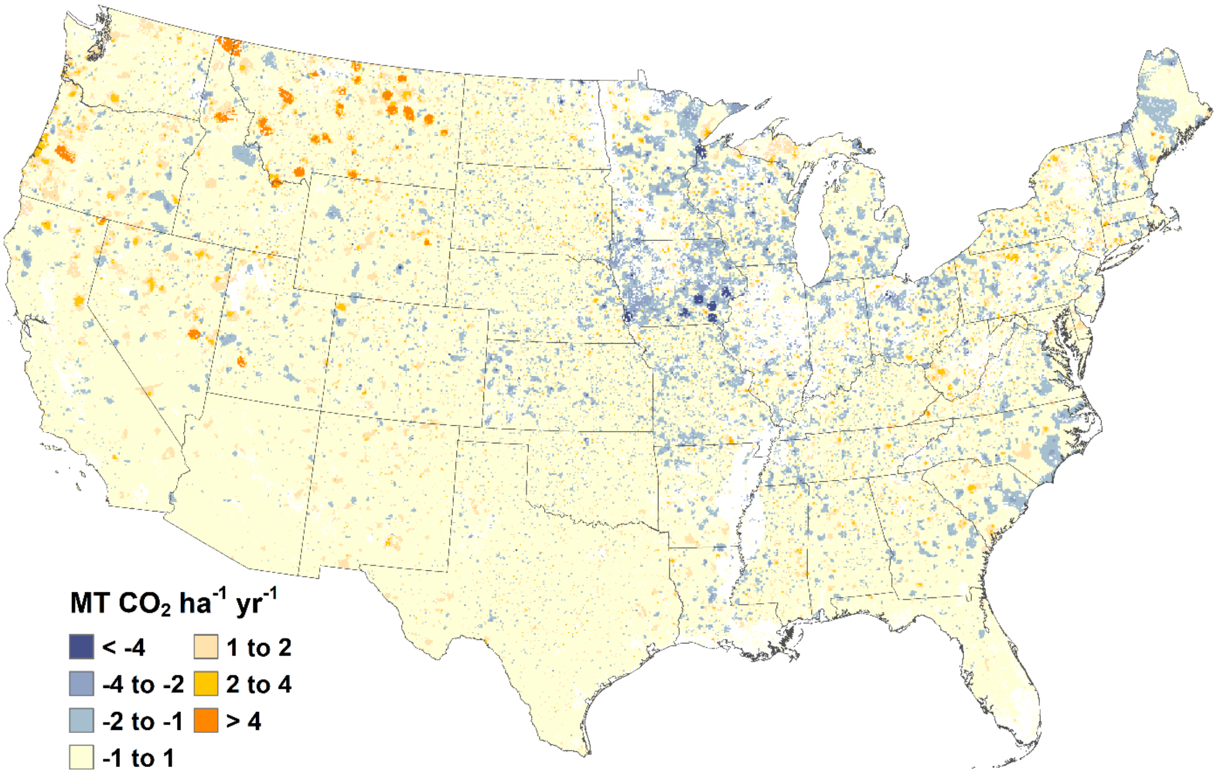
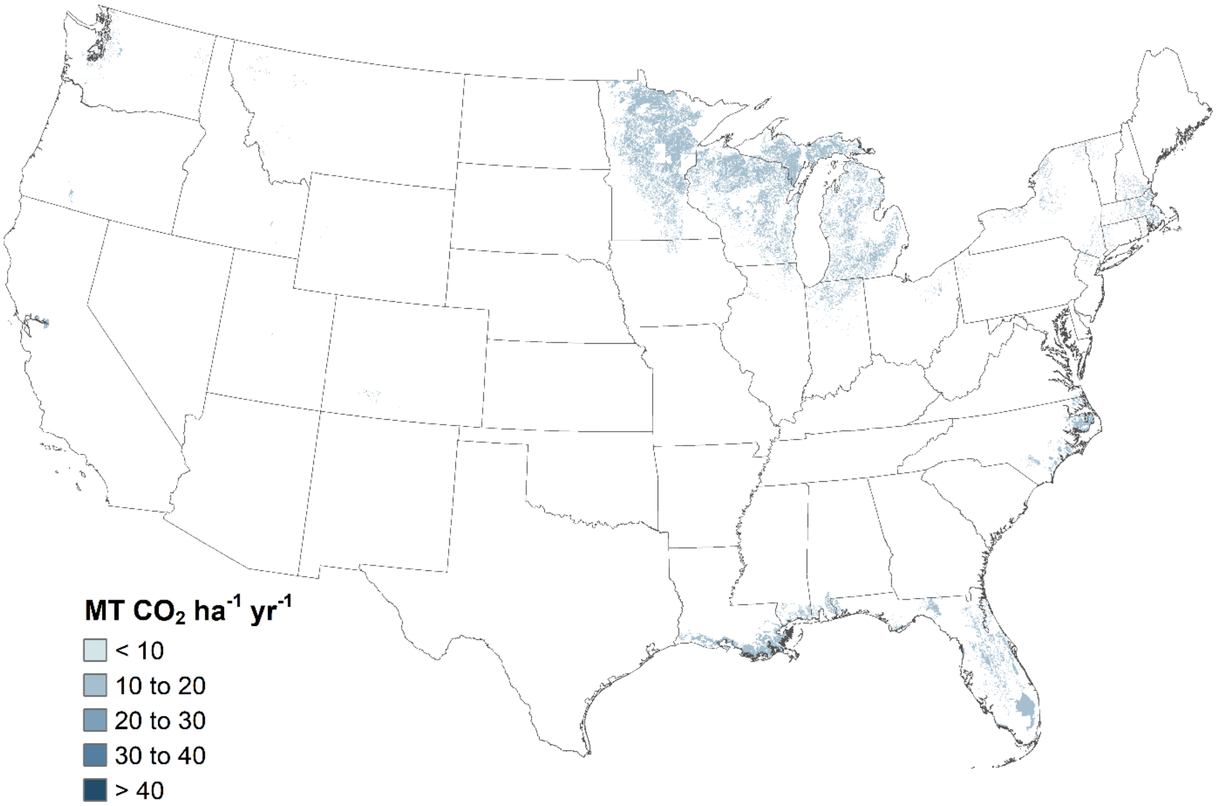
[48] Only national-scale emissions are estimated for 2021 to 2022 in the current *Inventory* using the surrogate data method, and therefore the fine-scale emission patterns in this map are based on land use data from 2020.

Figure 6-8: Total Net Annual Soil Carbon Stock Changes for Mineral Soils under Agricultural Management within States, 2020, Grassland Remaining Grassland



Note: Only national-scale soil organic carbon stock changes are estimated for 2021 to 2022 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 2020. Negative values represent a net increase in soil organic carbon stocks, and positive values represent a net decrease in soil organic carbon stocks.

Figure 6-9: Total Net Annual Soil Carbon Stock Changes for Organic Soils under Agricultural Management within States, 2020, Grassland Remaining Grassland



Note: Only national-scale soil organic carbon stock changes are estimated for 2021 to 2022 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 2020.

Methodology and Time-Series Consistency

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

Biomass, Dead Wood and Litter Carbon Stock Changes

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 carbon storage in aboveground and belowground biomass, dead wood and litter carbon (IPCC 2006) as described in the Forest Land Remaining Forest Land section. Carbon stocks and net annual carbon stock change were determined according to the stock-difference method for the conterminous United States, which involved applying carbon estimation factors to annual forest inventories across time to obtain carbon 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 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 2023) 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 2022 in order to ensure time-series consistency. This methodology is consistent with IPCC guidance (2006).

Soil Carbon Stock Changes

The following section includes a brief description of the methodology used to estimate changes in soil organic carbon 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 is provided in the Cropland Remaining Cropland section and Annex 3.12.

Soil organic carbon stock changes are estimated for grassland remaining grassland on non-federal lands according to land use histories recorded in the USDA National Resources Inventory (NRI) (USDA-NRCS 2020). Land use and some management information (e.g., grass type, soil attributes, and irrigation) were originally collected for each NRI survey location on a five-year cycle beginning in 1982. In 1998, the NRI program began collecting annual data, and the annual data are currently available through 2017 (USDA-NRCS 2020). For 2018-2020, the time series is extended with the data provided in the National Land Cover Dataset (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015). The areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the NLCD are harmonized with the NRI data. This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 Representation of the U.S. Land Base for more information).

NRI survey locations are classified as grassland remaining grassland in a given year between 1990 and 2020 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 NLCD (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Soil Carbon Stock Changes for Mineral Soils

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate carbon stock changes from 1990 to 2020 for most mineral soils in grassland remaining grassland. The carbon 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), as well as additional stock changes associated with biosolids (i.e., treated sewage sludge) amendments and federal land.[49]

A surrogate data method is used to estimate soil organic carbon stock changes from 2021 to 2022 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 2020 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 2022).

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[49] 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 2020).

See Box 6-4 in the Methodology section of cropland remaining cropland for more information about the surrogate data method.

Tier 3 Approach. Mineral soil organic carbon stocks and stock changes for grassland remaining grassland are estimated using the DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011), as described in Cropland Remaining Cropland. The DayCent model utilizes the soil carbon 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 2017 USDA NRI survey (USDA-NRCS 2020). 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 nitrogen deposition from grazing animals (i.e., pasture/range/paddock (PRP) manure) is an input to the DayCent model to estimate the influence of PRP manure on carbon stock changes for lands included in the Tier 3 method. Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2020 using the NRI survey data. Further elaboration on the Tier 3 methodology and data used to estimate carbon 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 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes from 2021 to 2022 are approximated using a linear extrapolation of emission patterns from 1990 to 2020. 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). Stock change estimates for 2021 to 2022 will be recalculated in future Inventories with an updated time series of activity data (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 the Cropland Remaining Cropland section for mineral soils, with the exception of the manure nitrogen 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 nitrogen 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 2020) 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 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 carbon 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 carbon 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 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes are approximated for the remainder of the time series with a linear extrapolation of emission patterns from 1990 to 2020. 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 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 2021 to 2022 will be recalculated.

Additional Mineral Carbon Stock Change Calculations

A Tier 2 method is used to adjust annual carbon stock change estimates for mineral soils between 1990 and 2022 to account for additional carbon stock changes associated with biosolids (i.e., treated sewage sludge) amendments. Estimates of the amounts of biosolids nitrogen applied to agricultural land are derived from national data on biosolids generation, disposition, and nitrogen content (see Section 7.2, Wastewater Treatment and Discharge 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 carbon storage rate is estimated at 0.38 metric tons carbon 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).

Soil Carbon Stock Changes for Organic Soils

Annual carbon emissions from drained organic soils in grassland remaining grassland are estimated using the Tier 2 method in IPCC (2006), which utilizes country-specific carbon 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 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes for the remainder of the time series (i.e., 2021 to 2022) are approximated with a linear extrapolation of emission patterns from 1990 to 2020. 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 for 2021 to 2022 will be recalculated in future *Inventories* with an updated time series of activity data.

Uncertainty

The uncertainty analysis for biomass, dead wood and litter carbon losses with woodlands is conducted in the same way as the uncertainty assessment for forest ecosystem carbon 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 soil organic carbon stock changes using the Tier 3 and Tier 2 methodologies are quantified from two variance components (Ogle et al. 2010), as described in Cropland Remaining Cropland. For 2021 to 2022, there is additional uncertainty propagated through the Monte Carlo analysis associated with the surrogate data method.

Uncertainty estimates are presented in Table 6-45 for each subcategory (i.e., soil organic carbon 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 total carbon stock changes in grassland remaining grassland ranges from more than 926 percent below and above the 2022 stock change estimate of 13.3 MMT CO_2 Eq. The large relative uncertainty in the 2022 estimate is mostly due to variation in soil organic carbon stock changes that is not explained by the surrogate data method, leading to high prediction error with this data splicing method.

Table 6-45: Approach 2 Quantitative Uncertainty Estimates for Carbon Stock Changes Occurring Within Grassland Remaining Grassland (MMT CO_2 Eq. and Percent)

Source	2022 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	(1.3)	(1.5)	(1.2)	-10%	12%
Belowground live biomass	(0.2)	(0.3)	(0.2)	-8%	8%
Dead wood	2.8	2.5	3.2	-13%	14%
Litter	+	+	0.1	-22%	22%
Mineral Soil C Stocks Grassland Remaining Grassland, Tier 3 Methodology	7.4	(116.1)	131.0	-1663%	1663%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	0.1	(0.4)	0.6	-448%	448%
Mineral Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology (Change in Soil C due to Biosolids [i.e., Treated Sewage Sludge] Amendments)	(1.0)	(1.5)	(0.5)	-50%	50%
Organic Soil C Stocks: Grassland Remaining Grassland, Tier 2 Methodology	5.5	1.2	9.9	-79%	79%
Combined Uncertainty for Flux Associated with Carbon Stock Changes Occurring in Grassland Remaining Grassland	**13.3**	**(110.3)**	**137.0**	**-926%**	**926%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates is 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 carbon stock changes for agroforestry systems. Changes in biomass and dead organic matter carbon stocks are assumed to be negligible in other grasslands, largely comprised of herbaceous biomass, although there are 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

Several improvements have been implemented in this *Inventory* leading to recalculations. These improvements included a) incorporating new USDA-NRCS NRI data through 2017; b) updated FIA data from 1990 to 2022 on biomass, dead wood and litter carbon stocks in woodlands for grassland remaining grassland; c) constraining manure N applications in the Tier 3 method at the state scale rather than the national scale; and d) re-calibrating the soil carbon module in the DayCent model using Bayesian methods. See the Recalculations Discussion in the cropland remaining cropland section for other improvements. As a result of these improvements, grassland remaining grassland has a larger average loss of 10.7 MMT CO_2 Eq. across the time series compared to the previous *Inventory*, which is a 1,850 percent change on average over the time series. The large average value for the percentage change is due to an increase from near zero to 7.0 MMT CO_2 Eq. for the estimated carbon stock change in 1994.

Planned Improvements

A key improvement planned for the *Inventory* includes conducting an analysis of carbon stock changes for grasslands in Alaska. This improvement will be a significant development that will resolve the majority of the discrepancy between the managed land base for grassland remaining grassland and amount of area currently included in grassland remaining grassland emissions and removals calculations (see Table 6-46).

Table 6-46: Comparison of Managed Land Area in Grassland Remaining Grassland and the Area in the current Grassland Remaining Grassland Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	**Managed Land**	***Inventory***	**Difference**
1990	328,565	279,705	48,861
1991	328,058	279,205	48,853
1992	327,601	278,755	48,846
1993	325,869	277,030	48,839
1994	324,249	275,418	48,831
1995	323,373	274,549	48,824
1996	322,517	273,701	48,816
1997	321,752	272,944	48,808
1998	319,811	271,010	48,801
1999	318,903	270,110	48,793
2000	317,917	269,131	48,785
2001	317,060	268,282	48,778
2002	316,443	267,883	48,560
2003	316,545	268,206	48,340
2004	316,350	268,232	48,118
2005	315,930	268,034	47,897
2006	315,422	267,748	47,675
2007	315,164	267,712	47,452
2008	315,090	267,861	47,228
2009	315,163	268,159	47,005
2010	314,765	267,984	46,781
2011	314,270	267,712	46,557
2012	313,977	267,586	46,391
2013	314,640	268,416	46,224
2014	315,329	269,271	46,058
2015	315,427	269,535	45,891
2016	315,327	269,602	45,725
2017	316,056	270,339	45,717
2018	318,959	273,168	45,791
2019	320,255	274,471	45,784
2020	320,855	275,079	45,777
2021	321,909	*	*
2022	322,779	*	*

Activity data on land use have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

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. For information about other improvements, see the Planned Improvements section in Cropland Remaining Cropland.

Non-CO_2 Emissions from Grassland Fires (CRT 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.[50] 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 grasslands 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 184 percent since 1990. In 2022, 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 2022 have averaged approximately 0.4 MMT CO_2 Eq. (14 kt) of CH_4 and 0.3 MMT CO_2 Eq. (1 kt) of N_2O (see Table 6-47 and Table 6-48).

Table 6-47: CH_4 and N_2O Emissions from Biomass Burning in Grassland (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
CH_4	0.1	0.4	0.6	0.2	0.6	0.5	0.3
N_2O	0.1	0.4	0.5	0.2	0.5	0.4	0.3
Total Net Flux	**0.2**	**0.8**	**1.1**	**0.3**	**1.1**	**0.9**	**0.6**

Table 6-48: CH_4, N_2O, CO, and NO_x Emissions from Biomass Burning in Grassland (kt)

	1990	2005	2018	2019	2020	2021	2022
CH_4	4	15	22	6	20	18	12
N_2O	+	1	2	1	2	2	1
CO	122	430	610	170	575	509	346
NO_x	7	26	37	10	35	31	21

+ 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 2020 (IPCC 2006). A data splicing method is used to estimate the emissions from 2021 to 2022, which is discussed later in this section.

The land area designated as managed grassland is based primarily on the USDA National Resources Inventory (NRI) (Nusser and Goebel 1997; USDA-NRCS 2020). 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

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[50] A planned improvement is underway to incorporate woodland tree biomass into the *Inventory* for non-CO_2 emissions from grassland fires.

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 burned area data from the Monitoring Trends in Burn Severity (MTBS) program for 1990 through 2020 (MTBS 2023; Picotte, et al. 2020).[51] 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 6-49).

Table 6-49: Thousands of Grassland Hectares Burned Annually

Year	1990	2005	2018	2019	2020	2021	2022
Thousand Hectares	457	1,612	2,290	637	2156	NE	NE

NE (Not Estimated)

Notes: Burned area was not estimated (NE) for 2021 to 2022, but will be updated in a future *Inventory*.

For 1990 to 2020, 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).

A linear extrapolation of the trend in the time series is applied to estimate emissions for 2021 to 2022. Specifically, a linear regression model with autoregressive moving-average (ARMA) errors (Brockwell and Davis 2016) is used to derive the trend in emissions over time from 1990 to 2020, and the trend is used to approximate the 2021 to 2022 emissions. The Tier 1 method described previously will be applied to recalculate the 2021 to 2022 emissions in a future *Inventory*.

The same methods are applied from 1990 to 2020, and a data splicing method is used to extend the time series from 2021 to 2022 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 2021 to 2022. The model produces estimates for the upper and lower bounds of the emission estimate and the results are summarized in Table 6-50. Methane emissions from biomass burning in grassland for 2022 are estimated to be between approximately 0.0 and 0.8 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 100 percent below and 137 percent above the 2022 emission estimate of 0.3 MMT CO_2 Eq. Nitrous oxide emissions are estimated to be between approximately 0.0 and 0.7 MMT CO_2 Eq., or 100 percent below and 137 percent above the 2022 emission estimate of 0.3 MMT CO_2 Eq.

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

Table 6-50: Uncertainty Estimates for Non-CO_2 Greenhouse Gas Emissions from Biomass Burning in Grassland (MMT CO_2 Eq. and Percent)

Source	Gas	2022 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	+	0.8	-100%	+137%
Grassland Burning	N_2O	0.3	+	0.7	-100%	+137%

+ 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 grasslands 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 on the 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.

Recalculations Discussion

While the methods for calculating non-CO_2 emissions from grassland burning remained the same, the two primary data sources have been updated from the previous *Inventory*. We used the current NRI 2017 dataset (USDA-NRCS 2020) and the current release of MTBS burn perimeter data (MTBS 2023). In the original estimation of non-CO_2 emissions, the same set of NRI survey locations was used for the entire time series, but the locations identified with burning were allowed to vary inter-annually with this revision. These changes resulted in a net increase in CO_2-equivalent emissions by an annual average of 0.1 MMT CO_2 Eq., or 19 percent from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

Two key planned improvements have been identified for this source category, including 1) incorporation of country-specific grassland biomass factors, and 2) 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. Lastly, a future *Inventory* will incorporate non-CO_2 greenhouse emissions from burning woodland tree biomass in grasslands. These 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 (CRT Category 4C2)

Land converted to grassland includes all current grassland in an inventory year that had been in another land use(s) during the previous 20 years (IPCC 2006).[52] 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.

Land use change can lead to large losses of carbon 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 carbon stocks due to land use change. All soil organic carbon 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 carbon from forest land converted to grassland are reported, as well as gains and losses associated with conversions to woodlands[53] from other land uses, including croplands converted to grasslands, settlements converted to grasslands and other lands converted to grasslands. However, the current *Inventory* does not include the gains and losses in aboveground and belowground biomass, dead wood and litter carbon for other land use conversions to grassland that are not woodlands.[54]

There is a discrepancy between the current land representation (see Section 6.1) and the area data that have been used in the inventory for land converted to grassland. Specifically, grassland in Alaska is not included in the *Inventory*, and this leads to a difference between the managed area in land converted to grassland in the land representation and the grassland area included in the emissions and removal calculations for land converted to grassland (Table 6-54). Improvements are underway to incorporate grassland area in Alaska as part of future *Inventories* (see Planned Improvements section).

The largest carbon losses with land converted to grassland are associated with aboveground biomass, belowground biomass, and litter carbon losses from forest land converted to grassland (see Table 6-51 and Table 6-52). These three pools led to net emissions in 2022 of 31.3, 4.3, and 8.0 MMT CO_2 Eq. (8.5, 1.2, and 2.2 MMT C), respectively. The losses associated with forest land converted to grassland are partially offset by gains associated with other land converted to grassland and due to cropland converted to grassland, which leads to less intensive management of the soil. Drainage of organic soils for grassland management led to CO_2 emissions to the atmosphere of 1.4 MMT CO_2 Eq. (0.4 MMT C). The total net carbon stock change in 2022 for land converted to

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[52] USDA 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.

[53] Woodlands are considered grasslands in the U.S. land representation because they do not meet the definition of forest land.

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

grassland is estimated as a loss of 25.6 MMT CO_2 Eq. (7.0 MMT C) or a net source of emissions, which represents a decrease in carbon stock loss by 27 percent compared to the initial reporting year of 1990.

Table 6-51: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes for Land Converted to Grassland (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Grassland	**(10.2)**	**(16.9)**	**(10.8)**	**(10.3)**	**(9.3)**	**(13.6)**	**(12.5)**
Aboveground Live Biomass	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	(0.1)	(0.1)	+	+	+	+	+
Litter	(0.1)	(0.1)	+	+	+	+	+
Mineral Soils	(10.4)	(18.1)	(11.7)	(11.1)	(10.1)	(14.4)	(13.3)
Organic Soils	0.6	1.4	1.1	1.1	1.0	1.0	1.0
Forest Land Converted to Grassland	**50.2**	**49.0**	**46.9**	**46.9**	**46.8**	**46.8**	**46.8**
Aboveground Live Biomass	34.5	33.4	31.8	31.8	31.8	31.8	31.8
Belowground Live Biomass	4.8	4.6	4.4	4.4	4.4	4.4	4.4
Dead Wood	2.4	2.4	2.4	2.4	2.4	2.4	2.4
Litter	8.6	8.5	8.2	8.2	8.2	8.2	8.2
Mineral Soils	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Other Lands Converted to Grassland	**(4.0)**	**(9.6)**	**(10.2)**	**(10.5)**	**(8.2)**	**(8.0)**	**(8.0)**
Aboveground Live Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Mineral Soils	(3.8)	(9.4)	(10.1)	(10.4)	(8.1)	(7.9)	(7.9)
Organic Soils	+	+	0.1	0.1	0.1	0.1	0.1
Settlements Converted to Grassland	**(0.6)**	**(0.7)**	**(0.8)**	**(0.8)**	**(0.8)**	**(0.8)**	**(0.8)**
Aboveground Live Biomass	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	(0.1)	(0.1)	+	+	+	+	+
Litter	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Mineral Soils	(0.1)	(0.3)	(0.5)	(0.5)	(0.4)	(0.4)	(0.4)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Grassland	**(0.1)**	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Aboveground Live Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Aboveground Live Biomass	**33.9**	**32.9**	**31.4**	**31.4**	**31.3**	**31.3**	**31.3**
Belowground Live Biomass	**4.7**	**4.5**	**4.4**	**4.3**	**4.3**	**4.3**	**4.3**
Dead Wood	**2.2**	**2.3**	**2.3**	**2.3**	**2.3**	**2.3**	**2.3**
Litter	**8.4**	**8.2**	**8.0**	**8.0**	**8.0**	**8.0**	**8.0**
Total Mineral Soil Flux	**(14.6)**	**(27.9)**	**(22.4)**	**(22.1)**	**(18.7)**	**(22.8)**	**(21.7)**
Total Organic Soil Flux	**0.7**	**1.8**	**1.5**	**1.5**	**1.4**	**1.4**	**1.4**
Total Net Flux	**35.3**	**21.8**	**25.2**	**25.4**	**28.7**	**24.5**	**25.6**

+ 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 6-52: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes for Land Converted to Grassland (MMT C)

	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Grassland	**(2.8)**	**(4.6)**	**(3.0)**	**(2.8)**	**(2.5)**	**(3.7)**	**(3.4)**
Aboveground Live Biomass	+	+	+	+	+	+	+
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	(2.8)	(4.9)	(3.2)	(3.0)	(2.8)	(3.9)	(3.6)
Organic Soils	0.2	0.4	0.3	0.3	0.3	0.3	0.3
Forest Land Converted to Grassland	**13.7**	**13.3**	**12.8**	**12.8**	**12.8**	**12.8**	**12.8**
Aboveground Live Biomass	9.4	9.1	8.7	8.7	8.7	8.7	8.7
Belowground Live Biomass	1.3	1.3	1.2	1.2	1.2	1.2	1.2
Dead Wood	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Litter	2.4	2.3	2.2	2.2	2.2	2.2	2.2
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	+	+	+	+	+	+
Other Lands Converted to Grassland	**(1.1)**	**(2.6)**	**(2.8)**	**(2.9)**	**(2.2)**	**(2.2)**	**(2.2)**
Aboveground Live Biomass	+	+	+	+	+	+	+
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	(1.0)	(2.6)	(2.8)	(2.8)	(2.2)	(2.2)	(2.2)
Organic Soils	+	+	+	+	+	+	+
Settlements Converted to Grassland	**(0.2)**	**(0.2)**	**(0.2)**	**(0.2)**	**(0.2)**	**(0.2)**	**(0.2)**
Aboveground Live Biomass	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	+	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Grassland	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Aboveground Live Biomass	+	+	+	+	+	+	+
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	+	+	+	+	+
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Aboveground Live Biomass	**9.2**	**9.0**	**8.6**	**8.6**	**8.5**	**8.5**	**8.5**
Belowground Live Biomass	**1.3**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**
Dead Wood	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**
Litter	**2.3**	**2.2**	**2.2**	**2.2**	**2.2**	**2.2**	**2.2**
Total Mineral Soil Flux	**(4.0)**	**(7.6)**	**(6.1)**	**(6.0)**	**(5.1)**	**(6.2)**	**(5.9)**
Total Organic Soil Flux	**0.2**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**
Total Net Flux	**9.6**	**5.9**	**6.9**	**6.9**	**7.8**	**6.7**	**7.0**

+ 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 carbon stock changes for land converted to grassland, including (1) loss of aboveground and belowground biomass, dead wood and litter carbon with forest land converted to grassland and other land use conversions to woodlands, as well as (2) the impact from all land use conversions to grassland on mineral and organic soil organic carbon stocks.

Biomass, Dead Wood, and Litter Carbon Stock Changes

A Tier 3 method is applied to estimate biomass, dead wood and litter carbon 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 2023) and in the Eastern US, IPCC (2006) defaults for biomass in grasslands. There is limited data on grassland carbon stocks so only default biomass estimates (IPCC 2006) for grasslands were used to estimate carbon stock changes (litter and dead wood carbon stocks were assumed to be zero since no reference carbon density estimates exist for croplands) in the eastern United States. 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 carbon that is lost abruptly with forest land converted to grasslands is estimated based on the amount of carbon before conversion and the amount of carbon 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 state is reached. It was determined that using an IPCC Tier 1 approach that assumes all carbon 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 carbon in woody biomass during abrupt or gradual land use change. To estimate this transfer of carbon in woody biomass, state-specific carbon densities for woody biomass remaining on these former forest lands following conversion to grasslands were developed and included in the estimation of carbon 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 carbon density was lost during conversion from forest land to grasslands. This estimate was used to develop state-specific carbon density estimates for biomass, dead wood, and litter for grasslands in the West and Great Plains states, and these state-specific carbon densities were applied in the compilation system to estimate the carbon losses associated with conversion from forest land to grassland in the West and Great Plains states. Further, losses from forest land to what are often characterized as woodlands are included in this category using FIA plot remeasurements and the methods and models briefly described below and in detail in Domke et al. (2022) and Westfall et al. (2023).

If FIA plots include data on individual trees, aboveground and belowground carbon density estimates are based on Woodall et al. (2011) and Westfall et al. (2023). 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 carbon mass is belowground (Smith et al. 2006). Estimates of carbon 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 carbon density is estimated following the basic method applied to live trees (Woodall et al. 2011, Westfall et al. 2023) with additional modifications to woodland species 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 carbon 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 carbon 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 carbon is the pool of organic carbon (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 carbon. If FIA plots include litter material, a modeling approach using litter carbon measurements from FIA plots is used to estimate litter carbon density (Domke et al. 2016). See Annex 3.13 for more information about reference carbon density estimates for forest land.

Soil Carbon Stock Changes

Soil organic carbon stock changes are estimated for land converted to grassland according to land use histories recorded in the 2017 USDA NRI survey for non-federal lands (USDA-NRCS 2020). Land use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI survey location on a five-year cycle beginning in 1982. In 1998, the NRI Program began collecting annual data, and the annual data are currently available through 2017 (USDA-NRCS 2020). For 2018 through 2020, the time series is extended with the crop data provided in USDA-NASS CDL (USDA-NASS 2021), while survey locations identified as grasslands are assumed to not change over this time period. However, the areas have been modified in the original NRI survey through a process in which the Forest Inventory and Analysis (FIA) survey data and the National Land Cover Dataset (NLCD; Yang et al. 2018) are harmonized with the NRI data. This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 Representation of the U.S. Land Base for more information).

NRI survey locations are classified as land converted to grassland in a given year between 1990 and 2020 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 NLCD (Yang et al. 2018; Homer et al. 2007; Fry et al. 2011; Homer et al. 2015).

Soil Carbon Stock Changes for Mineral Soils

An IPCC Tier 3 model-based approach (Ogle et al. 2010) is applied to estimate carbon stock changes in mineral soils for most of the area in land converted to grassland. Carbon 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 carbon stock changes from 2021 to 2022 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 2020 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 2022). See Box 6-4 in the Methodology section of cropland remaining cropland for more information about the surrogate data method.

Tier 3 Approach. Mineral soil organic carbon stocks and stock changes are estimated using the DayCent ecosystem model (Parton et al. 1998; Del Grosso et al. 2001, 2011). The DayCent model utilizes the soil carbon 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 2017 USDA NRI survey (USDA-NRCS 2018). Carbon stocks and 95 percent confidence intervals are estimated for each year between 1990 and 2020. 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 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes from 2021 to 2022 are approximated using a linear extrapolation of emission patterns from 1990 to 2020. 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). Stock change estimates for 2021 to 2022 will be recalculated in future Inventories with an updated time series of activity data (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 carbon 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 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes are approximated for the remainder of the time series with a linear extrapolation of emission patterns from 1990 to 2020. 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, stock change estimates for 2021 to 2022 will be recalculated in future Inventories with an updated time series of activity data.

Soil Carbon Stock Changes for Organic Soils

Annual carbon emissions from drained organic soils in land converted to grassland are estimated using the Tier 2 method provided in IPCC (2006), with country-specific carbon 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 2020 so that changes reflect anthropogenic activity and not methodological adjustments. In addition, soil organic carbon stock changes are approximated for the remainder of the time series with a linear extrapolation of emission patterns from 1990 to 2020. 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 estimating emissions at the end of a time series (IPCC 2006). Annual carbon emissions from drained organic soils from 2021 to 2022 will be recalculated in future *Inventories* with an updated time series of activity data.

Uncertainty

The uncertainty analyses for biomass, dead wood and litter carbon losses with forest land converted to grassland and other land use conversions to woodlands are conducted in the same way as the uncertainty assessment for forest ecosystem carbon 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 soil organic carbon stock changes using the Tier 3 and Tier 2 methodologies are quantified from two variance components (Ogle et al. 2010), as described in cropland remaining cropland. For 2021 to 2022, there is additional uncertainty propagated through the Monte Carlo analysis associated with a surrogate data method, which is also described in the Cropland Remaining Cropland section.

Uncertainty estimates are presented in Table 6-53 for each subsource (i.e., biomass carbon stocks, mineral and organic carbon 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 carbon stocks in land converted to grassland ranges from 156 percent below to 156 percent above the 2022 stock change estimate of 25.6 MMT CO_2 Eq. The large relative uncertainty around the 2022 stock change estimate is partly due to large uncertainties in biomass and dead organic matter carbon losses with forest land conversion to grassland, in addition to variation in soil organic carbon stock changes that is not explained by the surrogate data method.

Table 6-53: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass Carbon Stock Changes occurring within Land Converted to Grassland (MMT CO_2 Eq. and Percent)

Source	2022 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	**(12.5)**	**(32.1)**	**7.0**	**-156%**	**156%**
Aboveground Live Biomass	(0.1)	(0.3)	+	-136%	134%
Belowground Live Biomass	+	+	+	-78%	100%
Dead Wood	+	(0.1)	+	-128%	100%
Litter	+	(0.1)	+	-170%	100%
Mineral Soil C Stocks: Tier 3	(11.6)	(31.0)	7.8	-167%	167%
Mineral Soil C Stocks: Tier 2	(1.7)	(3.7)	0.2	-114%	114%
Organic Soil C Stocks: Tier 2	1.0	+	2.0	-96%	96%
Forest Land Converted to Grassland	**46.8**	**12.2**	**81.4**	**-74%**	**74%**
Aboveground Live Biomass	31.8	(1.4)	64.9	-104%	104%
Belowground Live Biomass	4.4	(0.2)	9.0	-104%	105%
Dead Wood	2.4	(0.1)	5.0	-105%	104%
Litter	8.2	(0.4)	16.8	-104%	104%
Mineral Soil C Stocks: Tier 2	(0.1)	(0.2)	+	-140%	140%
Organic Soil C Stocks: Tier 2	0.1	(0.0)	0.2	-130%	130%
Other Lands Converted to Grassland	**(8.0)**	**(12.9)**	**(3.1)**	**-61%**	**61%**
Aboveground Live Biomass	(0.1)	(0.1)	+	-69%	44%
Belowground Live Biomass	+	+	+	-100%	100%
Dead Wood	+	(0.1)	+	-85%	100%
Litter	(0.1)	(0.1)	+	-60%	47%
Mineral Soil C Stocks: Tier 2	(7.9)	(12.8)	(3.0)	-62%	62%
Organic Soil C Stocks: Tier 2	0.1	+	0.1	-111%	111%
Settlements Converted to Grassland	**(0.8)**	**(1.0)**	**(0.5)**	**-35%**	**35%**
Aboveground Live Biomass	(0.2)	(0.3)	(0.1)	-56%	61%
Belowground Live Biomass	+	+	+	-42%	100%
Dead Wood	+	(0.1)	+	-67%	100%
Litter	(0.1)	(0.1)	+	-66%	59%
Mineral Soil C Stocks: Tier 2	(0.4)	(0.6)	(0.2)	-56%	56%
Organic Soil C Stocks: Tier 2	+	+	+	-432%	432%
Wetlands Converted to Grasslands	**0.1**	**(0.2)**	**0.3**	**-289%**	**283%**
Aboveground Live Biomass	(0.1)	(0.1)	+	-85%	38%
Belowground Live Biomass	+	+	+	-100%	100%
Dead Wood	+	+	+	-95%	100%
Litter	+	+	+	-112%	100%
Mineral Soil C Stocks: Tier 2	+	+	+	-173%	173%
Organic Soil C Stocks: Tier 2	0.2	+	0.4	-112%	112%
Total: Land Converted to Grassland	**25.6**	**(14.4)**	**65.7**	**-156%**	**156%**
Aboveground Live Biomass	**31.3**	**(1.8)**	**64.5**	**-106%**	**106%**
Belowground Live Biomass	**4.3**	**(0.2)**	**9.0**	**-106%**	**106%**
Dead Wood	**2.3**	**(0.3)**	**4.8**	**-111%**	**111%**
Litter	**8.0**	**(0.6)**	**16.6**	**-107%**	**107%**
Mineral Soil C Stocks: Tier 3	**(11.6)**	**(31.0)**	**7.8**	**-167%**	**167%**
Mineral Soil C Stocks: Tier 2	**(10.1)**	**(15.4)**	**(4.9)**	**-52%**	**52%**

Organic Soil C Stocks: Tier 2	**1.4**	**0.4**	**2.4**	**-74%**	**74%**

+ Absolute value does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates is 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 carbon stock changes for conversions to agroforestry systems and herbaceous grasslands. The influence of agroforestry is difficult to address because there are currently no datasets to evaluate the trends in the area and associated carbon stocks in agroforestry systems. The influence of land use change to herbaceous grasslands and agroforestry 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

Several improvements have been implemented in this *Inventory* leading to recalculations. These improvements included a) incorporating new USDA-NRCS NRI data through 2017; b) updated FIA data from 1990 to 2022 on biomass, dead wood and litter carbon stocks associated with forest land converted to grassland (see Recalculations Discussion of Chapter 6.2 Forest Land Remaining Forest Land for more details); c) constraining manure nitrogen applications in the Tier 3 method at the state scale rather than the national scale; and d) re-calibrating the soil carbon module in the DayCent model using Bayesian methods. See the Recalculations Discussion in the cropland remaining cropland section for other improvements. Finally, see further updates in Section 6.2 Forest Land Remaining Forest Land, describing updates to the estimates for aboveground volume and biomass which impacted lands converted to grassland estimates. As a result, land converted to grassland has an estimated increase in losses of carbon stock changes, leading to a net change of 53 MMT CO_2 Eq. on average over the time series, representing a 237 percent change on average compared to the previous *Inventory*. Land converted to grassland is a net source of emissions across the time series based on the recalculations in this *Inventory*. This change from a net sink to a net source is mostly due to larger estimated losses of biomass and dead organic matter with forest land converted to grassland, and smaller estimated gains in mineral soil carbon stocks for cropland and other lands converted to grasslands.

Planned Improvements

The key improvement planned for the inventory is conducting an analysis of carbon stock changes for grassland in Alaska. This will resolve the majority of the discrepancy between the managed land base for land converted to grassland and amount of area currently included in land converted to grassland emissions and removals calculations (see Table 6-54).

Table 6-54: Comparison of Managed Land Area in Land Converted to Grassland and Area in the current Land Converted to Grassland Inventory (Thousand Hectares)

	Area (Thousand Hectares)		
Year	**Managed Land**	***Inventory***	**Difference**
1990	9,301	9,297	4
1991	9,492	9,488	4
1992	9,710	9,706	4
1993	11,619	11,615	4
1994	13,372	13,368	4

1995	14,039	14,035	4
1996	14,727	14,723	4
1997	15,411	15,408	4
1998	19,289	19,285	4
1999	20,143	20,139	4
2000	21,257	21,253	4
2001	22,349	22,345	4
2002	23,087	22,817	270
2003	22,986	22,445	541
2004	23,920	23,108	811
2005	24,091	23,009	1,082
2006	24,693	23,341	1,352
2007	24,694	23,072	1,622
2008	25,266	23,373	1,893
2009	25,424	23,260	2,163
2010	25,769	23,336	2,434
2011	26,176	23,471	2,704
2012	26,164	23,292	2,871
2013	25,154	22,116	3,038
2014	23,981	20,776	3,205
2015	24,101	20,730	3,372
2016	23,531	19,993	3,538
2017	22,808	19,270	3,538
2018	19,968	16,429	3,538
2019	19,546	16,008	3,538
2020	18,706	15,168	3,538
2021	17,351	*	*
2022	16,269	*	*

Activity data on land use have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

In addition, the amount of biomass carbon 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 carbon before conversion and an estimated level of carbon 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 carbon 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 carbon pools. In addition, biomass carbon stock changes will be estimated for conversions from other land uses to herbaceous grasslands. For information about other improvements, see the Planned Improvements section in Cropland Remaining Cropland.

6.8 Wetlands Remaining Wetlands (CRT Category 4D1)

Wetlands remaining wetlands includes all wetlands in an inventory year that have been classified as a 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 eliminated 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 to estimate emissions and removals from 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 IPCC methodologies estimate only on-site N_2O and CH_4 emissions. This is because off-site N_2O estimates are complicated by the risk of double-counting emissions from nitrogen fertilizers added to horticultural peat where subsequent runoff or leaching into waterbodies can result in indirect N_2O emissions that are already included within the agricultural soil management category.

On-site emissions from managed peatlands occur as the land is drained and cleared of vegetation, and the underlying peat is exposed to sun, weather and oxygen. As this occurs, some of the 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 occurring on highly fertile/nutrient-rich soils, mostly located in the southern peatlands in Florida, contain significant amounts of organic nitrogen in inert/microbially inaccessible forms. Draining land in preparation for peat extraction allows bacteria to convert the organic nitrogen into nitrates through nitrogen mineralization which leach to the surface where they are reduced to N_2O during nitrification. Nitrate availability also 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 dissolved organic 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 are estimated to be 0.6 MMT CO_2 Eq. in 2022 (see Table 6-55 and Table 6-56) comprising 0.6 MMT CO_2 Eq. (572 kt) of CO_2, 0.004 MMT CO_2 Eq. (0.13 kt) of CH_4 and 0.0004 MMT CO_2 Eq. (0.002 kt) of N_2O. Total emissions in 2022 are 4.7 percent greater than total emissions in 2021.

Total emissions from peatlands remaining peatlands have fluctuated between 0.6 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 2021, however, total emissions from peatlands increased slightly in 2022 compared to 2021. Carbon dioxide emissions from peatlands remaining peatlands have fluctuated between 0.6 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.

Table 6-55: Emissions from Peatlands Remaining Peatlands (MMT CO_2 Eq.)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	**1.1**	**1.1**	**0.7**	**0.6**	**0.6**	**0.5**	**0.6**
Off-site	1.0	1.0	0.6	0.6	0.5	0.5	0.5
On-site	0.1	0.1	+	+	+	+	+
CH_4 (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**
N_2O (On-site)	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Total	**1.1**	**1.1**	**0.7**	**0.6**	**0.6**	**0.6**	**0.6**

+ Does not exceed 0.05 MMT CO_2 Eq.

Note: Totals may not sum due to independent rounding.

Table 6-56: Emissions from Peatlands Remaining Peatlands (kt)

Gas	1990	2005	2018	2019	2020	2021	2022
CO_2	**1,055**	**1,101**	**650**	**613**	**590**	**547**	**572**
Off-site	985	1,030	608	572	550	509	533
On-site	70	71	42	41	41	38	39

CH_4 (On-site)	+	+	+	+	+	+	+
N_2O (On-site)	+	+	+	+	+	+	+

+ Does not exceed 0.5 kt.
Note: 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 6-57) 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 conterminous 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; USGS 1995 through 2018; USGS 2023a; USGS 2023b; USGS 2023c). Hawaii is assumed to have no peat production due to its absence from these sources. To develop these data, the 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; USGS estimates data for non-respondents on the basis of prior-year production levels (Apodaca 2011).

The estimates for Alaska 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 conterminous United States and Alaska, large variations in peat production can also result from variation in precipitation and the subsequent changes in moisture conditions, since unusually wet years can hamper peat production. The methodology estimates emissions from Alaska separately from the conterminous United States because Alaska previously conducted its own mineral surveys and reported peat production by volume, rather than by weight (Table 6-58). 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).[55] 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 2021 (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 carbon were estimated by multiplying the area of managed peatlands by the default emission factor for dissolved organic C provided in IPCC (2013).

The United States has largely imported peat from Canada for horticultural purposes; in 2022, imports of *Sphagnum* moss (nutrient-poor) peat from Canada represented 96 percent of total U.S. peat imports and 80 percent of U.S. domestic consumption (USGS 2023c). Most peat produced in the United States is reed-sedge peat, generally from southern states, which is classified as nutrient-rich by IPCC (2006). To be consistent with the Tier 1 method, only

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[55] 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).

domestic peat production is accounted for when estimating off-site emissions. 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 6-57: Peat Production of Conterminous 48 States (kt)

Type of Deposit	1990	2005	2018	2019	2020	2021	2022
Nutrient-Rich	595.1	657.6	338.4	329.4	343.4	291.6	306.0
Nutrient-Poor	55.4	27.4	50.6	36.6	10.6	32.4	34.0
Total Production	**692.0**	**685.0**	**389.0**	**366.0**	**354.0**	**324.0**	**340.0**

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) (2023) *Mineral Commodity Summaries: Peat (2023).*

Table 6-58: Peat Production of Alaska (Thousand Cubic Meters)

	1990	2005	2018	2019	2020	2021	2022
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 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 a land 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).[56] The area of land managed for peat extraction in the conterminous United States was estimated using both 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 6-59. 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 6-60. The IPCC (2006) on-site emissions equation also includes a term that accounts for emissions resulting from the change in carbon 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 carbon stocks in living biomass on managed peatlands are also assumed to be zero under the Tier 1 methodology (IPCC 2006 and 2013).

Table 6-59: Peat Production Area of Conterminous 48 States (Hectares)

	1990[a]	2005	2018	2019	2020	2021	2022

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[56] 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).

Nutrient-Rich	5,951	6,576	3,384	3,294	3,434	2,916	3,060
Nutrient-Poor	554	274	506	366	106	324	340
Total Production	**6,920**	**6,850**	**3,890**	**3,660**	**3,540**	**3,240**	**3,400**

[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.

Table 6-60: Peat Production Area of Alaska (Hectares)

	1990	2005	2018	2019	2020	2021	2022
Nutrient-Rich	0	0	0	0	0	0	0
Nutrient-Poor	286	104	212	329	428	428	428
Total Production	**286**	**104**	**212**	**329**	**428**	**428**	**428**

On-site N_2O Emissions

IPCC (2006) indicates the calculation of on-site N_2O emission estimates using Tier 1 methodology only considers 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 nutrient-rich area data from production data. In order to estimate N_2O emissions, the land area estimate of nutrient-rich peatlands remaining peatlands was multiplied by the appropriate default emission factor taken from IPCC (2013). See the Planned Improvements section for additional information on identified research activities to improve peatland land area estimates.

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 land area estimate 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 6-61 for the calculated area of ditches and drained land.

Table 6-61: Peat Production (Hectares)

	1990	2005	2018	2019	2020	2021	2022
Conterminous 48 States							
Area of Drained Land	6,574	6,508	3,696	3,477	3,363	3,078	3,230
Area of Ditches	346	343	195	183	177	162	170
Total Production	**6,920**	**6,850**	**3,890**	**3,660**	**3,540**	**3,240**	**3,400**
Alaska							
Area of Drained Land	272	99	202	312	407	407	407
Area of Ditches	14	5	11	16	21	21	21
Total Production	**286**	**104**	**212**	**329**	**428**	**428**	**428**

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022. 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 estimated 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 2022, 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 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 conterminous United 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 6-62. Carbon dioxide emissions from peatlands remaining peatlands in 2022 were estimated to be between 0.5 and 0.7 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 16 percent below to 16 percent above the 2022 emission estimate of 0.6 MMT CO_2 Eq. Methane emissions from peatlands remaining peatlands in 2022 were estimated to be between 0.001 and 0.006 MMT CO_2 Eq. This indicates a range of 59 percent below to 79 percent above the 2022 emission estimate of 0.004 MMT CO_2 Eq. Nitrous oxide emissions from peatlands remaining peatlands in 2022 were estimated to be between 0.0002 and 0.0006 MMT CO_2 Eq. at the 95 percent confidence level. This indicates a range of 52 percent below to 53 percent above the 2022 emission estimate of 0.0004 MMT CO_2 Eq.

Table 6-62: 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	2022 Emission Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emission Estimate[a] (%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Peatlands Remaining Peatlands	CO_2	0.6	0.5	0.7	-16%	+16%
Peatlands Remaining Peatlands	CH_4	+	+	+	-59%	+79%
Peatlands Remaining Peatlands	N_2O	+	+	+	-52%	+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 conterminous United States peat production estimates for peatlands remaining peatlands were updated using the Peat section of the *Mineral Commodity Summaries 2023*. The 2023 edition updated 2018, 2019, 2020, and 2021 peat production data and provided peat type production estimates for 2022. Updated data decreased previously estimated emissions for 2018 by 18 percent, 2019 by 19 percent, 2020 by 19 percent, and 2021 by 22 percent versus estimated emissions for 2018, 2019, 2020, and 2021 in the previous (i.e., 1990 through 2021) *Inventory* for peatlands remaining peatlands. According to USGS, peat production estimations for 2018 through 2022 were revised in the *Mineral Commodity Summaries 2023* due to a company having shut down sometime in 2017 (USGS 2023d). Previously, USGS was estimating production for this company due to lack of peat production survey responses.

Although Alaska peat production data for 2015 through 2022 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 through 2022 value 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 2023) *Inventory* report.

Planned Improvements

Edits to the trends and methodology sections are planned based on expert review comments.

EPA notes the following improvements may be implemented or investigated within the next two or three *Inventory* cycles pending time and resource:

- 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 (see Methodology and Time Series Consistency in this chapter), so estimating the implied emission factor per total land area is not appropriate. The inclusion of implied emission factors in this chapter will provide another method of QA/QC and verification for *Inventory* data.

EPA notes the following improvements will continue to be investigated as time and resources allow, but there are no immediate plans to implement until data are available or identified:

- 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 of land undergoing peat extraction.
- EPA plans 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.

Coastal Wetlands Remaining Coastal Wetlands

Consistent with ecological definitions of wetlands,[57] 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

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[57] See https://water.usgs.gov/nwsum/WSP2425/definitions.html; accessed August 2023.

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 (C) 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; there is currently no IPCC methodological guidance for lateral fluxes of carbon.

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 carbon stock losses occur when vegetated coastal wetlands are converted to Unvegetated open water coastal wetlands.

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

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,

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 carbon in all five carbon pools (i.e., aboveground biomass, belowground biomass, dead organic matter [DOM; dead wood and litter], and soil), though typically soil carbon 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 carbon over centuries to millennia as soils accumulate carbon under anaerobic soil conditions and carbon accumulates in plant biomass. Large emissions from soil carbon 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 carbon stock losses resulting from conversion to unvegetated open water coastal wetlands can cause the release of decades to centuries of accumulated soil carbon, as well as the standing stock of biomass carbon. Conversion of unvegetated open water coastal wetlands to vegetated coastal wetlands, either through restoration efforts or naturally, initiates the building of carbon stocks within soils and biomass. In applying the *Wetlands Supplement* methodologies for estimating 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. Therefore, 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 nitrogen derived from consumption of the applied food stock that is then excreted as nitrogen load available for conversion to N_2O. While N_2O emissions can also occur due to anthropogenic nitrogen 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 carbon stock changes and CH_4 emissions from mangroves, tidal marshes and seagrasses. Depending upon their height and area, carbon 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 because they meet the definition of forest land. Mangrove forests that are less than 5 m are reported under coastal wetlands because they meet the definition of wetlands. All other non-drained, intact coastal marshes are 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 carbon stock changes, emissions of CH_4, and emissions of N_2O from aquaculture from all coastal wetlands 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)[58] with NRI, FIA and NLDC data used to compile the land representation (see Section 6.1). 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 6-63. Coastal wetlands remaining coastal wetlands are generally a net carbon sink, with the fluxes ranging from -5.6 to -6.7 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 3.2 to 53.5 MMT CO_2 Eq.), resulting from a large loss of vegetated coastal wetlands to open water due to hurricanes (Table 6-63). Recognizing removals of CO_2 to soil of 12.5 MMT CO_2 Eq. and CH_4 emissions of 4.3 MMT CO_2 Eq. in 2022, vegetated coastal wetlands remaining vegetated coastal wetlands are a net sink of 8.2MMT 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 vegetated coastal wetlands converted to unvegetated coastal wetlands, drive an emission of 1.5 MMT CO_2 Eq. since 2011, primarily from soils. Building of new wetlands from open water, recognized as unvegetated coastal wetlands converted to vegetated coastal, results each year in removal of 0.1 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 total, coastal wetlands are a net sink of 6.7 MMT CO_2 Eq. in 2022.

Table 6-63: Emissions and Removals from Coastal Wetlands Remaining Coastal Wetlands (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands	**(8.4)**	**(8.4)**	**(8.3)**	**(8.3)**	**(8.3)**	**(8.2)**	**(8.2)**
Biomass C Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Flux	(12.5)	(12.6)	(12.5)	(12.5)	(12.5)	(12.5)	(12.5)
Net CH_4 Flux	4.2	4.2	4.3	4.3	4.3	4.3	4.3
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	**(+)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**

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[58] See https://coast.noaa.gov/digitalcoast/tools/lca.html; accessed September 2023.

Coastal Wetlands							
Biomass C Flux	(+)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
Dead Organic Matter C Flux	(+)	(+)	+	+	+	+	+
Soil C Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Net N_2O Flux from Aquaculture in Coastal Wetlands	**0.1**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Total Biomass C Flux	**+**	**+**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**	**(0.1)**
Total Dead Organic Matter C Flux	**(+)**	**(+)**	**+**	**+**	**+**	**+**	**+**
Total Soil C Flux	**(10.8)**	**(10.1)**	**(11.0)**	**(11.0)**	**(11.0)**	**(11.0)**	**(11.1)**
Total CH_4 Flux	**4.2**	**4.2**	**4.3**	**4.3**	**4.3**	**4.3**	**4.3**
Total N_2O Flux	**0.1**	**0.2**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Total Flux	**(6.5)**	**(5.7)**	**(6.7)**	**(6.7)**	**(6.7)**	**(6.7)**	**(6.7)**

\+ 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 (663,014 ha), palustrine scrub shrub (133,582 ha) and estuarine emergent marsh (1,892,507 ha), estuarine scrub shrub (95,225 ha) and estuarine forested wetlands (195,199 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 (53,968 ha), warm temperate (896,583 ha), subtropical (1,966,101 ha) and Mediterranean (62,874 ha) climate zones.

Soils are the largest carbon 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 carbon emissions are not assumed to occur in coastal wetlands that remain vegetated. This *Inventory* includes changes in carbon stocks in both biomass and soils. Changes in DOM carbon stocks are not included. 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 carbon stock changes or CH_4 emissions.

Table 6-64 through Table 6-66 summarize nationally aggregated biomass and soil carbon 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 carbon stock of 35.96 MMT C. Removals from biomass carbon stocks in 2022 were 0.05 MMT CO_2 Eq. (0.01 MMT C), which has increased over the time series (Table 6-64 and Table 6-65). Carbon dioxide emissions from biomass in vegetated coastal wetlands remaining vegetated coastal wetlands between 2002 and 2011, with very low sequestration between 2002 and 2006 and emissions of 0.21 MMT CO_2 Eq. between 2007 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 carbon stock within the top 1 meter of soil (estimated to be 804 MMT C) to which carbon accumulated at a rate of 12.5 MMT CO_2 Eq. (3.4 MMT C) in 2022, a value that has remained relatively constant across the reporting period. For vegetated coastal wetlands remaining vegetated coastal wetlands, methane emissions of 4.3 of MMT CO_2 Eq. (154 kt CH_4) in 2022 (Table 6-66) offset carbon removals resulting in a net removal of 8.2 MMT CO_2 Eq. in 2022; 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 carbon stock change and CH_4 emissions are relatively constant over time.

Table 6-64: Net CO_2 Flux from Carbon Stock Changes in Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
Biomass Flux	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil Flux	(12.5)	(12.6)	(12.5)	(12.5)	(12.5)	(12.5)	(12.5)
Total C Stock Change	**(12.6)**	**(12.6)**	**(12.5)**	**(12.5)**	**(12.5)**	**(12.5)**	**(12.5)**

+ Absolute value does not exceed 0.05 MMT $C0_2$ Eq.

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

Table 6-65: Net CO_2 Flux from Carbon Stock Changes in Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands (MMT C)

Year	1990	2005	2018	2019	2020	2021	2022
Biomass Flux	(+)	+	(+)	(+)	(+)	(+)	(+)
Soil Flux	(3.4)	(3.4)	(3.4)	(3.4	(3.4)	(3.4)	(3.4)
Total C Stock Change	**(3.4)**	**(3.4)**	**(3.4)**	**(3.4**	**(3.4)**	**(3.4)**	**(3.4)**

+ Absolute value does not exceed 0.05 MMT C.

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

Table 6-66: CH_4 Emissions from Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands (MMT CO_2 Eq. and kt CH_4)

Year	1990	2005	2018	2019	2020	2021	2022
Methane Emissions (MMT CO_2 Eq.)	4.2	4.2	4.3	4.3	4.3	4.3	4.3
Methane Emissions (kt CH_4)	149	151	153	153	154	154	154

Methodology and Time-Series Consistency

The following section includes a description of the methodology used to estimate changes in biomass carbon stocks, soil carbon 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 2022.

Biomass Carbon Stock Changes

Above- and belowground biomass carbon 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 2022 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 6-67). Biomass is not sensitive to soil organic matter 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 subtropical 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 6-69; 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 carbon 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 6-67: 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	2018	2019	2020	2021	2022
Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands	2,975,477	2,985,783	2,974,523	2,975,789	2,977,055	2,978,322	2,979 588
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	952	1,769	2,406	2,406	2,406	2,406	2,406

Table 6-68: 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	N/A	N/A	17.83	N/A
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); N/A means there are currently no estuarine forested wetlands that are less than 5 meters tall; these forested wetlands meet the definition of forest land and are included in the Forest Land section.

Table 6-69: 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	N/A	N/A	0.96	N/A
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); N/A means there are currently no estuarine forested wetlands that are less than 5 meters tall; these forested wetlands meet the definition of forest land and are included in the Forest Land section.

Soil Carbon Stock Changes

Soil carbon stock changes are estimated for vegetated coastal wetlands remaining vegetated coastal wetlands for both mineral and organic soils. Soil carbon stock changes, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature (Table 6-70; Lynch 1989; Orson et al. 1990; Kearny & Stevenson 1991; Thom et al. 1992; Roman et al. 1997; Craft et al. 1998; Orson et al. 1998; Merrill 1999; Weis et al.

2001; Hussein et al. 2004; Church et al. 2006; Köster et al. 2007; Drexler et al. 2009; Boyd 2012; Callaway et al. 2012a&b; Bianchi et al. 2013; Drexler et al. 2013; Watson and Byrne 2013; Breithaupt et al. 2014; Crooks et al. 2014; Weston et al. 2014; Smith et al. 2015; Villa & Mitsch 2015; Boyd and Sommerfield 2016; Marchio et al. 2016; Noe et al. 2016; Arriola and Cable 2017; Boyd et al. 2017; Gerlach et al. 2017; Giblin and Forbrich 2018; Krauss et al. 2018; Abbott et al. 2019; Drexler et al. 2019; Poppe and Rybczyk 2019; Ensign et al. 2020; Kemp et al. 2020; Lagomasino et al. 2020; Luk et al. 2020; McTigue et al. 2020; Peck et al. 2020; Vaughn et al. 2020; Weston et al. 2020; Arias-Ortiz et al. 2021; Baustian et al. 2021; Allen et al. 2022; Miller et al. 2022).

Tier 2 estimates of soil carbon removals associated with annual soil carbon accumulation on managed vegetated coastal wetlands remaining vegetated coastal wetlands were developed with country-specific soil carbon 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 carbon stock changes, no differentiation is made between organic and mineral soils since currently, no statistical evidence supports disaggregation (Holmquist et al. 2018).

Table 6-70: 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	1.010	1.544	0.45	0.845
Palustrine Emergent Wetland	1.010	1.544	0.454	0.845
Estuarine Forested Wetland	N/A	N/A	0.821	N/A
Estuarine Scrub/Shrub Wetland	1.254	1.039	0.821	0.845
Estuarine Emergent Wetland	1.254	1.039	1.587	0.845

Source: All data from CCRCN (2023)[59]; N/A means there are no estuarine forested wetlands outside of subtropical regions.

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 carbon stock changes and CH_4 emissions include uncertainties associated with Tier 2 literature values of soil carbon stocks, biomass carbon stocks and CH_4 flux, assumptions that underlie the methodological approaches applied and uncertainties linked to interpretation of remote sensing data. Uncertainty specific to vegetated coastal wetlands remaining vegetated coastal wetlands include differentiation of palustrine and estuarine community classes, which determines the soil carbon stock and CH_4 flux applied. Uncertainties for soil and biomass carbon stock data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment of a carbon stock to a disaggregation of a community class. Because mean soil and biomass carbon stocks for each available community

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[59] Coastal Carbon Network (2023). Database: Coastal Carbon Library (Version 1.0.0). Smithsonian Environmental Research Center. Dataset. https://doi.org/10.25573/serc.21565671. Accessed September 2023.

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 carbon stock value should be applied in the calculation of error propagation; 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 6-71 for each subcategory (i.e., soil carbon, biomass carbon and CH_4 emissions). The combined uncertainty across all subcategory is 37.0 percent below and above the estimate of -6.4 MMT CO_2 Eq, 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 2021, the total flux was -8.2 MMT CO_2 Eq., with lower and upper estimates of -11.3 and -5.2 MMT CO_2 Eq.

Table 6-71: IPCC Approach 1 Quantitative Uncertainty Estimates for Carbon Stock Changes and CH_4 Emissions occurring within Vegetated Coastal Wetlands Remaining Vegetated Coastal Wetlands in 2021 (MMT CO_2 Eq. and Percent)

Source/Sink	Gas	2022 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	(12.5)	(14.7)	(10.3)	-17.7	+17.7
CH_4 emissions	CH_4	4.3	3.0	5.6	-29.9%	+29.9%
Total Flux		**(8.2)**	**(11.3)**	**(5.2)**	**-36.5**	**+36.5**

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

QA/QC and Verification

NOAA provided the 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 carbon 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 carbon 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 carbon stock change data are based upon peer-reviewed literature and CH_4 emission factors derived from the *Wetlands Supplement*.

Recalculations Discussion

A recalculation of emission factors for soil carbon accretion rates was performed using the same methodology and criteria as in Lu and Megonigal (2017) and described above. This new analysis incorporated data published since 2016 and other relevant data that were not previously included. Table 6-70 shows the new values. The updated synthesis resulted in a general increase in soil carbon accumulation rates for estuarine emergent and scrub/shrub wetlands, which resulted in an annual average increase of removals of 2.3 MMT CO_2 Eq. for the entire time series.

For vegetated coastal wetlands remaining vegetated coastal wetlands in 2022, inclusion of the updated values resulted in an increase of the sink from -5.9 MMT CO_2 Eq. to -8.2 MMT CO_2 Eq.

Planned Improvements

Harmonization across all spatial datasets used to calculate activity data is underway. Once completed, a better representation of forested tidal wetlands, palustrine tidal wetlands, and forest land near the tidal boundary will be obtained.

Work is currently underway to examine the feasibility of incorporating seagrass soil and biomass carbon 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.

Box 6-6: State-Level Case Studies for the Estimation of GHG Removals in Seagrasses

North Carolina and Maryland are the first states to include seagrasses within their state-level inventory. North Carolina has the largest extent of seagrass coverage along the U.S. Atlantic coast, measuring approximately 86,412 acres in 2021. Seagrass mapping efforts occurred in 2007, 2013, and 2020 using a field-validated aerial image classification. The Tier 1 soil carbon accumulation rate was used and currently, biomass is not included due to lack of local data. The analysis shows that these high salinity seagrass habitats provided a net carbon sink to the state, although greenhouse gas removals decreased over time due to loss in seagrass coverage. Overall, seagrass beds in 2021 sequestered approximately 0.055 MMT CO_2 Eq. (55.14 kt CO_2 Eq.) in the soils alone.

In Maryland, the state greenhouse gas inventory comprises blue carbon stocks and fluxes from estuarine wetlands and seagrasses. Maryland currently has long-term monitoring of submerged aquatic vegetation (SAV) extent and density through annual surveying, and the rate of carbon sequestration and methane emission was a regional average for coastal wetlands. This study at state-level calculation offers an opportunity to maintain consistency in reporting across spatial scales and allows positioning SAV in its role as a carbon sink, in addition to its benefits in water quality and habitat conservation, perpetuating Maryland's role as a leader in blue carbon accounting.

These two case studies demonstrate the importance of refining emission factor data and harmonizing the inclusion of this ecosystem in the land representation analysis (reconciling the National Ocean and Atmospheric Administration [NOAA] Coastal Change Analysis Program [C-CAP] data with the National Resource Inventory, Forest Inventory Analysis, and the National Land Cover Database).

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 carbon stocks. An estimated 1,488 ha of vegetated coastal wetlands were converted to unvegetated open water coastal wetlands in 2022, 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 aquifer 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 coastal 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 carbon 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 carbon is immediately returned to the atmosphere (as assumed for terrestrial land-use categories), rather than redeposited in long-term carbon storage. The science is currently under evaluation to adopt more refined emissions factors for mobilized coastal wetland carbon based upon the geomorphic setting of the depositional environment.

In 2022, there were 1,488 ha of vegetated coastal wetlands converted to unvegetated open water coastal wetlands (Table 6-67) across all wetland types and climates, which resulted in 1.5 MMT CO_2 Eq. (0.4 MMT C) and 0.06 MMT CO_2 Eq. (0.02 MMT C) lost through soil and biomass, respectively, with minimal DOM C stock loss (Table 6-72, and Table 6-73). 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 6-67).

Table 6-72: Net CO_2 Flux from Carbon Stock Changes in Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
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 6-73: Net CO_2 Flux from Carbon Stock Changes in Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands (MMT C)

Year	1990	2005	2018	2019	2020	2021	2022
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 carbon 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 2022.

Biomass Carbon Stock Changes

Biomass carbon 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 2021 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 carbon stocks are not sensitive to soil organic content but are differentiated based on climate zone. Non-forested aboveground biomass carbon 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[60]; Table 6-68). Aboveground biomass carbon stock data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment of a carbon 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 6-69; IPCC 2014). Above- and belowground values were summed to obtain total biomass carbon stocks. Conversion to open water results in emissions of all biomass carbon 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 2021 time series. Conversion to open water results in emissions of all DOM carbon 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 carbon stock.

Soil Carbon Stock Changes

Soil carbon stock changes are estimated for vegetated coastal wetlands converted to unvegetated open water coastal wetlands. Country-specific soil carbon 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

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[60] See https://github.com/Smithsonian/Coastal-Wetland-NGGI-Data-Public; accessed September 2023.

demonstrated that it was not justified to stratify carbon stocks based upon mineral or organic soil classification, climate zone, or wetland classes; therefore, a single soil carbon 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 carbon loss with conversion of vegetated coastal wetlands to unvegetated open water coastal wetlands is assumed to affect soil carbon 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 carbon 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 carbon stock applied. Because mean soil and biomass carbon 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, the largest uncertainty for any soil carbon stock value should be applied in the calculation of error propagation; IPCC 2000). For aboveground biomass carbon 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.

Uncertainty estimates are presented in Table 6-74 for each subcategory (i.e., soil carbon, biomass carbon, and DOM emissions). The combined uncertainty across all subcategory is 32.0 percent above and below the estimate of 1.5 MMT CO_2 Eq, which is driven by the uncertainty in the soil carbon estimates. In 2022, the total carbon flux was 1.5 MMT CO_2 Eq., with lower and upper estimates of 1.0 and 2.0 MMT CO_2 Eq.

Table 6-74: Approach 1 Quantitative Uncertainty Estimates for CO_2 Flux Occurring within Vegetated Coastal Wetlands Converted to Unvegetated Open Water Coastal Wetlands in 2022 (MMT CO_2 Eq. and Percent)

Source	2022 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 carbon 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 carbon 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 performed 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. Improvements are underway to address this, first conducting a review of literature publications. 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. This is a longer-term improvement.

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 carbon 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 carbon 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). Wetland 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 2022, 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 6-66). 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 6-75 and Table 6-76). The soil carbon stock has increased during the *Inventory* reporting period, likely due to increasing vegetated coastal wetland restoration over time. While DOM carbon 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 2022), 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 6-75: CO_2 Flux from Carbon Stock Changes from Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands (MMT CO_2 Eq.)

Year	1990	2005	2018	2019	2020	2021	2022
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.

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

Table 6-76: CO_2 Flux from Carbon Stock Changes from Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands (MMT C)

Year	1990	2005	2018	2019	2020	2021	2022
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.

Notes: 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 carbon 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 2022.

Biomass Carbon Stock Changes

Quantification of regional coastal wetland biomass carbon 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 2022 from these datasets (Table 6-65). C-CAP provides peer reviewed high resolution level mapping of coastal wetland distribution, including conversion to and from open water. Biomass carbon 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 6-68; Byrd et al. 2017; Byrd et al. 2018; Byrd et al. 2020). The aboveground biomass carbon stock for subtropical 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[61]). Aboveground biomass carbon stock data for all subcategories are not available and thus assumptions were applied using expert judgment about the most appropriate assignment of a carbon 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 6-69; 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 carbon 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 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 2021 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 carbon 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.

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[61] See https://doi.org/10.25573/serc.21565671; accessed September 2023.

Soil Carbon Stock Change

Soil carbon stock changes are estimated for unvegetated open water coastal wetlands converted to vegetated coastal wetlands. Country-specific soil carbon removal factors associated with soil carbon 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; Thom et al. 1992; Roman et al. 1997; Craft et al. 1998; Orson et al. 1998; Merrill 1999; Weis et al. 2001; Hussein et al. 2004; Church et al. 2006; Köster et al. 2007; Drexler et al. 2009; Boyd 2012; Callaway et al. 2012 a & b; Bianchi et al. 2013; Drexler et al. 2013; Watson and Byrne 2013; Crooks et al. 2014; Breithaupt et al. 2014; Weston et al. 2014; Smith et al. 2015; Villa & Mitsch 2015; Boyd and Sommerfield 2016; Marchio et al. 2016; Noe et al. 2016; Arriola and Cable 2017; Boyd et al. 2017; Gerlach et al. 2017; Giblin and Forbrich 2018; Krauss et al. 2018; Abbott et al. 2019; Drexler et al. 2019; Poppe and Rybczyk 2019; Ensign et al. 2020; Kemp et al. 2020; Lagomasino et al. 2020; Luk et al. 2020; McTigue et al. 2020; Peck et al. 2020; Vaughn et al. 2020; Weston et al. 2020; Arias-Ortiz et al. 2021; Baustian et al. 2021; Allen et al. 2022; Miller et al. 2022). Soil carbon stock changes are stratified based upon wetland class (Estuarine, Palustrine) and subclass (Emergent Marsh, Scrub Shrub). For soil carbon stock change, no differentiation is made for soil type (i.e., mineral, organic). Soil carbon removal factors were developed from literature references that provided soil carbon 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 6-70 for values).

Tier 2 level estimates of carbon stock changes associated with annual soil carbon accumulation in vegetated coastal wetlands were developed using country-specific soil carbon 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 carbon stock changes include uncertainties associated with country-specific (Tier 2) literature values of these carbon stocks, 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 carbon stock applied. Because mean soil and biomass carbon 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, the largest uncertainty for any soil carbon stock value should be applied in the calculation of error propagation; IPCC 2000). For aboveground biomass carbon 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 6-69), 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 6-77 for each subcategory (i.e., soil carbon, biomass carbon and DOM emissions). The combined uncertainty across all subsources is 33.43 percent above and below the estimate of -0.1 MMT CO_2 Eq. In 2022, the total carbon flux was -0.1 MMT CO_2 Eq., with lower and upper estimates of -0.1 and -0.08 MMT CO_2 Eq.

Table 6-77: Approach 1 Quantitative Uncertainty Estimates for Carbon Stock Changes Occurring within Unvegetated Open Water Coastal Wetlands Converted to Vegetated Coastal Wetlands in 2022 (MMT CO_2 Eq. and Percent)

Source	2022 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	(0.008)	(0.009)	(0.006)	-17.7%	+17.7%
Total Flux	**(0.1)**	**(0.14)**	**(0.01)**	**-33.3%**	**+33.3%**

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 carbon 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 carbon 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

A recalculation of emission factors for soil carbon accretion rates was performed using the same methodology and criteria as in Lu and Megonigal (2017) and described above. This new analysis incorporated data published since 2016 and other relevant data that were not previously included. Table 6-70 shows the new values. The updated synthesis resulted in a general increase in soil carbon accumulation rates for estuarine emergent and scrub/shrub wetlands, which resulted in a minimal annual average increases in removals of 0.001 MMT CO_2 Eq. for the entire time series.

Planned Improvements

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 between 0.1 and 0.2 MMT CO_2 Eq. between 1990 and 2022 (Table 6-78). Aquaculture production data were updated through 2019; data through 2022 are not yet available and in this analysis are held constant with 2019 emissions of 0.2 MMT CO_2 Eq. (0.5 Kt N_2O).

Table 6-78: N_2O Emissions from Aquaculture in Coastal Wetlands (MMT CO_2 Eq. and kt N_2O)

Year	1990	2005	2018	2019	2020	2021	2022
Emissions (MMT CO_2 Eq.)	0.1	0.2	0.1	0.1	0.1	0.1	0.1
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 2022), from which activity data for this analysis is derived.[62] 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.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022.

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

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[62] See https://www.fisheries.noaa.gov/resource/document/fisheries-united-states-2020; accessed September August 2023.

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 6-79 for N_2O emissions. The combined uncertainty is 116 percent above and below the estimate of 0.13 MMT CO_2 Eq. In 2022, the total flux was 0.13 MMT CO_2 Eq., with lower and upper estimates of 0.00 and 0.29 MMT CO_2 Eq.

Table 6-79: Approach 1 Quantitative Uncertainty Estimates for N_2O Emissions from Aquaculture Production in Coastal Wetlands in 2022 (MMT CO_2 Eq. and Percent)

Source	2022 Emissions Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Emissions Estimate[a] (MMT CO_2 Eq.)		Uncertainty Range Relative to Emissions Estimate[a] (%)	
		Lower Bound	Upper Bound	Lower Bound	Upper Bound
Combined Uncertainty for N_2O Emissions for Aquaculture Production in Coastal Wetlands	0.13	0.00	0.29	-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

No recalculations were performed for the current *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). Other constructed waterbodies include canals/ditches and ponds (flooded land <8 ha surface area). Reservoirs are defined as flooded land greater than 8 ha. IPCC guidance (IPCC 2019) provides default emission factors for reservoirs, ponds, and canals/ditches.

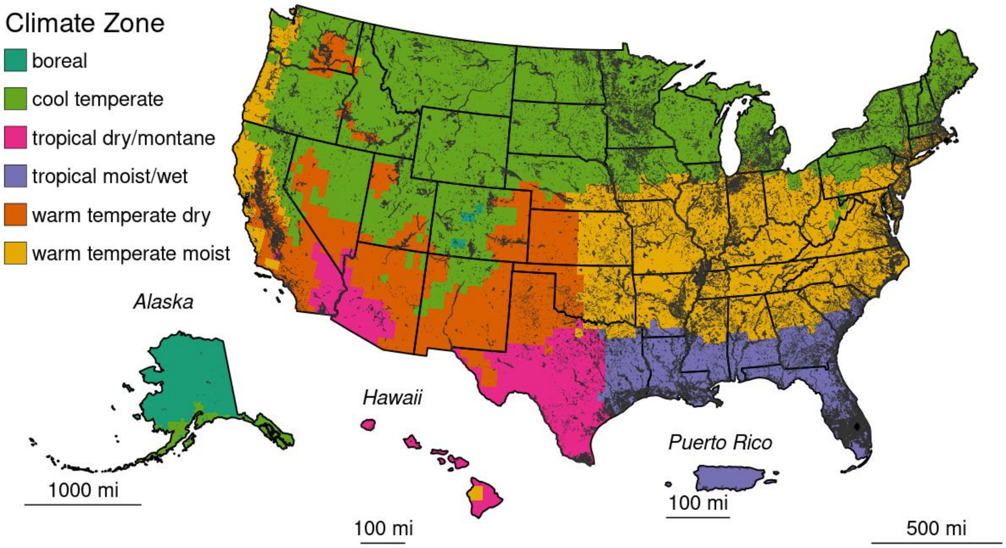
Land that has been flooded for greater than 20 years is defined as flooded land remaining flooded land and land flooded for 20 years or less is defined as land converted to flooded land. The distinction is based on literature reports that CH_4 and CO_2 emissions are high immediately following flooding, but decline to a steady background level approximately 20 years after flooding (Abril et al. 2005; Barros et al. 2011; Teodoru et al. 2012). 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 and are captured in Chapter 6, Land Use, Land-Use Change, and Forestry.

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 (Section 5.4, Agricultural Soil Management) and wastewater management (Section 7.2, Wastewater Treatment and Discharge).

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. In 2022, the United States and Puerto Rico hosted 10.2 million ha of reservoir surface area in the flooded land remaining flooded land category (see Methodology and Time-Series Consistency 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).

Figure 6-10: U.S. Reservoirs (black polygons) in the Flooded Land Remaining Flooded Land Category in 2022



Note: 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 reservoir surface or exported from the reservoir when CH_4-rich water passes through the dam. This exported CH_4 can be released to the atmosphere as the water passes through hydropower turbines or the downstream river channel. Methane emitted to the atmosphere via this pathway is referred to as “downstream emissions.”

Table 6-80 and Table 6-81 below summarize nationally aggregated CH_4 emissions from reservoirs. 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 6-80: CH_4 Emissions from Flooded Land Remaining Flooded Land—Reservoirs (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoirs							
Surface Emission	26.2	27.7	27.9	27.9	27.9	27.9	27.9
Downstream Emission	2.4	2.5	2.5	2.5	2.5	2.5	2.5
Total	**28.6**	**30.2**	**30.4**	**30.4**	**30.4**	**30.4**	**30.4**

Note: Totals may not sum to due independent rounding.

Table 6-81: CH_4 Emissions from Flooded Land Remaining Flooded Land—Reservoirs (kt CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoirs							
Surface Emission	937	989	997	997	997	997	997
Downstream Emission	84	89	90	90	90	90	90
Total	**1,022**	**1,078**	**1,086**	**1,086**	**1,087**	**1,087**	**1,087**

Note: Totals may not sum to due independent rounding.

Methane emissions from reservoirs in Texas, Florida, and Louisiana (Figure 6-11, Table 6-82) compose 34 percent of national CH_4 emissions from reservoirs in 2022. Emissions from these states are particularly high due to 1) the large expanse of reservoirs in these states (Table 6-85) and 2) the high CH_4 emission factor for the tropical dry/montane and topical moist climate zones which encompass a majority of the flooded land area in these states (Figure 6-10, Table 6-83).

Methane emissions from reservoirs in flooded land remaining flooded land increased 6.4 percent from 1990 to 2022 due to the matriculation of reservoirs in land converted to flooded land to flooded land remaining flooded land.

Figure 6-11: Total CH_4 Emissions (Downstream + Surface) from Reservoirs in Flooded Land Remaining Flooded Land in 2022 (kt CH_4)

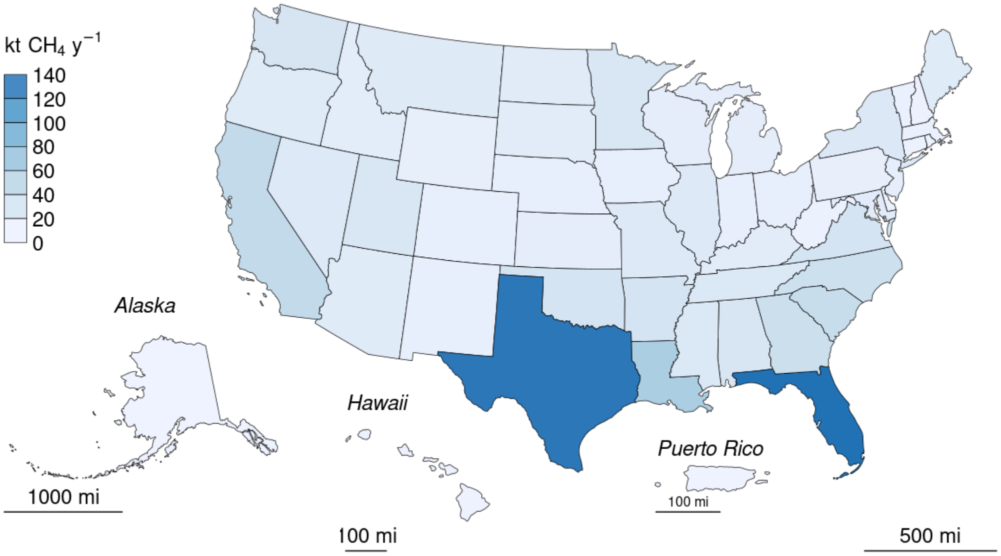


Table 6-82: Surface and Downstream CH_4 Emissions from Reservoirs in Flooded Land Remaining Flooded Land in 2022 (kt CH_4)

State	Surface	Downstream	Total
Alabama	22	2	24
Alaska	1	+	1
Arizona	14	1	16
Arkansas	25	2	27
California	42	4	46
Colorado	7	1	7
Connecticut	3	+	3
Delaware	3	+	3
District of Columbia	+	+	+
Florida	143	13	155
Georgia	35	3	38
Hawaii	1	+	1
Idaho	12	1	13
Illinois	17	2	19
Indiana	7	1	7
Iowa	7	1	7
Kansas	10	1	11
Kentucky	13	1	14
Louisiana	58	5	64
Maine	14	1	15
Maryland	13	1	14
Massachusetts	5	+	5
Michigan	9	1	10
Minnesota	21	2	23
Mississippi	20	2	21
Missouri	17	1	18
Montana	16	1	17
Nebraska	7	1	7
Nevada	17	2	19
New Hampshire	3	+	4
New Jersey	9	1	9
New Mexico	7	1	7
New York	18	2	20
North Carolina	33	3	36
North Dakota	14	1	15
Ohio	7	1	7
Oklahoma	26	2	28
Oregon	14	1	16
Pennsylvania	7	1	8
Puerto Rico	+	+	+
Rhode Island	1	+	1
South Carolina	38	3	41
South Dakota	12	1	14
Tennessee	20	2	21
Texas	138	12	150
Utah	21	2	23
Vermont	5	+	5
Virginia	25	2	27
Washington	23	2	25
West Virginia	3	+	3
Wisconsin	10	1	11
Wyoming	7	1	8

+ Indicates values less than 0.5 kt.

Methodology and Time-Series Consistency

Estimates of CH_4 emission for reservoirs 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 6-83). Downstream emissions are calculated as nine percent of the surface emission (Tier 1 default). Total CH_4 emissions from reservoirs 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 six climate zones using a regression tree approach. All six aggregated climate zones are present in the United States.

Table 6-83: IPCC (2019) Default CH_4 Emission Factors for Surface Emission from Reservoirs 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

Note: downstream CH_4 emissions are calculated as 9 percent of surface emissions. Downstream emissions are not calculated for CO_2.

Area estimates

U.S. reservoirs were identified from the NHDWaterbody layer in the National Hydrography Dataset Plus V2 (NHD),[63] the National Inventory of Dams (NID),[64] the National Wetlands Inventory (NWI),[65] the Navigable Waterways (NW) network,[66] and the EPA's Safe Drinking Water Information System (SDWIS).[67] The NHD only covers the conterminous U.S., whereas the NID, NW and NWI also include Alaska, Hawaii, and Puerto Rico.

Waterbodies in the NHDWaterbody layer that were greater than or equal to 8 ha in surface area, not identified as canal/ditch in NHD, and met any of the following criteria were considered reservoirs: 1) the waterbody was classified as "Reservoir" in the NHDWaterbody layer, 2) the waterbody name in the NHDWaterbody layer included "Reservoir", 3) the waterbody in the NHDWaterbody layer was located in close proximity (up to 100 m) to a dam in the NID, 4) the NHDWaterbody GNIS name was similar to a nearby NID feature (between 100 m to 1000 m), 5) the waterbody intersected a public drinking water intake.

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

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

[65] See https://www.fws.gov/program/national-wetlands-inventory/data-download.

[66] See https://hifld-geoplatform.opendata.arcgis.com/maps/aaa3767c7d2b41f69e7528f99cf2fb76_0/about.

[67] See https://www.epa.gov/enviro/sdwis-overview. Not publicly available due to security concerns.

EPA assumes that all features included in the NW network are subject to water-level management to maintain minimum water depths required for navigation and are therefore managed flooded lands. Navigable Waterway features greater than 8 ha in surface area are defined as reservoirs.

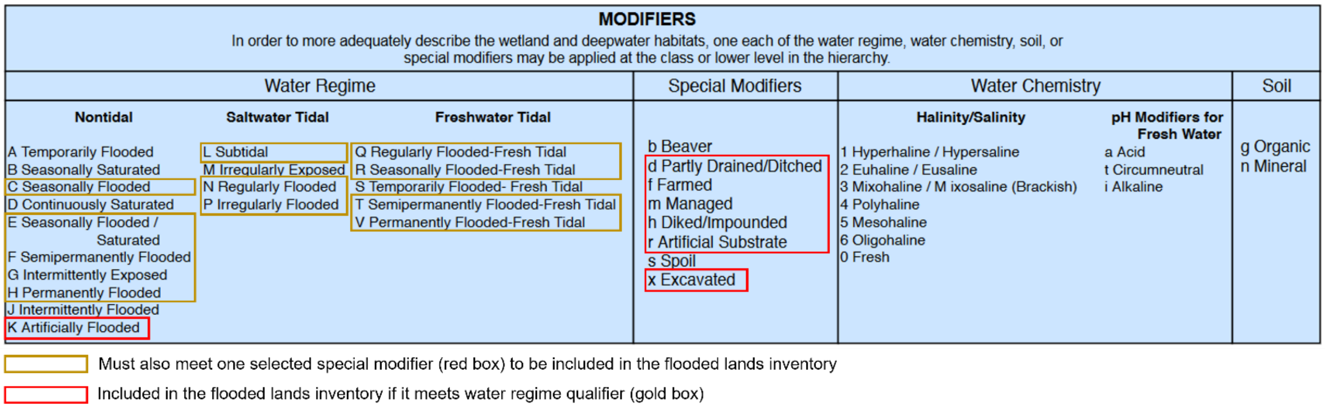
NWI features were considered "managed" if they had a Special Modifier value indicating the presence of management activities (Figure 6-12). To be included in the flooded lands inventory, the managed flooded land had to be wet or saturated for at least one season per year (see "Water Regime" in Figure 6-12). NWI features that met these criteria, were greater than 8 ha in surface area, and were not a canal/ditch (see emissions from land converted to flooded land – other constructed waterbodies) were defined as reservoirs.

Any NWI or NHD feature that intersected a drinking water intake point from SDWIS was assumed to be "managed." The rational being that a waterbody used as a source for public drinking water is typically managed in some capacity - by flow and/or volume control.

Surface areas for identified flooded lands were taken from the NHD, NWI or NW. If features from the NHD, NWI, or NW datasets overlapped, duplicated areas were erased. The first step was to take the final NWI flooded lands features and use it to identify overlapping NHD features. If the NHD feature had its center in a NWI feature, it was removed from analysis. Next, remaining NHD features were erased from any remaining overlapping NWI features. Final selections of NHD and NWI features were used to erase any overlapping NW waterbodies.

Reservoir age was determined by assuming the waterbody was created the same year as a nearby (up to 100 m) NID feature. If no nearby NID feature was identified, it was assumed the waterbody was greater than 20-years old throughout the time series.

Figure 6-12: Selected Features from NWI that Meet Flooded Lands Criteria



MODIFIERS

In order to more adequately describe the wetland and deepwater habitats, one each of the water regime, water chemistry, soil, or special modifiers may be applied at the class or lower level in the hierarchy.

Water Regime			Special Modifiers	Water Chemistry		Soil
Nontidal	**Saltwater Tidal**	**Freshwater Tidal**		**Halinity/Salinity**	**pH Modifiers for Fresh Water**	
A Temporarily Flooded	L Subtidal	Q Regularly Flooded-Fresh Tidal	b Beaver	1 Hyperhaline / Hypersaline	a Acid	g Organic
B Seasonally Saturated	M Irregularly Exposed	R Seasonally Flooded-Fresh Tidal	d Partly Drained/Ditched	2 Euhaline / Eusaline	t Circumneutral	n Mineral
C Seasonally Flooded	N Regularly Flooded	S Temporarily Flooded- Fresh Tidal	f Farmed	3 Mixohaline / M ixosaline (Brackish)	i Alkaline	
D Continuously Saturated	P Irregularly Flooded	T Semipermanently Flooded-Fresh Tidal	m Managed	4 Polyhaline		
E Seasonally Flooded / Saturated		V Permanently Flooded-Fresh Tidal	h Diked/Impounded	5 Mesohaline		
F Semipermanently Flooded			r Artificial Substrate	6 Oligohaline		
G Intermittently Exposed			s Spoil	0 Fresh		
H Permanently Flooded			x Excavated			
J Intermittently Flooded						
K Artificially Flooded						

🟨 Must also meet one selected special modifier (red box) to be included in the flooded lands inventory

🟥 Included in the flooded lands inventory if it meets water regime qualifier (gold box)

Source (modified): https://www.fws.gov/sites/default/files/documents/wetlands-and-deepwater-map-code-diagram.pdf

IPCC (2019) allows for the exclusion of managed waterbodies 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 nor water residence time was substantially altered by their associated dams.

Reservoirs were disaggregated by state (using boundaries from the 2016 U.S. Census Bureau[68]) 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.

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

The surface area of reservoirs in flooded land remaining flooded land increased by approximately 6 percent from 1990 to 2022 (Table 6-84) due to reservoirs matriculating into flooded land remaining flooded land when they reached 20 years of age.

Table 6-84: National Totals of Reservoir Surface Area in Flooded Land Remaining Flooded Land (millions of ha)

Surface Area (millions of ha)	1990	2005	2018	2019	2020	2021	2022
Reservoir	9.6	10.1	10.2	10.2	10.2	10.2	10.2

Table 6-85: State Breakdown of Reservoir Surface Area in Flooded Land Remaining Flooded Land (millions of ha)

State	1990	2005	2018	2019	2020	2021	2022
Alabama	0.22	0.23	0.23	0.23	0.23	0.23	0.23
Alaska	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Arizona	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Arkansas	0.28	0.29	0.29	0.29	0.29	0.29	0.29
California	0.37	0.39	0.39	0.39	0.39	0.39	0.39
Colorado	0.08	0.09	0.09	0.09	0.09	0.09	0.09
Connecticut	0.03	0.03	0.04	0.04	0.04	0.04	0.04
Delaware	0.03	0.03	0.03	0.03	0.03	0.03	0.03
District of Columbia	+	+	+	+	+	+	+
Florida	0.98	1.01	1.01	1.01	1.01	1.01	1.01
Georgia	0.27	0.29	0.29	0.29	0.29	0.29	0.29
Hawaii	+	+	+	+	+	+	+
Idaho	0.17	0.19	0.19	0.19	0.19	0.19	0.19
Illinois	0.17	0.18	0.22	0.22	0.22	0.22	0.22
Indiana	0.07	0.08	0.08	0.08	0.08	0.08	0.08
Iowa	0.08	0.09	0.10	0.10	0.10	0.10	0.10
Kansas	0.09	0.11	0.11	0.11	0.11	0.11	0.11
Kentucky	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Louisiana	0.40	0.41	0.41	0.41	0.41	0.41	0.41
Maine	0.25	0.26	0.26	0.26	0.26	0.26	0.26
Maryland	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Massachusetts	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Michigan	0.16	0.17	0.17	0.17	0.17	0.17	0.17
Minnesota	0.38	0.38	0.39	0.39	0.39	0.39	0.39
Mississippi	0.18	0.19	0.19	0.19	0.19	0.19	0.19
Missouri	0.19	0.21	0.21	0.21	0.21	0.21	0.21
Montana	0.27	0.29	0.29	0.29	0.29	0.29	0.29
Nebraska	0.07	0.08	0.08	0.08	0.08	0.08	0.08
Nevada	0.09	0.09	0.09	0.09	0.09	0.09	0.09
New Hampshire	0.06	0.06	0.06	0.06	0.06	0.06	0.06
New Jersey	0.11	0.11	0.11	0.11	0.11	0.11	0.11
New Mexico	0.05	0.05	0.05	0.05	0.05	0.05	0.05
New York	0.31	0.32	0.32	0.32	0.32	0.32	0.32
North Carolina	0.39	0.41	0.41	0.41	0.41	0.41	0.41
North Dakota	0.10	0.25	0.26	0.26	0.26	0.26	0.26
Ohio	0.08	0.09	0.09	0.09	0.09	0.09	0.09
Oklahoma	0.24	0.27	0.27	0.27	0.27	0.27	0.27
Oregon	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Pennsylvania	0.09	0.11	0.11	0.11	0.11	0.11	0.11
Puerto Rico	+	+	+	+	+	+	+
Rhode Island	0.02	0.02	0.02	0.02	0.02	0.02	0.02
South Carolina	0.31	0.32	0.33	0.33	0.33	0.33	0.33

South Dakota	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Tennessee	0.18	0.24	0.24	0.24	0.24	0.24	0.24
Texas	0.63	0.70	0.71	0.71	0.71	0.71	0.71
Utah	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Vermont	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Virginia	0.30	0.31	0.31	0.31	0.31	0.31	0.31
Washington	0.24	0.24	0.24	0.24	0.24	0.24	0.24
West Virginia	0.03	0.03	0.04	0.04	0.04	0.04	0.04
Wisconsin	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Wyoming	0.12	0.13	0.14	0.14	0.14	0.14	0.14
Total	**9.47**	**10.10**	**10.20**	**10.20**	**10.20**	**10.20**	**10.20**

+ Indicates values less than 0.005 million ha.

Note: Totals may not sum due to independent rounding.

Uncertainty

Uncertainty in estimates of CH_4 emissions from reservoirs in flooded land remaining flooded land (Table 6-86) 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, NWI, and NW, and 2) uncertainty in the location of dams in the NID and drinking water intakes in SDWIS. Overall uncertainties in these spatial datasets are unknown, but uncertainty for remote sensing products is assumed to be ± 10 - 15 percent based on IPCC guidance (IPCC 2003). An uncertainty range of ± 15 percent for the reservoir area estimates is assumed and is based on expert judgment.

Table 6-86: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Reservoirs in Flooded Land Remaining Flooded Land

Source	Gas	2022 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	27.9	27.4	28.4	-1.7%	+1.7%
Downstream	CH_4	2.5	2.4	3.1	-5.6%	+22.4%
Total	**CH_4**	**30.4**	**29.9**	**31.3**	**-1.6%**	**2.9%**

[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 Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation Statistics (BTS) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis. U.S. Fish and Wildlife Service is the principal agency in charge of wetland mapping including the National Wetlands Inventory (NWI). Quality and consistency of the Wetlands Layer is supported by federal wetlands mapping and classification standards, which were developed under the oversight of the Federal Geographic Data Committee (FGDC) with input by the FGDC Wetlands Subcommittee. This dataset is part of the FGDC Water-Inland Theme, which is co-chaired by the FWS and the U.S.

Geological Survey. The EPA's Safe Drinking Water Information System (SDWIS) tracks information on drinking water contamination levels as required by the 1974 Safe Drinking Water Act and its 1986 and 1996 amendments.

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the U.S. Inventory QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). 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

The EPA's SDWIS is a new data source used in the current (1990 through 2022) *Inventory*. The assumption is that any waterbody used as a public drinking water source is managed in some capacity - by flow and/or volume control. This data source added 418 reservoirs totaling 736,344 ha.

The National Inventory of Dams (NID) data are updated regularly. The version of NID used for the current *Inventory* contains 47 new dams and updated values for “year of dam completion” for 975 dams relative to the previous (1990 through 2021) *Inventory* data. Similarly, the National Wetlands Inventory (NWI) is periodically updated. The NWI version used for the current *Inventory* has major updates for MS, ND, NM, and MT.

The net effect of these recalculations was an average annual increase in CH_4 emission estimates from reservoirs of 1.23 MMT CO_2 Eq., or 4 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

The EPA recently completed a survey of greenhouse gas emissions from 108 reservoirs in the conterminous United States.[69] The data will be used to develop country-specific emission factors for U.S. reservoirs to be used in the 1990 through 2024 *Inventory* submission.

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 (<1 m wide) and concrete lined aqueducts in excess of 50 m wide. Canals and ditches can be

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[69] See https://www.epa.gov/air-research/research-emissions-us-reservoirs.

extensive in many agricultural, forest and settlement areas, and may also be significant sources of emissions in some circumstances.

Methane emissions from freshwater ponds in flooded land remaining flooded land increased by approximately 1 percent from 1990 to 2022. Methane emissions from canals and ditches have remained constant throughout the time series because age data are not available for canals and ditches, thus they are assumed to be greater than 20-years old in 1990 and are included in flooded land remaining flooded land throughout the time series. Overall, CH_4 emissions from other constructed waterbodies have remained fairly constant since 1990 (Table 6-87 and Table 6-88).

Table 6-87: CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Other Constructed Waterbodies							
Canals and Ditches	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Freshwater Ponds	11.4	11.5	11.5	11.5	11.5	11.5	11.5
Total	**13.7**	**13.8**	**13.8**	**13.8**	**13.8**	**13.8**	**13.8**

Note: Totals may not sum due to independent rounding.

Table 6-88: CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land (kt CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Other Constructed Waterbodies							
Canals and Ditches	80.9	80.9	80.9	80.9	80.9	80.9	80.9
Freshwater Ponds	406.6	411.0	411.7	411.8	411.8	411.8	411.9
Total	**487.5**	**491.9**	**492.6**	**492.6**	**492.7**	**492.7**	**492.7**

Note: Totals may not sum due to independent rounding.

Florida and Louisiana have the greatest methane emissions from canals and ditches in the United States (Figure 6-13, Table 6-89). Presumably, most of these canals serve to drain the extensive wetland complexes in these states (Davis, 1973). California has the third greatest methane emissions from canals and ditches. Canals and ditches in California primarily serve to convey water from the mountains to urban and agricultural areas. Michigan and Minnesota have the fourth and fifth largest methane emissions from canals and ditches. These systems serve to drain historic wetlands to facilitate row-crop agriculture. Texas, Florida, and Georgia have the greatest methane emissions from freshwater ponds, although states throughout the eastern United States make significant contributions to the national total. These patterns of emissions are in accordance with the distribution of other constructed waterbodies in the United States.

Table 6-89: CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land in 2022 (kt CH_4)

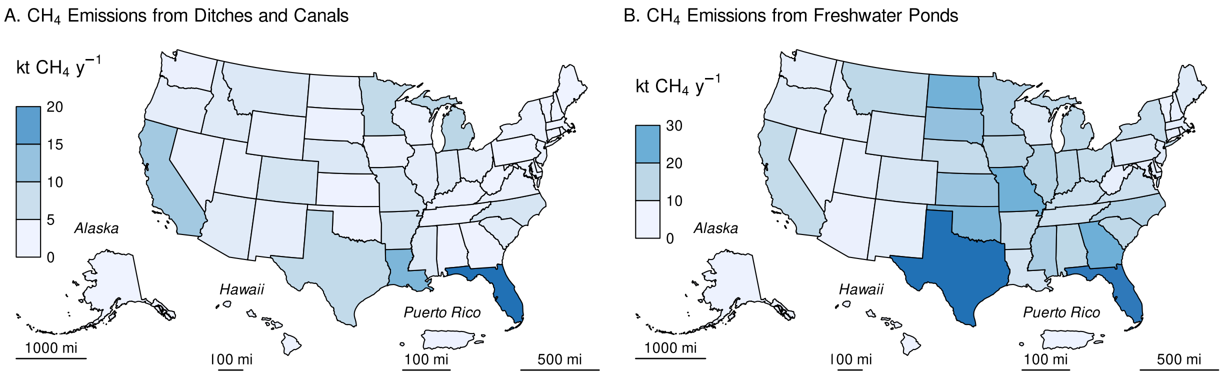
State	Canals and Ditches	Freshwater Ponds	Total
Alabama	+	10.5	10.6
Alaska	+	+	+
Arizona	1.5	1.0	2.4
Arkansas	3.1	9.4	12.4
California	7.0	9.2	16.2
Colorado	2.9	4.8	7.7
Connecticut	+	1.8	1.8
Delaware	+	0.9	0.9
District of Columbia	+	+	+
Florida	15.6	30.7	46.2
Georgia	+	21.0	21.2

Hawaii	+	+	0.5
Idaho	1.7	2.4	4.1
Illinois	1.0	11.7	12.8
Indiana	1.7	10.6	12.3
Iowa	+	11.2	11.6
Kansas	+	15.4	15.5
Kentucky	+	7.7	7.9
Louisiana	9.4	5.9	15.3
Maine	+	3.5	3.5
Maryland	+	2.3	2.7
Massachusetts	+	2.3	2.3
Michigan	5.4	10.0	15.4
Minnesota	4.7	12.7	17.3
Mississippi	1.6	13.4	15.1
Missouri	2.4	20.7	23.1
Montana	2.0	10.5	12.5
Nebraska	2.0	9.1	11.1
Nevada	0.7	0.8	1.5
New Hampshire	+	1.0	1.1
New Jersey	+	3.0	3.4
New Mexico	0.8	2.1	2.9
New York	+	8.3	8.7
North Carolina	2.6	12.2	14.8
North Dakota	0.8	20.6	21.3
Ohio	0.8	8.9	9.7
Oklahoma	+	19.3	19.4
Oregon	1.0	3.6	4.6
Pennsylvania	+	4.1	4.1
Puerto Rico	+	+	+
Rhode Island	+	+	+
South Carolina	1.3	10.4	11.7
South Dakota	+	16.6	16.9
Tennessee	+	6.7	6.8
Texas	4.6	32.1	36.8
Utah	0.8	2.0	2.8
Vermont	+	0.8	0.8
Virginia	0.5	7.3	7.9
Washington	+	2.0	2.5
West Virginia	+	1.5	1.5
Wisconsin	+	3.8	4.2
Wyoming	0.9	4.8	5.7
Total	**80.9**	**411.9**	**492.7**

+ Indicates values less than 0.5 kt.

Note: Totals may not sum due to independent rounding.

Figure 6-13: 2022 CH_4 Emissions from A) Ditches and Canals and B) Freshwater Ponds in Flooded Land Remaining Flooded Land (kt CH_4)


A. CH_4 Emissions from Ditches and Canals

B. CH_4 Emissions from Freshwater Ponds

Methodology and Time-Series Consistency

Estimates of CH_4 emissions 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 6-90). 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 6-90). 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 6-90: 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

Other constructed waterbodies were identified from the NHDWaterbody layer in the National Hydrography Dataset Plus V2 (NHD)[70], the National Inventory of Dams (NID)[71], the National Wetlands Inventory (NWI)[72], the Navigable Waterways (NW) network[73], and the EPA's Safe Drinking Water Information System (SDWIS)[74]. The NHD

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

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

[72] See https://www.fws.gov/program/national-wetlands-inventory/data-download.

[73] See https://hifld-geoplatform.opendata.arcgis.com/maps/aaa3767c7d2b41f69e7528f99cf2fb76_0/about.

[74] See https://www.epa.gov/enviro/sdwis-overview. Not publicly available due to security concerns.

only covers the conterminous US, whereas the NID, NW and NWI also include Alaska, Hawaii, District of Columbia, and Puerto Rico. The following paragraphs present the criteria used to identify other constructed waterbodies in the NHD, NW, and NWI.

Waterbodies in the NHDWaterbody layer that were greater than 20-years old, less than 8 ha in surface area, not identified as canal/ditch in NHD, and met any of the following criteria were considered freshwater ponds in flooded land remaining flooded land: 1) the waterbody was classified "Reservoir" in the NHDWaterbody layer, 2) the waterbody name in the NHDWaterbody layer included "Reservoir", 3) the waterbody in the NHDWaterbody layer was located in close proximity (up to 100 m) to a dam in the NID, 4) the NHDWaterbody GNIS name was similar to nearby NID feature (between 100 m to 1000 m), the waterbody intersected a drinking water intake.

EPA assumes that all features included in the NW are subject to water-level management to maintain minimum water depths required for navigation and are therefore managed flooded lands. NW features that were less than 8 ha in surface area and not identified as canals/ditch (see below) were considered freshwater ponds. Only 2.1 percent of NW features met these criteria, and they were primarily associated with larger navigable waterways, such as lock chambers on impounded rivers.

NWI features were considered "managed" if they had a special modifier value indicating the presence of management activities (Figure 6-12). To be included in the flooded lands inventory, the managed flooded land had to be wet or saturated for at least one season per year (see "Water Regime" in Figure 6-12). NWI features that met these criteria, were less than 8 ha in surface area, and were not a canal/ditch (see below) were defined as freshwater ponds.

Any NWI or NHD feature that intersected a drinking water intake point from SDWIS was assumed to be "managed." The rational being that a waterbody used as a source for public drinking water is typically managed in some capacity - by flow and/or volume control.

Canals and ditches, a subset of other constructed waterbodies, were identified in the NWI by their morphology. Unlike a natural water body, canals and ditches are typically narrow, linear features with abrupt angular turns. Figure 6-14 contrasts the unique shape of ditches/canals vs more natural water features.

Figure 6-14: Left: NWI Features Identified as Canals/Ditches (pink) by Unique Narrow, Linear/Angular Morphology. Right: Non-Canal/Ditches with More Natural Morphology (blue)

This morphology was identified systematically using shape attributes in a decision tree model. A training set of 752 features were identified as either "ditch" or "not ditch" using expert judgment. The training set was used to train a decision tree which was used to categorize millions of NWI features based on three shape attribute ratios (Figure 6-12).

Table 6-91: Predictors used in Decision Tree to Identify Canal/Ditches

Shape Length : # of Shape Vertices
Shape Area : Shape Length
Shape Area : # of Shape Vertices

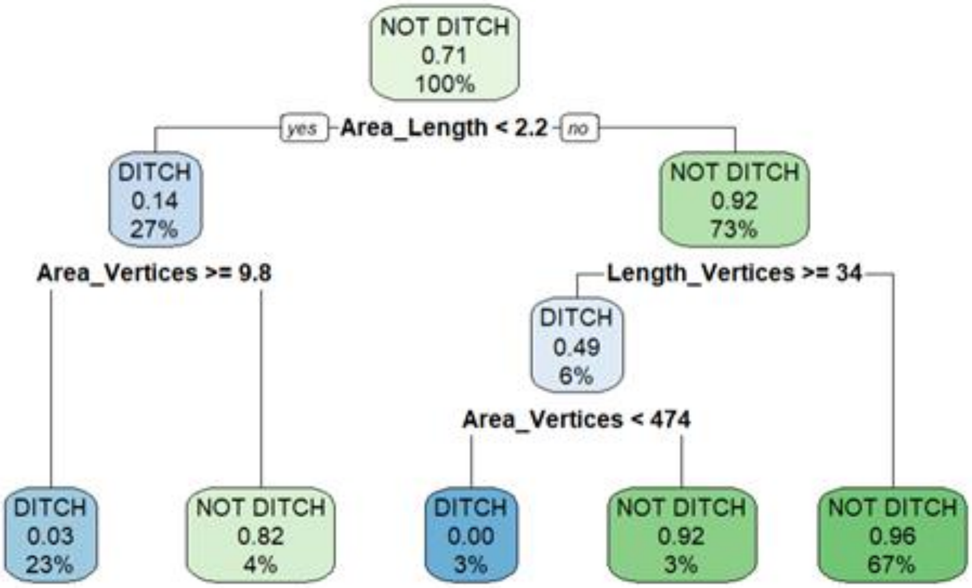
The decision tree built a model using 80 percent of the 752 training features and used the 20 percent to validate the model. The model was 93.1 percent accurate. Below are the validation results (Table 6-92).

Table 6-92: Validation Results for Ditch/Canal Classification Decision Tree

	Truth	
Prediction	Ditch/Canal	Not Ditch/Canal
Ditch/Canal	49	5
Not Ditch/Canal	8	27

The decision tree model was then applied to the entire NWI dataset using the following shape attribute ratios (Figure 6-15).

Figure 6-15: Structure of Decision Tree Used to Identify Canals/Ditches



Surface areas for other constructed waterbodies were taken from NHD, NWI or the NW. If features from the NHD, NWI, or the NW datasets overlapped, these areas were erased. The first step was to take the final NWI flooded lands features and use it to identify overlapping NHD features. If the NHD feature had its center in a NWI feature, it was removed from analysis. Next, remaining NHD features were erased from any remaining overlapping NWI features. Final selections of NHD and NWI features were used to erase any overlapping NW waterbodies.

The age of other constructed waterbody features was determined by assuming the waterbody was created the same year as a nearby (up to 100 m) NID feature. If no nearby NID feature was identified, it was assumed the waterbody was greater than 20-years old throughout the time series. No canal/ditch features were associated with a nearby dam, therefore all canal/ditch features were assumed to be greater than 20-years old through the time series.

For the year 2022, this *Inventory* contains 2,250,662 ha of freshwater ponds and 194,412 ha of canals and ditches in flooded land remaining flooded land (Table 6-93). The surface area of freshwater ponds increased by 28,632 ha (1.3 percent) from 1990 to 2022 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.

Table 6-93: National Surface Area Totals in Flooded Land Remaining Flooded Land - Other Constructed Waterbodies (ha)

	1990	2005	2018	2019	2020	2021	2022
Canals and ditches	194,412	194,412	194,412	194,412	194,412	194,412	194,412
Freshwater ponds	2,222,030	2,245,881	2,249,672	2,250,007	2,250,337	2,250,540	2,250,662
Total	**2,416,442**	**2,440,292**	**2,444,084**	**2,444,418**	**2,444,749**	**2,444,951**	**2,445,074**

Note: Totals may not sum due to independent rounding.

Canals and ditches in the conterminous United States are most abundant in the Gulf Coast states and California (Figure 6-16A, Table). Florida contains 19 percent of all U.S. canal and ditch surface area, most of which were constructed in the early 1900s for drainage, flood protection, and water storage purposes. Freshwater ponds are more widely distributed across the United States (Figure 6-16B, Table 6-95). Texas has the greatest surface area of freshwater ponds, equivalent to 8 percent of all freshwater pond surface area in the United States, closely followed by Florida.

Figure 6-16: 2022 Surface Area of A) Ditches and Canals and B) Freshwater Ponds in Flooded Land Remaining Flooded Land (ha)

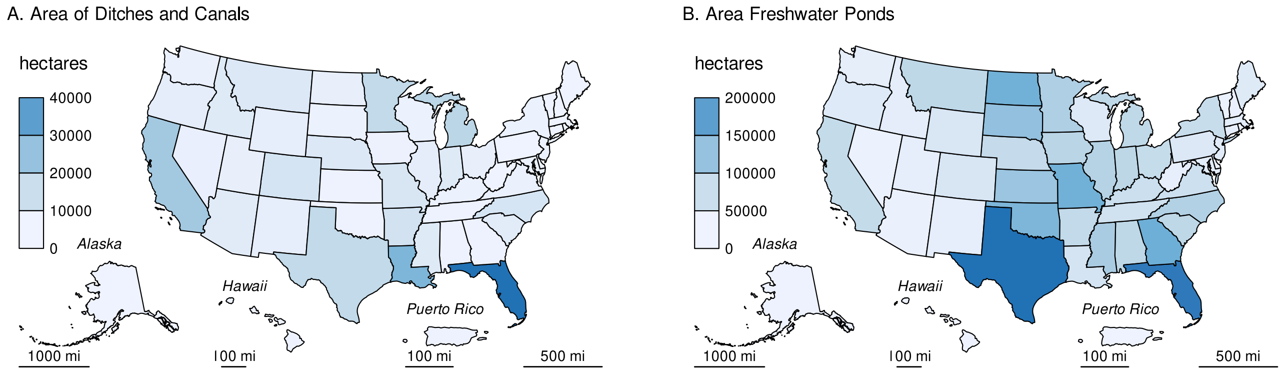


Table 6-94: State Totals of Surface Area in Flooded Land Remaining Flooded Land— Canals and Ditches (ha)

State	1990	2005	2018	2019	2020	2021	2022
Alabama	228	228	228	228	228	228	228
Alaska	115	115	115	115	115	115	115
Arizona	3,536	3,536	3,536	3,536	3,536	3,536	3,536
Arkansas	7,349	7,349	7,349	7,349	7,349	7,349	7,349
California	16,725	16,725	16,725	16,725	16,725	16,725	16,725
Colorado	6,874	6,874	6,874	6,874	6,874	6,874	6,874
Connecticut	28	28	28	28	28	28	28
Delaware	130	130	130	130	130	130	130
District of Columbia	1	1	1	1	1	1	1
Florida	37,482	37,482	37,482	37,482	37,482	37,482	37,482
Georgia	352	352	352	352	352	352	352

Hawaii	538	538	538	538	538	538	538
Idaho	4,027	4,027	4,027	4,027	4,027	4,027	4,027
Illinois	2,489	2,489	2,489	2,489	2,489	2,489	2,489
Indiana	4,064	4,064	4,064	4,064	4,064	4,064	4,064
Iowa	867	867	867	867	867	867	867
Kansas	258	258	258	258	258	258	258
Kentucky	672	672	672	672	672	672	672
Louisiana	22,565	22,565	22,565	22,565	22,565	22,565	22,565
Maine	56	56	56	56	56	56	56
Maryland	967	967	967	967	967	967	967
Massachusetts	132	132	132	132	132	132	132
Michigan	12,897	12,897	12,897	12,897	12,897	12,897	12,897
Minnesota	11,235	11,235	11,235	11,235	11,235	11,235	11,235
Mississippi	3,936	3,936	3,936	3,936	3,936	3,936	3,936
Missouri	5,670	5,670	5,670	5,670	5,670	5,670	5,670
Montana	4,740	4,740	4,740	4,740	4,740	4,740	4,740
Nebraska	4,864	4,864	4,864	4,864	4,864	4,864	4,864
Nevada	1,587	1,587	1,587	1,587	1,587	1,587	1,587
New Hampshire	103	103	103	103	103	103	103
New Jersey	944	944	944	944	944	944	944
New Mexico	2,002	2,002	2,002	2,002	2,002	2,002	2,002
New York	925	925	925	925	925	925	925
North Carolina	6,321	6,321	6,321	6,321	6,321	6,321	6,321
North Dakota	1,819	1,819	1,819	1,819	1,819	1,819	1,819
Ohio	1,819	1,819	1,819	1,819	1,819	1,819	1,819
Oklahoma	278	278	278	278	278	278	278
Oregon	2,498	2,498	2,498	2,498	2,498	2,498	2,498
Pennsylvania	143	143	143	143	143	143	143
Puerto Rico	249	249	249	249	249	249	249
Rhode Island	1	1	1	1	1	1	1
South Carolina	3,226	3,226	3,226	3,226	3,226	3,226	3,226
South Dakota	703	703	703	703	703	703	703
Tennessee	442	442	442	442	442	442	442
Texas	11,152	11,152	11,152	11,152	11,152	11,152	11,152
Utah	1,875	1,875	1,875	1,875	1,875	1,875	1,875
Vermont	95	95	95	95	95	95	95
Virginia	1,306	1,306	1,306	1,306	1,306	1,306	1,306
Washington	1,125	1,125	1,125	1,125	1,125	1,125	1,125
West Virginia	28	28	28	28	28	28	28
Wisconsin	887	887	887	887	887	887	887
Wyoming	2,086	2,086	2,086	2,086	2,086	2,086	2,086
Total	**194,412**	**194,412**	**194,412**	**194,412**	**194,412**	**194,412**	**194,412**

Table 6-95: State Totals of Surface Area in Flooded Land Remaining Flooded Land—Freshwater Ponds (ha)

State	1990	2005	2018	2019	2020	2021	2022
Alabama	57,034	57,342	57,355	57,355	57,355	57,355	57,355
Alaska	2,367	2,370	2,370	2,370	2,370	2,370	2,370
Arizona	5,199	5,236	5,249	5,249	5,253	5,253	5,253
Arkansas	50,880	51,211	51,211	51,211	51,211	51,211	51,211
California	50,219	50,426	50,499	50,504	50,511	50,513	50,519
Colorado	26,174	26,448	26,478	26,479	26,480	26,480	26,494
Connecticut	9,630	9,697	9,699	9,699	9,699	9,699	9,699
Delaware	4,717	4,721	4,721	4,721	4,721	4,721	4,721
District of Columbia	16	16	16	16	16	16	16
Florida	167,317	167,453	167,496	167,502	167,502	167,508	167,508

Georgia	113,254	114,898	114,969	114,972	114,972	114,972	114,972
Hawaii	1,580	1,592	1,595	1,595	1,595	1,595	1,595
Idaho	13,220	13,352	13,359	13,359	13,359	13,360	13,360
Illinois	63,516	64,044	64,144	64,149	64,159	64,160	64,169
Indiana	57,593	58,065	58,170	58,175	58,175	58,175	58,185
Iowa	57,450	59,612	60,745	60,929	61,051	61,147	61,168
Kansas	81,828	83,900	83,976	83,985	83,985	84,002	84,004
Kentucky	41,427	41,808	41,837	41,837	41,837	41,837	41,837
Louisiana	32,085	32,210	32,221	32,221	32,226	32,226	32,226
Maine	19,102	19,149	19,159	19,159	19,159	19,159	19,159
Maryland	12,569	12,739	12,810	12,810	12,812	12,815	12,818
Massachusetts	12,359	12,413	12,457	12,464	12,470	12,472	12,476
Michigan	54,525	54,672	54,701	54,701	54,709	54,709	54,709
Minnesota	68,801	69,082	69,173	69,176	69,202	69,210	69,220
Mississippi	72,832	73,209	73,336	73,343	73,363	73,375	73,383
Missouri	109,573	112,993	113,068	113,071	113,073	113,077	113,079
Montana	56,860	57,246	57,263	57,268	57,269	57,269	57,269
Nebraska	48,051	49,380	49,649	49,667	49,697	49,706	49,709
Nevada	4,452	4,455	4,508	4,509	4,512	4,512	4,515
New Hampshire	5,427	5,526	5,585	5,585	5,586	5,587	5,587
New Jersey	16,192	16,232	16,253	16,253	16,253	16,253	16,253
New Mexico	11,379	11,394	11,398	11,401	11,401	11,401	11,406
New York	45,224	45,485	45,590	45,592	45,592	45,598	45,598
North Carolina	66,205	66,661	66,744	66,744	66,747	66,750	66,751
North Dakota	112,310	112,384	112,469	112,475	112,485	112,489	112,492
Ohio	48,028	48,393	48,591	48,605	48,637	48,651	48,656
Oklahoma	103,243	105,224	105,288	105,304	105,318	105,324	105,333
Oregon	19,304	19,487	19,532	19,534	19,539	19,539	19,539
Pennsylvania	22,018	22,256	22,289	22,289	22,289	22,289	22,289
Puerto Rico	708	708	708	708	708	708	708
Rhode Island	2,204	2,213	2,220	2,220	2,220	2,220	2,220
South Carolina	55,794	56,456	56,673	56,682	56,686	56,686	56,686
South Dakota	90,237	90,447	90,504	90,515	90,516	90,521	90,521
Tennessee	35,927	36,307	36,332	36,337	36,343	36,344	36,344
Texas	172,580	175,497	175,569	175,574	175,575	175,575	175,575
Utah	10,703	10,764	10,772	10,772	10,773	10,773	10,773
Vermont	4,316	4,381	4,392	4,392	4,392	4,392	4,392
Virginia	39,938	39,996	40,000	40,000	40,000	40,000	40,000
Washington	10,943	11,081	11,119	11,119	11,122	11,123	11,123
West Virginia	8,027	8,156	8,166	8,166	8,166	8,166	8,166
Wisconsin	20,845	20,989	21,003	21,003	21,003	21,003	21,003
Wyoming	25,851	26,106	26,243	26,243	26,244	26,246	26,250
Total	**2,222,030**	**2,245,881**	**2,249,672**	**2,250,007**	**2,250,337**	**2,250,540**	**2,250,662**

Uncertainty

Uncertainty in estimates of CH_4 emissions from other constructed waterbodies (ponds, canals/ditches) in flooded land remaining flooded land (Table 6-96) are estimated using IPCC Approach 2 and include uncertainty in the default emission factors and the flooded land area inventory. Uncertainty in default 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, NWI, 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 6-96: Approach 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Other Constructed Waterbodies in Flooded Land Remaining Flooded Land

Source	Gas	2022 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
Canals and ditches	CH_4	2.3	2.1	2.4	-5.1	+7.0
Freshwater pond	CH_4	11.5	11.5	11.5	-0.04	+0.04
Total	**CH_4**	**13.8**	**13.7**	**13.9**	**-0.8**	**+1.0**

[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.[75] The Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation Statistics (BTS) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis. U.S. Fish and Wildlife Service is the principal agency in charge of wetland mapping including the National Wetlands Inventory (NWI). Quality and consistency of the Wetlands Layer is supported by federal wetlands mapping and classification standards, which were developed under the oversight of the Federal Geographic Data Committee (FGDC) with input by the FGDC Wetlands Subcommittee. This dataset is part of the FGDC Water-Inland Theme, which is co-chaired by the FWS and the U.S. Geological Survey. The EPA's Safe Drinking Water Information System (SDWIS) tracks information on drinking water contamination levels as required by the 1974 Safe Drinking Water Act and its 1986 and 1996 amendments.

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the U.S. Inventory QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of *2006 IPCC Guidelines* (see Annex 8 for more details). 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

The EPA's SDWIS is a new data source used in the current (1990 through 2022) *Inventory*. The assumption is that any waterbody used as a public drinking water source is managed in some capacity—by flow and/or volume control. This data source added 54 features totaling 173 ha of other constructed waterbodies.

The National Inventory of Dams (NID) data are updated regularly. The version of NID used for the current (1990 through 2022) *Inventory* contains 47 new dams and updated values for “year of dam completion” for 975 dams relative to the previous (1990 through 2021) *Inventory* data. Similarly, the National Wetlands Inventory (NWI) is periodically updated. The NWI version used for the current *Inventory* has major updates for MS, ND, NM, and MT.

The net effect of these recalculations was an average annual decrease in CH_4 emission estimates from other constructed waterbodies of 2.7 MMT CO_2 Eq., or 17 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

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[75] See https://www.epa.gov/national-aquatic-resource-surveys/national-lakes-assessment-2017-quality-assurance-project-plan.

Planned Improvements

Default emission factors for canals/ditches were derived from a global dataset that include few measurements from U.S. systems. The EPA plans to conduct a literature survey to determine if sufficient data are available to derive a country-specific emission factor for the 1990 through 2024 *Inventory* submission.

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 2023) *Inventory*.

Features less than 8 ha in the NW that were not identified as Canal/Ditch were defined as freshwater ponds. Many of these features are lock chambers connected to an upstream reservoir. These systems likely have emission rates more similar to a reservoir than freshwater pond. In the next (1990 through 2023) *Inventory* these systems will be classified as reservoirs.

6.9 Land Converted to Wetlands (CRT 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. 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 All other land categories (i.e., forest land, cropland, grassland, settlements and other lands) are identified as having some area converting to vegetated coastal wetlands. This *Inventory* does not include land converted to unvegetated open water coastal wetlands (see Planned Improvements section below). Between 1990 and 2022 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.[76] 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.[77] 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.[78]

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[76] Data from C-CAP; see https://coast.noaa.gov/digitalcoast/tools/. Accessed October 2023.

[77] 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*.

[78] At the present stage of *Inventory* development, coastal wetlands are not explicitly shown in the land representation analysis (Section 6.1) 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).

Conversion to coastal wetlands resulted in a biomass carbon stock loss of 0.2 MMT CO_2 Eq. (0.03 MMT C) in 2022 (Table 6-97 and Table 6-98). Loss of forest biomass through conversion of forest lands to vegetated coastal wetlands is the primary driver behind biomass carbon 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 2022 (Table 6-97 and Table 6-98), 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 Across all time periods, soil carbon accumulation resulting from lands converted to vegetated coastal wetlands is a carbon sink and has ranged between -0.14 and -0.3 MMT CO_2 Eq. (-0.04 and -0.07 MMT C; Table 6-97 and Table 6-98). Conversion of lands to coastal wetlands resulted in CH_4 emissions of 0.17 MMT CO_2 Eq. (6.1 kt CH_4) in 2022 (Table 6-99). 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 2002 (0.28 MMT CO_2 Eq., 10.0 kt CH_4) and have continually decreased to current levels. This decrease was driven by a reduction in the rate of conversion of forest land to palustrine scrub-shrubs and emergent wetlands.

Table 6-97: Net CO_2 Flux from Carbon Stock Changes in Land Converted to Vegetated Coastal Wetlands (MMT CO_2 Eq.)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Vegetated Coastal Wetlands	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Forest Land Converted to Vegetated Coastal Wetlands	**0.49**	**0.50**	**(+)**	**0.01**	**0.02**	**0.03**	**0.04**
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	(0.24)	(0.24)	(0.16)	(0.15)	(0.14)	(0.13)	(0.12)
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	(0.02)	(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)**	**(0.18)**	**(0.17)**	**(0.16)**	**(0.15)**	**(0.14)**
Total Flux	**0.46**	**0.47**	**(0.02)**	**(0.02)**	**(0.01)**	**0.00**	**0.01**

+ 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 6-98: Net CO_2 Flux from Carbon Stock Changes in Land Converted to Vegetated Coastal Wetlands (MMT C)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Vegetated Coastal	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**	**(+)**

Wetlands							
Biomass C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(+)	(+)	(+)	(+)	(+)	(+)
Forest Land Converted to Vegetated Coastal Wetlands	**0.13**	**0.14**	**+**	**+**	**0.006**	**0.008**	**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)	(0.04)	(0.04)	(0.04)	(0.04)	(0.03)
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	(+)	(0.01)	(+)	(+)	(+)	(+)	(+)
Soil C Stock	(+)	(0.01)	(+)	(+)	(+)	(+)	(+)
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)**	**(0.04)**	**(0.04)**	**(0.04)**
Total Flux	**0.13**	**0.13**	**(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 6-99: CH_4 Emissions from Land Converted to Vegetated Coastal Wetlands (MMT CO_2 Eq. and kt CH_4)

Land Use/Carbon Pool	1990	2005	2018	2019	2020	2021	2022
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	0.05	0.05	0.05
Forest Land Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	0.28	0.27	0.19	0.18	0.17	0.16	0.15
CH_4 Emissions (kt CH_4)	9.88	9.74	6.85	6.48	6.10	5.76	5.41
Grassland Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	+	+	+	+	+
CH_4 Emissions (kt CH_4)	0.01	0.01	0.07	0.07	0.08	0.08	0.09
Other Land Converted to Vegetated Coastal Wetlands							
CH_4 Emissions (MMT CO_2 Eq.)	+	+	0.01	0.01	0.01	0.01	0.02
CH_4 Emissions (kt CH_4)	0.08	0.14	0.43	0.47	0.50	0.52	0.54
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.)	**0.28**	**0.28**	**0.21**	**0.20**	**0.19**	**0.18**	**0.17**
Total CH_4 Emissions (kt CH_4)	**9.98**	**9.91**	**7.39**	**7.06**	**6.73**	**6.41**	**6.09**

+ 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 carbon 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 2022.

Biomass Carbon Stock Changes

Biomass carbon 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 2021 from these datasets using the C-CAP change data closest in date to a given year. 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 carbon 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[79]). 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 carbon 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 carbon 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 carbon 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 carbon 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 be 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 2022 time series. Dead organic matter removals are calculated by multiplying the C-CAP derived area gained that year by the

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[79] See https://github.com/Smithsonian/Coastal-Wetland-NGGI-Data-Public; accessed October 2023.

difference between Tier 1 DOM carbon 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 carbon removals are estimated for land converted to vegetated coastal wetlands across all years. Soil carbon stock changes, stratified by climate zones and wetland classes, are derived from a synthesis of peer-reviewed literature[80] (Lynch 1989; Orson et al. 1990; Kearny & Stevenson 1991; Thom et al. 1992; Roman et al. 1997; Craft et al. 1998; Orson et al. 1998; Merrill 1999; Weis et al. 2001; Hussein et al. 2004; Church et al. 2006; Koster et al. 2007; Drexler et al. 2009; Boyd 2012; Callaway et al. 2012 a & b; Bianchi et al. 2013; Drexler et al. 2013; Watson and Byrne 2013; Breithaupt et al. 2014; Crooks et al. 2014; Weston et al. 2014; Smith et al. 2015; Villa & Mitsch 2015; Boyd and Sommerfield 2016; Marchio et al. 2016; Noe et al. 2016; Arriola and Cable 2017; Boyd et al. 2017; Gerlach et al. 2017; Giblin and Forbrich 2018; Krauss et al. 2018; Abbott et al. 2019; Drexler et al. 2019; Poppe and Rybczyk 2019; Ensign et al. 2020; Kemp et al. 2020; Lagomasino et al. 2020; Luk et al. 2020; McTigue et al. 2020; Peck et al. 2020; Vaughn et al. 2020; Weston et al. 2020; Arias-Ortiz et al. 2021; Baustian et al. 2021; Allen et al. 2022; Miller et al. 2022). To estimate soil carbon 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 carbon stock changes associated with annual soil carbon accumulation from land converted to vegetated coastal wetlands were developed using country-specific soil carbon 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 carbon accumulation to be instantaneously equivalent to that in natural settings and that soil carbon 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 2022 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 carbon 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* and a global warming potential of 28 is used (IPCC 2013). 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 carbon removal factors, biomass change, DOM, and CH_4 emissions

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[80] Coastal Carbon Network (2023). Database: Coastal Carbon Library (Version 1.0.0). Smithsonian Environmental Research Center. Dataset. https://doi.org/10.25573/serc.21565671. Accessed October 2023

include error in uncertainties associated with Tier 2 literature values of soil carbon 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 carbon 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 carbon 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 6-100 for each carbon pool and the CH_4 emissions. The combined uncertainty is 42.6 percent above and below the estimate of 0.17 MMT CO_2 Eq. In 2022, the total flux was 0.17 MMT CO_2 Eq., with lower and upper estimates of 0.10 and 0.24 MMT CO_2 Eq.

Table 6-100: Approach 1 Quantitative Uncertainty Estimates for Carbon Stock Changes occurring within Land Converted to Vegetated Coastal Wetlands in 2022 (MMT CO_2 Eq. and Percent)

Source	2022 Estimate (MMT CO_2 Eq.)	Uncertainty Range Relative to Estimate[a] (MMT CO_2 Eq.)		(%)	
		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	(0.14)	(0.2)	(0.1)	-17.7%	17.7%
Methane Emissions	0.17	0.12	0.22	-29.9%	29.9%
Total Uncertainty	**0.18**	**0.11**	**0.26**	**-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 carbon stock dataset has been provided by the Smithsonian Environmental Research Center and coastal wetland inventory team leads. Biomass carbon 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. A team of two evaluated and verified there were no computational errors within the calculation worksheets. Soil carbon stock, emissions/removals data are based upon peer-reviewed literature and CH_4 emission factors are derived from the *Wetlands Supplement*.

Recalculations Discussion

A recalculation of emission factors for soil carbon accretion rates was performed using the same methodology and criteria as in Lu and Megonigal (2017) and described above. This new analysis incorporated data published since

2016 and other relevant data that were not previously included. The updated synthesis resulted in a general increase in soil carbon accumulation rates for estuarine emergent and scrub/shrub wetlands, which resulted in a minimal annual average increase (0.001 MMT CO_2 Eq.) for the entire time series.

Planned Improvements

Currently, the only coastal wetland conversion that is reported in the *Inventory* is lands converted to vegetated coastal wetlands. The next (1990 through 2023) *Inventory* submission is expected to include carbon 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 (Abril et al. 2005, Barros et al. 2011, Teodoru et al. 2012). Both CO_2 and CH_4 emissions are estimated for land converted to flooded land.

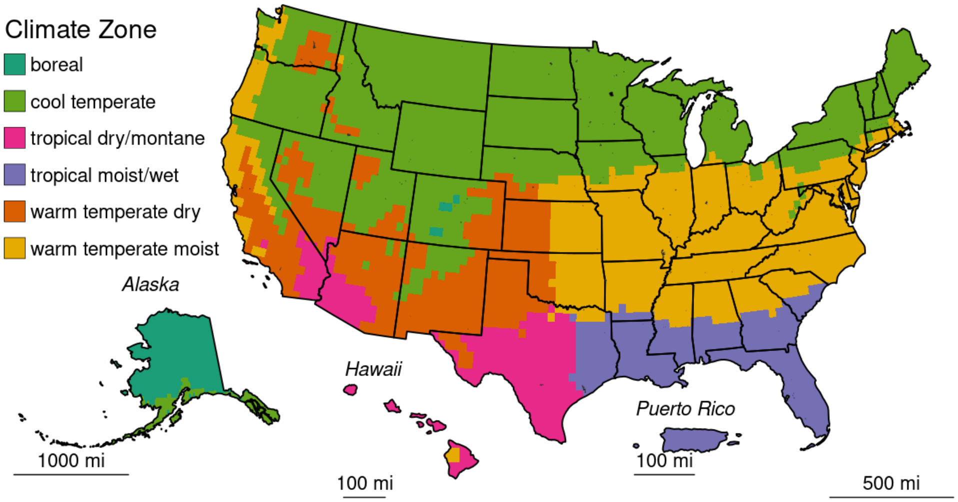
Nitrous oxide emissions from flooded lands are largely related to inputs of organic or inorganic nitrogen from the watershed. These inputs from runoff/leaching/deposition are largely driven by anthropogenic activities such as land-use change, wastewater disposal or fertilizer application in the watershed or application of fertilizer or feed in aquaculture. These emissions are not included here to avoid double-counting N_2O emissions which are captured in other source categories, such as indirect N_2O emissions from managed soils (Section 5.4, Agricultural Soil Management) and wastewater management (Section 7.2, Wastewater Treatment and Discharge).

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 2022, the United States and Puerto Rico contained 72,461 ha of reservoir surface area in land converted to flooded land (see Methodology and Time-Series Consistency below for calculation details) distributed across all six of the aggregated climate zones used to define flooded land emission factors (Figure 6-17) (IPCC 2019).

Figure 6-17: U.S. Reservoirs (black polygons) in the Land Converted to Flooded Land Category in 2022



Note: Colors represent climate zone used to derive IPCC default emission factors. Reservoirs (indicated by black polygons) are sparsely distributed across United States, but can be seen in MN, IL, and IN in this image.

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 6-101 and Table 6-102 below summarize nationally aggregated CH_4 and CO_2 emissions from reservoirs 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 17 years.

Table 6-101: CH_4 Emissions from Land Converted to Flooded Land—Reservoirs (MMT CO_2 Eq.)

Source	**1990**	**2005**	**2018**	**2019**	**2020**	**2021**	**2022**
Reservoirs							
Surface Emissions	2.5	0.4	0.2	0.2	0.2	0.2	0.2
Downstream Emissions	0.2	+	+	+	+	+	+
Total	**2.7**	**0.4**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**

+Indicates values less than 0.05 MMT CO_2

Note: Totals may not sum due to independent rounding.

Table 6-102: CH_4 Emissions from Land Converted to Flooded Land—Reservoirs (kt CH_4)

Source	**1990**	**2005**	**2018**	**2019**	**2020**	**2021**	**2022**
Reservoirs							
Surface Emissions	90	14	7	7	7	7	7
Downstream Emissions	8	1	1	1	1	1	1
Total	**98**	**15**	**8**	**8**	**8**	**7**	**7**

Table 6-103: CO$_2$ Emissions from Land Converted to Flooded Land—Reservoirs (MMT CO$_2$)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoir	3.5	0.6	0.3	0.3	0.3	0.3	0.3

Table 6-104: CO$_2$ Emissions from Land Converted to Flooded Land—Reservoirs (MMT C)

Source	1990	2005	2018	2019	2020	2021	2022
Reservoir	0.9	0.2	0.1	0.1	0.1	0.1	0.1

Methane and CO$_2$ emissions from reservoirs in Minnesota were 8-fold greater than from any other state (Figure 6-18 and Table 6-105). This is attributed to nineteen reservoirs created in Minnesota after 2001 which impound 54,064 ha of water, 96 percent of which is located in Mille Lacs Lake.

North Dakota is the second largest source of CO$_2$ and CH$_4$ from reservoirs in land converted to flooded land. Over ninety-nine 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 6-18: 2022 A) CH$_4$ and B) CO$_2$ Emissions from U.S. Reservoirs in Land Converted to Flooded Land

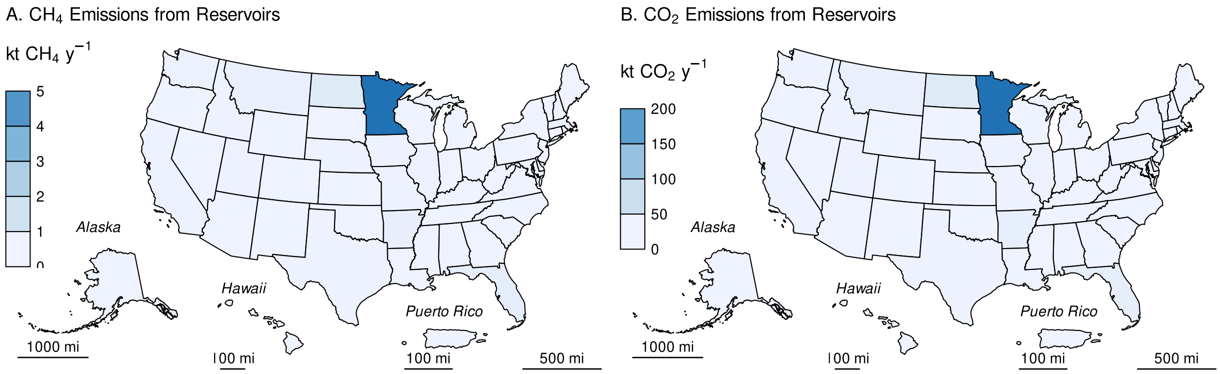


Table 6-105: Methane and CO$_2$ Emissions from Reservoirs in Land Converted to Flooded Land in 2022 (kt CH$_4$; kt CO$_2$)

	CH$_4$			CO$_2$[a]
State	Surface	Downstream	Total	Surface
Alabama	0	0	0	0
Alaska	0	0	0	0
Arizona	0	0	0	0
Arkansas	+	+	+	9
California	+	+	+	3
Colorado	+	+	+	1
Connecticut	+	+	+	+
Delaware	0	0	0	0
District of Columbia	0	0	0	0
Florida	+	+	+	13
Georgia	+	+	+	1
Hawaii	0	0	0	0
Idaho	+	+	+	2

Illinois	+	+	+	4
Indiana	+	+	+	+
Iowa	+	+	+	2
Kansas	+	+	+	+
Kentucky	0	0	0	0
Louisiana	+	+	+	+
Maine	+	+	+	+
Maryland	+	+	+	+
Massachusetts	+	+	+	5
Michigan	+	+	+	+
Minnesota	5	+	5	202
Mississippi	+	+	+	+
Missouri	+	+	+	2
Montana	+	+	+	8
Nebraska	+	+	+	1
Nevada	+	+	+	+
New Hampshire	+	+	+	1
New Jersey	0	0	0	0
New Mexico	+	+	+	1
New York	+	+	+	+
North Carolina	+	+	+	1
North Dakota	+	+	1	22
Ohio	+	+	+	1
Oklahoma	0	0	0	0
Oregon	+	+	+	1
Pennsylvania	+	+	+	1
Puerto Rico	0	0	0	0
Rhode Island	0	0	0	0
South Carolina	0	0	0	0
South Dakota	+	+	+	+
Tennessee	+	+	+	1
Texas	+	+	+	3
Utah	+	+	+	1
Vermont	0	0	0	0
Virginia	0	0	0	0
Washington	+	+	+	3
West Virginia	+	+	+	+
Wisconsin	+	+	+	1
Wyoming	+	+	+	1

+ Indicates values greater than zero and less than 0.5 kt.

[a] CO_2: Only surface CO_2 emissions are included in the *Inventory.*

Methodology and Time-Series Consistency

Estimates of CH_4 and CO_2 emissions for reservoirs 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 6-106). 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 zones are present in the United States.

Table 6-106: IPCC (2019) Default CH_4 and CO_2 Emission Factors for Surface Emissions from Reservoirs 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
Warm Temperate Moist	0.1275	5.35
Tropical Dry/Montane	0.3923	10.82
Tropical Moist/Wet	0.2516	10.16

Note: Downstream CH_4 emissions are calculated as 9 percent of surface emissions. Downstream emissions are not calculated for CO_2.

Area estimates

U.S. reservoirs were identified from the NHDWaterbody layer in the National Hydrography Dataset Plus V2 (NHD),[81] the National Inventory of Dams (NID),[82] the National Wetlands Inventory (NWI),[83] and the Navigable Waterways (NW) network,[84] and the EPA's Safe Drinking Water Information System (SDWIS).[85] The NHD only covers the conterminous United States, whereas the NID, NW and NWI also include Alaska, Hawaii, and Puerto Rico. The following paragraphs present the criteria used to identify other constructed waterbodies in the NHD, NW, and NWI.

Waterbodies in the NHDWaterbody layer that were less than or equal to 20-years old, greater than or equal to 8 ha in surface area, not identified as canal/ditch in NHD, and met any of the following criteria were considered reservoirs in land converted to flooded land: 1) the waterbody was classified "Reservoir" in the NHDWaterbody layer, 2) the waterbody name in the NHDWaterbody layer included "Reservoir", 3) the waterbody in the NHDWaterbody layer was located in close proximity (up to 100 m) to a dam in the NID, 4) the NHDWaterbody GNIS name was similar to nearby NID feature (between 100 m to 1000 m).

EPA assumes that all features included in the NW are subject to water-level management to maintain minimum water depths required for navigation and are therefore managed flooded lands. NW features greater than 8 ha in surface area are defined as reservoirs.

NWI features were considered "managed" if they had a special modifier value indicating the presence of management activities (Figure 6-19). To be included in the flooded lands inventory, the managed flooded land had to be wet or saturated for at least one season per year (see 'Water Regime' in Figure 6-19). NWI features that met these criteria, were greater than 8 ha in surface area, and were not a canal/ditch (see emissions from land converted to flooded land–other constructed waterbodies) were defined as reservoirs.

Any NWI or NHD feature that intersected a drinking water intake point from SDWIS was assumed to be "managed." The rational being that a waterbody used as a source for public drinking water is typically managed in some capacity - by flow and/or volume control.

Surface areas for identified flooded lands were taken from NHD, NWI or the NW. If features from the NHD, NWI, or the NW datasets overlapped, duplicate areas were erased. The first step was to take the final NWI flooded lands

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

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

[83] See https://www.fws.gov/program/national-wetlands-inventory/data-download.

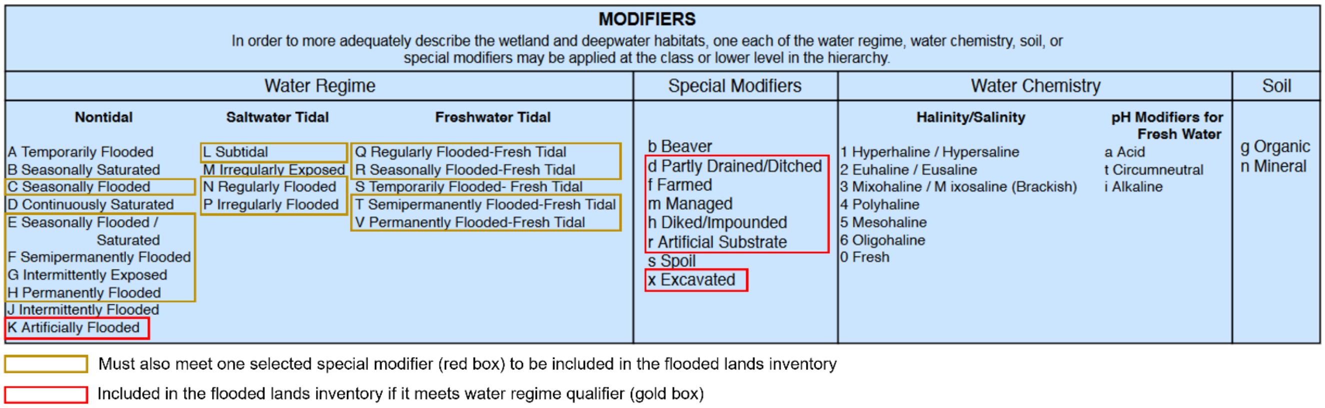
[84] See https://www.census.gov/geographies/mapping-files/time-series/geo/carto-boundary-file.html.

[85] See https://www.epa.gov/enviro/sdwis-overview. Not publicly available due to security concerns.

features and use it to identify overlapping NHD features. If the NHD feature had its center in a NWI feature, it was removed from analysis. Next, remaining NHD features were erased from any remaining overlapping NWI features. Final selections of NHD and NWI features were used to erase any overlapping NW waterbodies.

Reservoir age was determined by assuming they were created the same year as a nearby (up to 100 m) NID feature. If no nearby NID feature was identified, it was assumed the feature was greater than 20-years old throughout the time series. Only reservoirs less than or equal to 20-years old are included in land converted to flooded land.

Figure 6-19: Selected Features from NWI that meet Flooded Lands Criteria



MODIFIERS

In order to more adequately describe the wetland and deepwater habitats, one each of the water regime, water chemistry, soil, or special modifiers may be applied at the class or lower level in the hierarchy.

Water Regime			Special Modifiers	Water Chemistry		Soil
Nontidal	**Saltwater Tidal**	**Freshwater Tidal**		**Halinity/Salinity**	**pH Modifiers for Fresh Water**	
A Temporarily Flooded B Seasonally Saturated C Seasonally Flooded D Continuously Saturated E Seasonally Flooded / Saturated F Semipermanently Flooded G Intermittently Exposed H Permanently Flooded J Intermittently Flooded K Artificially Flooded	L Subtidal M Irregularly Exposed N Regularly Flooded P Irregularly Flooded	Q Regularly Flooded-Fresh Tidal R Seasonally Flooded-Fresh Tidal S Temporarily Flooded- Fresh Tidal T Semipermanently Flooded-Fresh Tidal V Permanently Flooded-Fresh Tidal	b Beaver d Partly Drained/Ditched f Farmed m Managed h Diked/Impounded r Artificial Substrate s Spoil x Excavated	1 Hyperhaline / Hypersaline 2 Euhaline / Eusaline 3 Mixohaline / M ixosaline (Brackish) 4 Polyhaline 5 Mesohaline 6 Oligohaline 0 Fresh	a Acid t Circumneutral i Alkaline	g Organic n Mineral

🟨 Must also meet one selected special modifier (red box) to be included in the flooded lands inventory

🟥 Included in the flooded lands inventory if it meets water regime qualifier (gold box)

Source (modified): https://www.fws.gov/sites/default/files/documents/wetlands-and-deepwater-map-code-diagram.pdf

IPCC (2019) allows for the exclusion of managed waterbodies 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 nor water residence time was substantially altered by their associated dams.

Reservoirs were disaggregated by state (using boundaries from the 2016 U.S. Census Bureau[86]) 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*.

The surface area of reservoirs in land converted to flooded land decreased by nearly 90 percent from 1990 to 2022 (Table 6-107). This is due to reservoirs that were less than 20-years old at the beginning of time series entering the flooded land remaining flooded land category when they exceeded 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 only nine new dams constructed in 2022,[87] versus 552 in 1990 (Figure 6-20).

Table 6-107: National Totals of Reservoir Surface Area in Land Converted to Flooded Land (thousands of ha)

Surface Area (thousands of ha)	1990	2005	2018	2019	2020	2021	2022
Reservoir	566	115	78	77	75	74	73

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

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

Figure 6-20: Number of Dams Built per Year from 1990 through 2022

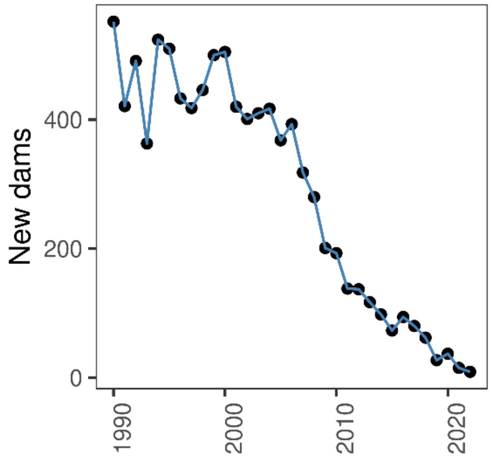

Table 6-108: State Breakdown of Reservoir Surface Area in Land Converted to Flooded Land (thousands of ha)

State	1990	2005	2018	2019	2020	2021	2022
Alabama	7.5	0.0	0.0	0.0	0.0	0.0	0.0
Alaska	0.6	0.0	0.0	0.0	0.0	0.0	0.0
Arizona	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Arkansas	10.1	2.9	1.8	1.8	1.8	1.8	1.8
California	19.6	2.1	0.5	0.5	0.5	0.5	0.5
Colorado	5.9	1.3	0.3	0.3	0.3	0.3	0.3
Connecticut	2.3	2.2	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	25.7	3.8	1.5	1.5	1.4	1.2	1.2
Georgia	20.6	4.9	0.1	0.1	0.1	0.1	0.1
Hawaii	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Idaho	17.7	1.2	0.5	0.5	0.5	0.5	0.5
Illinois	49.2	39.4	1.4	1.3	1.3	0.8	0.8
Indiana	10.6	0.3	0.1	0.1	0.1	0.1	0.1
Iowa	12.3	3.1	1.0	1.0	0.7	0.7	0.5
Kansas	19.6	0.4	0.2	0.2	0.1	0.1	0.0
Kentucky	1.3	0.1	0.0	0.0	0.0	0.0	0.0
Louisiana	9.4	0.2	0.0	0.0	0.0	0.0	0.0
Maine	10.9	4.4	0.0	0.0	0.0	0.0	0.0
Maryland	0.8	0.1	0.1	0.1	0.1	0.1	0.1
Massachusetts	1.6	0.5	1.5	1.5	1.4	1.4	1.2
Michigan	11.6	0.9	0.1	0.1	0.1	0.1	0.1
Minnesota	9.9	6.4	54.6	54.6	54.3	54.2	54.1
Mississippi	6.2	0.6	0.1	0.1	0.1	0.1	0.1
Missouri	16.4	0.5	0.4	0.4	0.4	0.4	0.4
Montana	14.4	3.9	2.1	2.1	2.1	2.1	2.1
Nebraska	5.8	1.7	0.6	0.6	0.3	0.3	0.3
Nevada	1.6	1.1	0.1	0.1	0.1	0.1	0.1
New Hampshire	0.4	0.2	0.1	0.1	0.1	0.1	0.1
New Jersey	0.7	0.6	0.0	0.0	0.0	0.0	0.0
New Mexico	1.3	0.1	0.1	0.1	0.1	0.1	0.1
New York	4.2	2.6	0.1	0.1	0.1	0.1	0.1

North Carolina	19.7	0.7	0.3	0.2	0.2	0.2	0.2
North Dakota	7.5	3.5	6.3	6.3	6.3	6.2	5.9
Ohio	7.2	1.3	0.3	0.3	0.2	0.2	0.1
Oklahoma	28.7	0.2	0.0	0.0	0.0	0.0	0.0
Oregon	6.2	0.4	0.2	0.2	0.2	0.1	0.1
Pennsylvania	12.6	1.3	0.1	0.1	0.1	0.1	0.1
Puerto Rico	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rhode Island	0.1	0.0	0.0	0.0	0.0	0.0	0.0
South Carolina	18.5	5.8	0.0	0.0	0.0	0.0	0.0
South Dakota	0.5	3.9	0.8	0.8	0.0	0.0	0.0
Tennessee	58.7	0.0	0.1	0.1	0.1	0.1	0.1
Texas	74.8	0.9	0.3	0.3	0.2	0.2	0.2
Utah	1.9	0.1	0.3	0.3	0.3	0.3	0.3
Vermont	0.2	0.1	0.0	0.0	0.0	0.0	0.0
Virginia	5.8	0.4	0.0	0.0	0.0	0.0	0.0
Washington	5.3	1.6	0.9	0.9	0.5	0.5	0.5
West Virginia	3.1	1.6	0.1	0.0	0.0	0.0	0.0
Wisconsin	1.9	0.4	0.2	0.2	0.2	0.2	0.2
Wyoming	15.1	6.5	0.4	0.2	0.2	0.2	0.2
Total	**565.8**	**114.6**	**77.6**	**77.1**	**74.7**	**73.7**	**72.5**

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 1-105). 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, NWI, and NW, and 2) uncertainty in the location of dams in the NID and drinking water intakes in SDWIS. 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 6-109: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Reservoirs in Land Converted to Flooded Land

Source	Gas	2022 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	0.19	0.17	0.21	-11.5%	+11.9%
Surface	CO_2	0.2	0.26	0.33	-11.7%	+12.4%
Downstream	CH_4	+	+	0.08	-54.1%	+397.0%
Total		**0.5**	**0.44**	**0.59**	**-12.2%**	**+18.8%**

+ 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 Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation

Statistics (BTS) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis. U.S. Fish and Wildlife Service is the principal agency in charge of wetland mapping including the National Wetlands Inventory (NWI). Quality and consistency of the Wetlands Layer is supported by federal wetlands mapping and classification standards, which were developed under the oversight of the Federal Geographic Data Committee (FGDC) with input by the FGDC Wetlands Subcommittee. This dataset is part of the FGDC Water-Inland Theme, which is co-chaired by the FWS and the U.S. Geological Survey. The EPA's Safe Drinking Water Information System (SDWIS) tracks information on drinking water contamination levels as required by the 1974 Safe Drinking Water Act and its 1986 and 1996 amendments.

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the U.S. Inventory QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). 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

The EPA's SDWIS is a new data source used in the current (1990 through 2022) *Inventory*. The assumption is that any waterbody used as a public drinking water source is managed in some capacity—by flow and/or volume control. This data source added 418 reservoirs totaling 736,344 ha.

The National Inventory of Dams (NID) data are updated regularly. The version of NID used for the current *Inventory* contains 47 new dams and updated values for "year of dam completion" for 975 dams relative to the previous (1990 through 2021) *Inventory* data. Similarly, the National Wetlands Inventory (NWI) is periodically updated. The NWI version used for the current 1990 through 2022 *Inventory* has major updates for MS, ND, NM, and MT.

Overall, the recalculations resulted in substantial increases in methane and carbon dioxide emissions in the first few years of the time series (e.g., increase of 3.8 MMT CO_2 Eq. in 1990), but the differences were minor by 2008 through 2021 (<0.1 MMT CO_2 Eq.).

Planned Improvements

The EPA recently completed a survey of greenhouse gas emissions from 108 reservoirs in the conterminous United States.[88] The data will be used to develop country-specific emission factors for U.S. reservoirs to be used in the 1990 through 2024 *Inventory* submission.

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) because age data are not available for canals and ditches. All canals and ditches are assumed to be greater than 20-years old throughout the time series and are included in flooded land remaining flooded land.

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 identified as "canal/ditch" (see Methods below) with

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[88] See https://www.epa.gov/air-research/research-emissions-us-reservoirs.

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 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 95 percent from 1990 to 2022 due to flooded land matriculating from land converted to flooded land to flooded land remaining flooded land. In 2022, states in the Great Plains region generally had the greatest CO_2 and CH_4 emissions from freshwater ponds in land converted to flooded land (Table 6-110 through + Indicates values less than 0.005 MMT C.

Table 6-114, Figure 6-21). Mississippi had the second greatest emissions of all states, partly due to the relatively high CO_2 emission factor for the tropical moist/wet climate zone (Figure 6-17, Table 6-115).

Table 6-110: CH_4 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (MMT CO_2 Eq.)

Source	1990	2005	2018	2019	2020	2021	2022
Freshwater Ponds	0.1	+	+	+	+	+	+

+ Indicates values less than 0.05 MMT CO_2 Eq.

Table 6-111: CH_4 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (kt CH_4)

Source	1990	2005	2018	2019	2020	2021	2022
Freshwater Ponds	5	1	+	+	+	+	+

+ Indicates values less than 0.5 kt.

Table 6-112: CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (MMT C)

Source	1990	2005	2018	2019	2020	2021	2022
Freshwater Ponds	+	+	+	+	+	+	+

+ Indicates values less than 0.05 MMT C.

Table 6-113: CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land (MMT C)

Source	1990	2005	2018	2019	2020	2021	2022
Freshwater Ponds	0.04	0.01	+	+	+	+	+

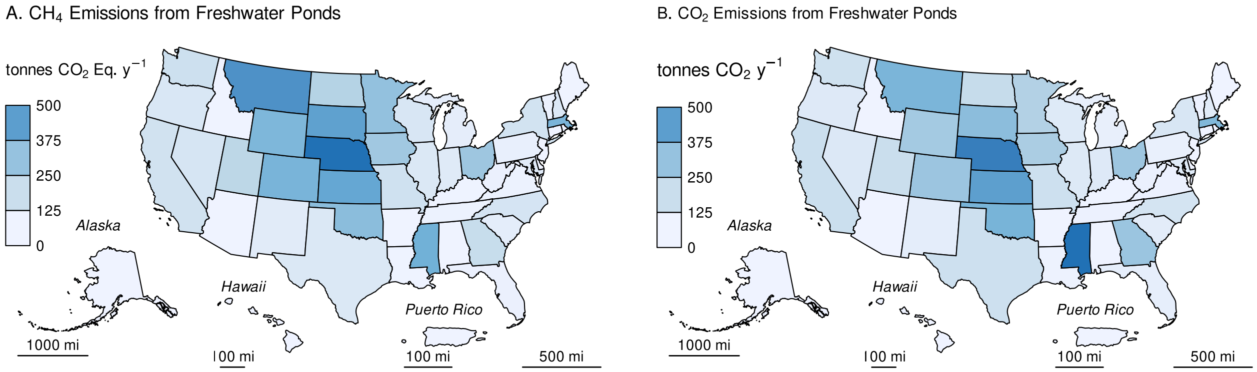
+ Indicates values less than 0.005 MMT C.

Table 6-114: CH_4 and CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land in 2022 (MT CO_2 Eq.)

	Freshwater Ponds		
State	CH_4	CO_2	Total
Alabama	0	0	0
Alaska	0	0	0
Arizona	0	0	0
Arkansas	1	1	3
California	126	146	272
Colorado	382	290	672
Connecticut	0	0	0
Delaware	0	0	1

District of Columbia	0	0	0
Florida	18	37	55
Georgia	164	293	457
Hawaii	0	0	0
Idaho	0	0	0
Illinois	83	74	157
Indiana	66	69	135
Iowa	282	254	535
Kansas	435	456	891
Kentucky	3	3	5
Louisiana	3	6	10
Maine	1	1	2
Maryland	58	60	118
Massachusetts	381	358	738
Michigan	41	30	71
Minnesota	317	232	549
Mississippi	400	612	1,012
Missouri	133	139	271
Montana	509	371	880
Nebraska	620	567	1,186
Nevada	103	80	183
New Hampshire	80	59	139
New Jersey	0	0	0
New Mexico	57	46	103
New York	120	96	215
North Carolina	107	112	219
North Dakota	229	167	396
Ohio	289	285	574
Oklahoma	339	378	717
Oregon	89	71	161
Pennsylvania	29	25	54
Puerto Rico	0	0	0
Rhode Island	0	0	0
South Carolina	47	49	95
South Dakota	455	332	788
Tennessee	11	11	22
Texas	83	138	222
Utah	207	151	359
Vermont	15	11	26
Virginia	10	11	21
Washington	140	132	272
West Virginia	19	19	38
Wisconsin	93	68	162
Wyoming	369	269	639
Total	**6,917**	**6,510**	**13,427**

Figure 6-21: 2022 A) CH_4 and B) CO_2 Emissions from Other Constructed Waterbodies (Freshwater Ponds) in Land Converted to Flooded Land (MT CO_2 Eq.)



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 6-115). 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 6-115: 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

Other constructed waterbodies were identified from the NHDWaterbody layer in the National Hydrography

Dataset Plus V2 (NHD),[89] the National Inventory of Dams (NID),[90] the National Wetlands Inventory (NWI),[91] and the Navigable Waterways (NW) network[92], and the EPA's Safe Drinking Water Information System (SDWIS)[93]. The NHD only covers the conterminous United States, whereas the NID, NW and NWI also include Alaska, Hawaii, and Puerto Rico.

Waterbodies in the NHDWaterbody layer that were less than or equal to 20-years old, less than 8 ha in surface area, not identified as canal/ditch in NHD, and met any of the following criteria were considered freshwater ponds in land converted to flooded land: 1) the waterbody was classified "Reservoir" in the NHDWaterbody layer, 2) the waterbody name in the NHDWaterbody layer included "Reservoir", 3) the waterbody in the NHDWaterbody layer was located in close proximity (up to 100 m) to a dam in the NID, 4) the NHDWaterbody GNIS name was similar to nearby NID feature (between 100 m to 1000 m).

EPA assumes that all features included in the NW are subject to water-level management to maintain minimum water depths required for navigation and are therefore managed flooded lands. NW features that were less than 8 ha in surface area and not identified as canals/ditch (see below) were considered freshwater ponds. Only 2.1 percent of NW features met these criteria, and they were primarily associated with larger navigable waterways, such as lock chambers on impounded rivers.

NWI features were considered "managed" if they had a special modifier value indicating the presence of management activities (Figure 6-19). To be included in the flooded lands inventory, the managed flooded land had to be wet or saturated for at least one season per year (see 'Water Regime' in Figure 6-19). NWI features that met these criteria, were less than 8 ha in surface area, and were not a canal/ditch were defined as freshwater ponds.

Any NWI or NHD feature that intersected a drinking water intake point from SDWIS was assumed to be "managed". The rational being that a waterbody used as a source for public drinking water is typically managed in some capacity - by flow and/or volume control.

Surface areas for other constructed waterbodies were taken from NHD, NWI or the NW. If features from the NHD, NWI, or the NW datasets overlapped, duplicate areas were erased. The first step was to take the final NWI flooded lands features and use it to identify overlapping NHD features. If the NHD feature had its center in a NWI feature, it was removed from analysis. Next, remaining NHD features were erased from any remaining overlapping NWI features. Final selections of NHD and NWI features were used to erase any overlapping NW waterbodies.

The age of other constructed waterbody features was determined by assuming the waterbody was created the same year as a nearby (up to 100 m) NID feature. If no nearby NID feature was identified, it was assumed the waterbody was greater than 20-years old throughout the time series. No canal/ditch features were associated with a nearby dam, therefore all canal/ditch features were assumed to be greater than 20-years old through the time series.

For the year 2022, this *Inventory* contains 1,350 ha of freshwater ponds in land converted to flooded land. The surface area of freshwater ponds decreased by 95 percent from 1990 to 2022 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 Iowa, Kansas, and Georgia (Table 6-117). Freshwater ponds in the 2021 inventory are most abundant in Nebraska, Montana, and Kansas (Figure 6-22).

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

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

[91] See https://www.fws.gov/program/national-wetlands-inventory/data-download.

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

[93] Not publicly available due to security concerns.

Table 6-116: National Surface Area Totals of Other Constructed Waterbodies in Land Converted to Flooded Land (ha)

Other Constructed Waterbodies	1990	2005	2018	2019	2020	2021	2022
Freshwater Ponds	25,492	5,357	2,604	2,317	1,983	1,673	1,472

Figure 6-22: Surface Area of Other Constructed Waterbodies in Land Converted to Flooded Land (ha) in 2022

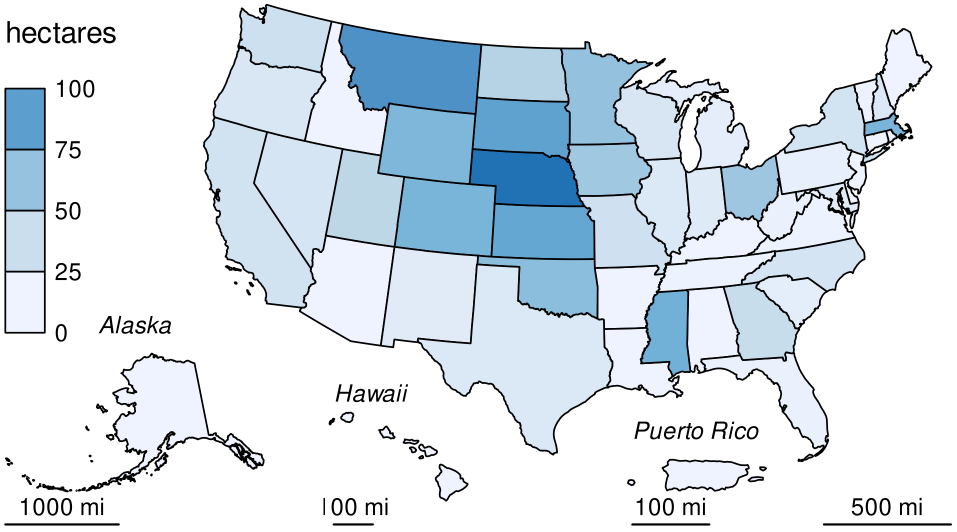

Table 6-117: State Surface Area Totals of Other Constructed Waterbodies in Land Converted to Flooded Land (ha)

State	1990	2005	2018	2019	2020	2021	2022
Alabama	317	13	0	0	0	0	0
Alaska	3	0	0	0	0	0	0
Arizona	39	16	4	4	0	0	0
Arkansas	331	0	0	0	0	0	0
California	263	103	45	40	33	31	25
Colorado	279	71	79	78	89	89	75
Connecticut	67	2	0	0	0	0	0
Delaware	4	0	0	0	0	0	0
District of Columbia	0	0	0	0	0	0	0
Florida	154	58	15	10	10	4	4
Georgia	1,686	83	35	32	32	32	32
Hawaii	11	4	0	0	0	0	0
Idaho	133	8	1	1	1	0	0
Illinois	557	133	42	37	27	26	16
Indiana	494	133	28	23	23	23	13
Iowa	2,592	1,580	474	290	172	76	55
Kansas	2,099	147	113	104	103	87	85
Kentucky	394	30	1	1	1	1	1
Louisiana	130	17	7	7	1	1	1
Maine	51	10	0	0	0	0	0
Maryland	226	81	20	20	18	15	11

Massachusetts	68	79	93	86	80	78	74
Michigan	162	37	16	16	8	8	8
Minnesota	344	142	103	101	79	71	62
Mississippi	414	200	124	117	98	85	78
Missouri	3,451	104	38	34	32	29	26
Montana	400	109	105	100	99	99	99
Nebraska	1,427	374	182	164	133	125	121
Nevada	21	64	26	26	22	22	20
New Hampshire	154	61	17	17	16	16	16
New Jersey	50	21	0	0	0	0	0
New Mexico	14	14	19	17	17	17	11
New York	312	124	31	29	29	24	23
North Carolina	498	92	28	28	25	22	21
North Dakota	90	135	67	61	51	48	45
Ohio	431	293	121	107	75	60	56
Oklahoma	2,008	147	111	95	81	75	66
Oregon	220	69	25	22	18	17	17
Pennsylvania	255	33	6	6	6	6	6
Puerto Rico	0	0	0	0	0	0	0
Rhode Island	9	7	0	0	0	0	0
South Carolina	826	230	22	13	9	9	9
South Dakota	227	98	105	94	93	89	89
Tennessee	389	37	14	9	2	2	2
Texas	2,950	89	21	16	17	16	16
Utah	68	19	42	42	40	40	40
Vermont	70	11	3	3	3	3	3
Virginia	58	4	2	2	2	2	2
Washington	153	57	31	31	28	27	27
West Virginia	130	10	4	4	4	4	4
Wisconsin	146	21	18	18	18	18	18
Wyoming	316	190	79	79	78	75	72
Total	**25,492**	**5,357**	**2,317**	**1,983**	**1,673**	**1,472**	**1,350**

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 and drinking water intakes in SDWIS. Overall uncertainties in the NHD, NWI, 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 6-118: Approach 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Other Constructed Waterbodies in Land Converted to Flooded Land

Source	**Gas**	**2022 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	6.90	6.80	7.10	-2.3%	+2.7%
Freshwater ponds	CO_2	6.51	6.38	6.62	-2.0%	+1.8%
Total		**13.42**	**13.18**	**13.70**	**-1.8%**	**+2.1%**

[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 Navigable Waterways (NW) dataset is part of the U.S. Department of Transportation (USDOT)/Bureau of Transportation Statistics (BTS) National Transportation Atlas Database (NTAD). The NW is a comprehensive network database of the nation's navigable waterways updated on a continuing basis. U.S. Fish and Wildlife Service is the principal agency in charge of wetland mapping including the National Wetlands Inventory. Quality and consistency of the Wetlands Layer is supported by federal wetlands mapping and classification standards, which were developed under the oversight of the Federal Geographic Data Committee (FGDC) with input by the FGDC Wetlands Subcommittee. This dataset is part of the FGDC Water-Inland Theme, which is co-chaired by the FWS and the U.S. Geological Survey. The EPA's Safe Drinking Water Information System (SDWIS) tracks information on drinking water contamination levels as required by the 1974 Safe Drinking Water Act and its 1986 and 1996 amendments.

General QA/QC procedures were applied to activity data, documentation, and emission calculations consistent with the U.S. Inventory QA/QC plan, which is in accordance with Vol. 1 Chapter 6 of the *2006 IPCC Guidelines* (see Annex 8 for more details). 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

The EPA's SDWIS is a new data source used in the current (1990 through 2022) *Inventory.* The assumption is that any waterbody used as a public drinking water source is managed in some capacity - by flow and/or volume control. This data source added 54 features totaling 173 ha of other constructed waterbodies.

The National Inventory of Dams (NID) data are updated regularly. The version of NID used for the current *Inventory* contains 47 new dams and updated values for “year of dam completion” for 975 dams relative to the previous (1990 through 2021) *Inventory* data. Similarly, the National Wetlands Inventory (NWI) is periodically updated. The NWI version used for the current *Inventory* has major updates for MS, ND, NM, and MT.

The net effect of these recalculations was an average annual increase in CH_4 and CO_2 emissions from other constructed waterbodies of 0.03 MMT CO_2 Eq., or 51 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

Features < 8 ha in the NW that were not identified as canal/ditch were defined as freshwater ponds. Many of these features are lock chambers connected to an upstream reservoir. These systems likely have emission rates more similar to a reservoir than freshwater pond. In the next (i.e., 1990 through 2023) *Inventory* these systems will be classified as reservoirs.

6.10 Settlements Remaining Settlements (CRT Category 4E1)

Soil Carbon Stock Changes (CRT 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 in this land use category. 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 carbon 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.[94] Due to the depth and richness of the organic layers, carbon 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 2017 United States Department of Agriculture (USDA) National Resources Inventory (NRI) (USDA-NRCS 2020)[95] 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). There are discrepancies between the current land representation (see Section 6.1) and the area data that have been used in the *Inventory* for settlements remaining settlements. Specifically, 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. 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* (see Planned Improvements section).

CO_2 emissions from drained organic soils in settlements are 15.4 MMT CO_2 Eq. (4.2 MMT C) in 2022 (see Table 6-119 and Table 6-120). Although the flux is relatively small, the amount has increased by 56 percent since 1990 due to an increase in area of drained organic soils in settlements.

Table 6-119: Net CO_2 Flux from Soil C Stock Changes in Settlements Remaining Settlements (MMT CO_2 Eq.)

Soil Type	1990	2005	2018	2019	2020	2021	2022
Organic Soils	9.9	10.1	14.4	14.6	15.1	15.4	15.4

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[94] N_2O emissions from drained organic soils are included in the N_2O Emissions from Settlement Soils section.

[95] 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 6-120: Net CO_2 Flux from Soil C Stock Changes in Settlements Remaining Settlements (MMT C)

Soil Type	1990	2005	2018	2019	2020	2021	2022
Organic Soils	2.7	2.7	3.9	4.0	4.1	4.2	4.2

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 2017 NRI (USDA-NRCS 2020) with additional information from the NLCD to the extend the time series through 2020 (Yang et al. 2018). Soils are classified as organic using data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2020). The areas have been modified through a process in which the Forest Inventory and Analysis (FIA) survey data are harmonized with the NRI data (Nelson et al. 2020). This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 Representation of the U.S. Land Base for more information). All settlements occurring on organic soil are assumed to be drained for the purposes of approximating greenhouse gas emissions. The area of drained organic soils is estimated from the NRI spatial weights and aggregated to the country (Table 6-121). The area of land on organic soils in settlements remaining settlements has increased from 216 thousand hectares in 1990 to over 327 thousand hectares in 2020.

Table 6-121: Thousands of Hectares of Drained Organic Soils in Settlements Remaining Settlements

	1990	2005	2014	2015	2016	2017	2018	2019	2020	2021	2022
Area (Thousand Hectares)	216	219	276	283	291	302	311	317	327	*	*

NRI data have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

To estimate CO_2 emissions from drained organic soils across the time series from 1990 to 2020, the area of organic soils by climate (i.e., cool temperate, warm temperate, subtropical) in settlements remaining settlements is multiplied by the appropriate 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 2020, and a linear extrapolation method is used to approximate emissions for the remainder of the 2021 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 2020 emissions data, and is a standard data splicing method for imputing missing emissions data in a time series (IPCC 2006). The Tier 2 method described previously will be applied in future inventories to recalculate the estimates beyond 2020 as new activity data are integrated into the analysis.

Uncertainty

The total uncertainty was quantified with two variance components (Ogle et al. 2010) that 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. The first variance component is associated with uncertainty in the emission factor, and the second variance component is associated with scaling of the data from the NRI survey to the entire area of drained organic soils in settlements remaining settlements, and is computed using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). There is also additional uncertainty associated with the fit of the linear regression model for the data splicing methods that was incorporated into the analysis for the latter part of the time series. Soil carbon losses from drained organic soils in settlements remaining settlements for 2022 are estimated to be between 7.7 and 23.2 MMT CO_2 Eq. at a 95 percent confidence level (Table 6-115). This indicates a range of 50 percent below and 50 percent above the 2022 emission estimate of 15.4 MMT CO_2 Eq.

Table 6-122: Uncertainty Estimates for CO_2 Emissions from Drained Organic Soils in Settlements Remaining Settlements (MMT CO_2 Eq. and Percent)

Source	Gas	2022 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	15.4	7.7	23.2	-50%	+50%

[a] Range of emission estimates is 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

Recalculations are associated with updated land areas for drainage of organic soils in settlements remaining settlements, and update that was made by incorporating new USDA-NRCS NRI data through 2017 and extending the time series using NLCD. As a result of this change, CO_2-equivalent emissions changed annually with an average annual decrease of 1.8 MMT CO_2 Eq., or 14 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

A key improvement is to estimate CO_2 emissions from drainage of organic soils in settlements of Alaska and federal lands. This improvement will resolve most of the differences between the managed land base for settlements remaining settlements and amount of area currently included in this *Inventory* as settlements remaining settlements (see Table 6-123). This improvement will be made pending prioritization of resources to expand the inventory for this source category.

Table 6-123: 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	Difference
1990	30,548	30,366	182
1991	30,545	30,364	182
1992	30,543	30,361	182
1993	30,470	30,288	182
1994	30,385	30,203	182
1995	30,322	30,141	182
1996	30,263	30,081	182
1997	30,193	30,011	182
1998	30,127	29,945	182
1999	30,073	29,891	182
2000	30,015	29,834	182
2001	29,963	29,781	182
2002	29,956	29,774	182
2003	30,479	30,298	182
2004	30,973	30,791	182
2005	31,432	31,250	182
2006	31,940	31,758	182
2007	32,397	32,215	182
2008	33,015	32,833	182
2009	33,591	33,410	182
2010	34,166	33,984	182
2011	34,731	34,549	182
2012	35,302	35,120	182
2013	36,224	36,042	182
2014	37,159	36,977	182
2015	38,026	37,844	182
2016	38,938	38,756	182
2017	39,861	39,679	182
2018	40,756	40,574	182
2019	41,602	41,420	182
2020	42,452	42,270	182
2021	43,175	*	*
2022	43,734	*	*

NRI data have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

Changes in Carbon Stocks in Settlement Trees (CRT 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. Estimates included in this section include net CO_2 and carbon 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.

Trees in settlement areas of the United States are estimated to account for an average annual net sequestration of 118.2 MMT CO_2 Eq. (32.2 MMT C) over the period from 1990 through 2022. Net carbon sequestration from settlement trees in 2022 is estimated to be 138.5 MMT CO_2 Eq. (37.8 MMT C) (Table 6-124). 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 versus 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 carbon flux estimates. Annual sequestration increased by 43 percent between 1990 and 2022 due to increases in settlement area and changes in total 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 carbon storage per hectare of land is in fact smaller for settlement areas than for forest areas. Also, percent tree cover in settlement areas is less than in forests and this urban tree cover varies significantly across the United States (e.g., Nowak and Greenfield 2018a). To quantify the carbon 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 6-124: Net Flux from Trees in Settlements Remaining Settlements (MMT CO_2 Eq. and MMT C)[a]

Year	1990	2005	2018	2019	2020	2021	2022
MMT CO_2 Eq.	(96.6)	(117.0)	(134.4)	(135.6)	(136.7)	(137.8)	(138.5)
MMT C	(26.3)	(31.9)	(36.7)	(37.0)	(37.3)	(37.6)	(37.8)

[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

Settlement 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 latest NRI as updated through 2017, with the extension of the time series through 2022 based on assuming the settlement area is the same as 2017. The NRI data is also harmonized with the FIA dataset, which is available through 2022, and the 2019 NLCD dataset. 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 the net CO_2 flux (Table 6-124) 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. The NLCD developed land cover 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. 2016 and 2020 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 2016 NLCD tree cover adjusted with 2020 photo-interpreted values

Carbon Sequestration Density per Unit of Tree Cover

Methods for quantifying settlement tree biomass, carbon sequestration, and carbon emissions from tree mortality and decomposition were taken directly from Nowak et al. (2013), Nowak and Crane (2002), and Nowak (1994). In general, net carbon 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 carbon 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 carbon sequestration in settlement trees for all 50 states and the District of Columbia. Third, estimates of carbon emissions due to mortality and decomposition were subtracted from gross carbon sequestration estimates to obtain estimates of net carbon 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[96] and U.S. Forest Service urban forest inventory data (e.g., Nowak et al. 2016, 2017) (Table 6-125). 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 carbon stored and annual carbon 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 carbon by dividing by two (50 percent carbon content). An adjustment factor of 0.8 was used for open grown trees to account for settlement 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 carbon stored in wood. Estimated carbon storage was divided by tree cover in the area to estimate carbon storage per square meter of tree cover.

Table 6-125: 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

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[96] See http://www.itreetools.org.

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 carbon storage estimates between year 1 and year (x + 1) represents the gross amount of carbon sequestered. These annual gross carbon sequestration rates for each tree were then scaled up to city estimates using tree population information. Total carbon 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 carbon sequestration accounts for all carbon sequestered, net carbon sequestration for settlement trees considers carbon emissions associated with tree death and removals. The third step in the methodology estimates net carbon 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 carbon 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 6-126) were compiled in units of carbon 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 carbon 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 carbon 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 6-126). However, state specific ratios were used where available.

State Carbon Sequestration Estimates

The gross and net annual carbon 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

$$\text{Net state annual C sequestration (t C/yr)} = \text{Gross state sequestration rate (t C/ha/yr)} \times$$
$$\text{Net to Gross state sequestration ratio} \times \text{state settlement Area (ha)} \times \text{\% state tree cover in settlement area}$$

The results for all 50 states and the District of Columbia are given in Table 6-126. 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 carbon stocks in the living biomass of settlement trees. Instead, the methodology applied here uses estimates of net carbon sequestration based on modeled estimates of decomposition, as given by Nowak et al. (2013).

Table 6-126: Estimated Annual Carbon Sequestration, Tree Cover, and Annual Carbon Sequestration per Area of Tree Cover for settlement areas in the United States by State and the District of Columbia (2022)

State	Gross Annual Sequestration (Metric Tons C/Year)	Net Annual Sequestration (Metric Tons C/Year)	Tree Cover (Percent)	Gross Annual Sequestration per Area of Tree Cover (kg C/m^2/Year)	Net Annual Sequestration per Area of Tree Cover (kg C/m^2/Year)	Net: Gross Annual Sequestration Ratio
Alabama	2,268,736	1,653,170	53.1	0.376	0.274	0.73
Alaska	150,345	109,553	47.0	0.169	0.123	0.73

Arizona	165,494	120,591	4.5	0.388	0.283	0.73
Arkansas	1,316,764	959,492	48.5	0.362	0.264	0.73
California	2,015,461	1,468,615	16.8	0.426	0.311	0.73
Colorado	142,538	103,864	7.9	0.216	0.157	0.73
Connecticut	649,817	473,505	58.2	0.262	0.191	0.73
Delaware	101,819	74,193	24.2	0.366	0.267	0.73
DC	12,919	9,414	24.9	0.366	0.267	0.73
Florida	4,632,104	3,375,296	39.9	0.520	0.379	0.73
Georgia	3,886,939	2,832,313	55.9	0.387	0.282	0.73
Hawaii	302,023	220,076	41.4	0.637	0.464	0.73
Idaho	59,771	43,553	7.3	0.201	0.146	0.73
Illinois	669,891	488,132	15.4	0.310	0.226	0.73
Indiana	479,505	443,378	17.0	0.274	0.254	0.92
Iowa	177,874	129,612	8.5	0.263	0.191	0.73
Kansas	288,317	224,359	10.7	0.310	0.241	0.78
Kentucky	984,663	717,499	36.5	0.313	0.228	0.73
Louisiana	1,585,823	1,155,549	46.6	0.435	0.317	0.73
Maine	445,519	324,639	55.1	0.242	0.176	0.73
Maryland	857,152	624,585	39.8	0.353	0.257	0.73
Massachusetts	1,093,110	796,521	56.8	0.278	0.203	0.73
Michigan	1,410,284	1,027,638	34.4	0.241	0.175	0.73
Minnesota	325,047	236,853	13.0	0.251	0.183	0.73
Mississippi	1,630,583	1,188,165	56.9	0.377	0.275	0.73
Missouri	878,510	640,148	23.0	0.313	0.228	0.73
Montana	45,414	33,092	4.8	0.201	0.147	0.73
Nebraska	97,770	82,504	7.3	0.261	0.220	0.84
Nevada	35,783	26,074	4.8	0.226	0.165	0.73
New Hampshire	392,480	285,990	58.8	0.238	0.174	0.73
New Jersey	961,860	700,883	40.4	0.321	0.234	0.73
New Mexico	188,804	137,577	10.1	0.288	0.210	0.73
New York	1,606,981	1,170,966	39.6	0.263	0.192	0.73
North Carolina	3,457,794	2,519,606	53.7	0.341	0.249	0.73
North Dakota	18,730	8,900	1.7	0.244	0.116	0.48
Ohio	1,276,930	930,467	28.0	0.271	0.198	0.73
Oklahoma	718,922	523,860	21.9	0.364	0.265	0.73
Oregon	674,472	491,470	39.6	0.265	0.193	0.73
Pennsylvania	1,900,962	1,385,183	39.9	0.267	0.195	0.73
Rhode Island	127,720	93,066	49.6	0.283	0.206	0.73
South Carolina	2,052,656	1,495,718	53.3	0.370	0.269	0.73
South Dakota	29,351	25,453	2.8	0.258	0.224	0.87
Tennessee	1,678,890	1,501,125	40.8	0.332	0.297	0.89
Texas	4,416,309	3,218,052	28.2	0.403	0.294	0.73
Utah	119,794	87,291	11.6	0.235	0.172	0.73
Vermont	188,016	137,002	50.2	0.234	0.170	0.73
Virginia	2,111,293	1,538,445	52.5	0.321	0.234	0.73
Washington	1,139,218	830,119	37.3	0.282	0.206	0.73
West Virginia	774,594	564,427	63.6	0.264	0.192	0.73
Wisconsin	711,938	518,771	25.7	0.246	0.180	0.73
Wyoming	29,558	21,538	4.7	0.199	0.145	0.73
Total	**51,287,245**	**37,768,294**				

Uncertainty

Uncertainty associated with changes in carbon 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 carbon sequestration for each of the 50 states and the District of Columbia. A ten 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 carbon 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 6-127). 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 carbon sequestration and emission estimates (Nowak et al. 2002). These results also exclude changes in soil carbon stocks, and there is likely some overlap between the settlement tree carbon estimates and the forest tree carbon estimates (e.g., Nowak et al. 2013). Due to data limitations, settlement 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 2022. The results of this quantitative uncertainty analysis are summarized in Table 6-127. The change in carbon stocks in settlement trees in 2022 was estimated to be between -208.5 and -66.6 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 2022 flux estimate of -138.5 MMT CO_2 Eq.

Table 6-127: Approach 2 Quantitative Uncertainty Estimates for Net CO_2 Flux from Changes in Carbon Stocks in Settlement Trees (MMT CO_2 Eq. and Percent)

Source	Gas	2022 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	(138.5)	(208.5)	(66.6)	-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

The compilation methods remained the same in the latest *Inventory* relative to the previous *Inventory*. New data from the NRI and NLCD resulted in a small decrease in the settlement area for 2021, leading to no substantial change in the net carbon sequestration (Table 6-128).

Table 6-128: Recalculations of the Settlement Tree Categories

Category	2021 Estimate, Previous *Inventory*	2021 Estimate, Current *Inventory*	2022 Estimate, Current *Inventory*
Settlement Area (km²)	469,705	469,600	471,851
Settlement Tree Coverage (km²)	151,694	151,664	152,442

Net C Flux (MMT C)	(37.6)	(37.6)	(37.8)
Net CO_2 Flux MMT CO_2 Eq.	(137.8)	(137.8)	(138.5)

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. Work is needed to clarify how much of this settlement area tree cover may also be accounted for in “forest” area assessments as some of these forests may be adjacent to 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 carbon reported in the forest source category might also be counted in the urban areas. The potential overlap with settlement areas is unknown at this time but research is underway to develop spatially explicit and spatially continuous land representation products which will eliminate the potential for double counting. Future research may also enable more complete coverage of changes in the carbon stock of trees for all settlements land.

N_2O Emissions from Settlement Soils (CRT 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., volatilization of ammonia [NH_3] and nitrogen oxide [NO_x], and leaching/runoff of nitrate [NO_3^-]), 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[97] are 2.5 MMT CO_2 Eq. (10 kt of N_2O) in 2022. There is an overall increase of 23 percent from 1990 to 2022 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 6-129.

Table 6-129: N_2O Emissions from Soils in Settlements Remaining Settlements (MMT CO_2 Eq. and kt N_2O)

	1990	2005	2018	2019	2020	2021	2022
MMT CO_2 Eq.							
Direct N_2O Emissions from Soils	**1.7**	**2.6**	**2.1**	**2.1**	**2.2**	**2.2**	**2.2**

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[97] 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.

Synthetic Fertilizers	0.8	1.5	0.8	0.8	0.8	0.8	0.8
Biosolids	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Drained Organic Soils	0.8	1.0	1.2	1.2	1.2	1.2	1.2
Indirect N_2O Emissions from Soils	**0.3**	**0.5**	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**
Total	**2.1**	**3.1**	**2.4**	**2.5**	**2.5**	**2.5**	**2.5**
kt N_2O							
Direct N_2O Emissions from Soils	**7**	**10**	**8**	**8**	**8**	**8**	**8**
Synthetic Fertilizers	3	5	3	3	3	3	3
Biosolids	1	1	1	1	1	1	1
Drained Organic Soils	3	4	4	4	4	4	4
Indirect N_2O Emissions from Soils	**1**	**2**	**1**	**1**	**1**	**1**	**1**
Total	**8**	**12**	**9**	**9**	**9**	**10**	**10**

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 7.2—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 2017 are based on 2012 values adjusted for total annual total N fertilizer sales in the United States (AAPFCO 2016 through 2022) 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. Since the total N fertilizer sales is only available through 2017 (AAPFCO 2022), the amount of synthetic fertilization from 2018 to 2022 is determined using a linear extrapolation method (see Box 6-4 in cropland remaining cropland). This method is based on a linear regression model with moving-average (ARMA) errors using the 1990 to 2017 fertilization data. To estimate direct N_2O for the time series, the total amount of fertilizer N applied to settlements is multiplied by the IPCC default emission factor (1 percent) (IPCC 2006) for 1990 to 2022.

Biosolids applications are derived from national data on biosolids generation, disposition, and N content (see Section 7.2, Wastewater Treatment and Discharge 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 2022.

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 2017 National Resources Inventory (NRI) (USDA-NRCS 2020) using soils data from the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2020). The NRI time series has been extended through 2020 using the National Land Cover Dataset (Yang et al. 2018). The areas have been modified through a process in which the Forest Inventory and Analysis (FIA) survey data are harmonized with the NRI data (Nelson et al. 2020). This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 Representation of the U.S. Land Base for more information). All settlements occurring on organic soil are assumed to be drained for the purposes of approximating greenhouse gas emissions. To estimate annual emissions from 1990 to 2020, the total area is multiplied by the IPCC default emission factor for temperate regions (IPCC 2006). The annual emissions for 2021 to 2022 are estimated using a linear extrapolation method (see Box 6-4 in cropland remaining cropland). 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 2022 for biosolids and synthetic fertilization.

In order to ensure time-series consistency, the same methods are applied from 1990 to 2022 for biosolids. For synthetic fertilizer, a linear extrapolation method is used to approximate fertilizer application for the remainder of the 2018 to 2022 time series and then used to estimate emissions. For drainage of organic soils, the methods described above are applied for 1990 to 2020, and a linear extrapolation method is used to approximate emissions for the remainder of the 2021 to 2022 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 2020 emissions data, which is a standard data splicing method for imputing missing emissions data in a time series (IPCC 2006). The time series will be recalculated in a future *Inventory* with the methods described previously for drainage of organic soils.

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 these variables, except variation in the total amount of fertilizer N and biosolids application, which 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.[98] For emissions from drained organic soils, the total uncertainty was quantified with two variance components (Ogle et al. 2010) that 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. The first variance component is associated with uncertainty in the emission factor, and the second variance component is associated with scaling of the data from the NRI survey to the entire area of drained organic soils in settlements remaining settlements, and is computed using a standard variance estimator for a two-stage sample design (Särndal et al. 1992). There is also additional uncertainty associated with the fit of the linear regression model for the data splicing methods that was incorporated into the analysis for the latter part of the time series.

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 6-130. Direct N_2O emissions from soils in settlements remaining settlements in 2022 are estimated to be between 1.2 and 3.4 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 47 percent below to 54 percent above the 2022 emission estimate of 2.2 MMT CO_2 Eq. Indirect N_2O emissions in 2022 are between 0.1 and 1.1 MMT CO_2 Eq., ranging from 76 percent below to 218 percent above the estimate of 0.3 MMT CO_2 Eq.

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[98] 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.

Table 6-130: Quantitative Uncertainty Estimates of N_2O Emissions from Soils in Settlements Remaining Settlements (MMT CO_2 Eq. and Percent)

Source	Gas	2022 Emissions (MMT CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (MMT CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Settlements Remaining Settlements						
Direct N_2O Emissions from Soils	N_2O	2.2	1.2	3.4	-47%	+54%
Indirect N_2O Emissions from Soils	N_2O	0.3	0.1	1.1	-76%	+218%

[a] Range of emission estimates is 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 initial calculations for emissions from drained organic soils, which was corrected.

Recalculations Discussion

Recalculations are associated with updated land areas for drainage of organic soils in settlements remaining settlements, by incorporating new USDA-NRCS NRI data through 2017 and extending the time series using CDL and NLCD for grassland converted to settlements, cropland converted to settlements, other land converted to settlements and wetlands converted to settlements. In addition, recalculations are associated with revised fertilizer application data from the AAPFCO report. As a result of these changes, CO_2-equivalent emissions changed annually with an average annual increase of 0.36 MMT CO_2 Eq., or 17 percent, over the time series from 1990 to 2021 compared to the previous *Inventory*.

Planned Improvements

This source will be extended to include soil N_2O emissions from drainage of organic soils in Alaska and federal lands in order to provide a complete inventory of emissions for this category. Data on fertilizer amounts from 2018 to 2022 will be updated after data are released for the latter part of the time series. These improvements will be incorporated into a future I*nventory*, pending prioritization of resources.

Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (CRT 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. A portion of the carbon 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, carbon stock changes in yard trimmings and food scraps are reported under settlements remaining settlements because the bulk of the carbon, 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 carbon stock changes that occur entirely within landfills fits most appropriately within the settlements remaining settlements section. The CH_4 emissions resulting from anaerobic decomposition of yard trimmings and food scraps in landfills are reported in the Waste chapter, see Section 7.1—landfills.

The estimated amount of yard trimmings collected annually has stagnated since 1990 and the fraction that is landfilled has been declining since 1990. From 1970 to 1990, yard trimmings collected for disposal increased by about 51 percent. 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 in landfills have led to an increase in backyard composting and the use of mulching mowers, and consequently a slowing of year-over-year increases in the tonnage of yard trimmings generated. From 1990 to 2022, yard trimmings collected for disposal are estimated to have increased 1.1. percent. 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 2022. 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. Composting trends and emissions estimations are presented in the Waste chapter, Section 7.3 composting.

Food scrap generation has grown by an estimated 165 percent since 1990. Though 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 2022, the difference in the amount of food scraps added from one year to the next generally decreased, and consequently the annual *net changes* in carbon stock from food scraps have generally decreased as well (as shown in Table 6-131 and Table 6-132). Landfilled 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 decreasing annual changes 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 the annual net change in landfill carbon storage from 24.5 MMT CO_2 Eq. (6.7 MMT C) in 1990 to 11.8 MMT CO_2 Eq. (3.2 MMT C) in 2022 (Table 6-131 and Table 6-132), a decrease of 48 percent over the time series.

Table 6-131: Net Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (MMT CO_2 Eq.)

Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Yard Trimmings	**(20.1)**	**(7.5)**	**(8.3)**	**(8.2)**	**(8.2)**	**(8.2)**	**(8.1)**
Grass	(1.7)	(0.6)	(0.8)	(0.8)	(0.8)	(0.8)	(0.7)
Leaves	(8.7)	(3.4)	(3.8)	(3.8)	(3.8)	(3.8)	(3.7)
Branches	(9.8)	(3.4)	(3.7)	(3.7)	(3.7)	(3.7)	(3.6)
Food Scraps	**(4.4)**	**(3.9)**	**(5.2)**	**(4.8)**	**(4.5)**	**(4.3)**	**(3.7)**
Total Net Flux	**(24.5)**	**(11.4)**	**(13.4)**	**(13.1)**	**(12.8)**	**(12.5)**	**(11.8)**

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

Table 6-132: Net Changes in Yard Trimmings and Food Scrap Carbon Stocks in Landfills (MMT C)

Carbon Pool	1990	2005	2018	2019	2020	2021	2022
Yard Trimmings	**(5.5)**	**(2.0)**	**(2.3)**	**(2.2)**	**(2.2)**	**(2.2)**	**(2.2)**
Grass	(0.5)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)	(0.2)
Leaves	(2.4)	(0.9)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)
Branches	(2.7)	(0.9)	(1.0)	(1.0)	(1.0)	(1.0)	(1.0)
Food Scraps	**(1.2)**	**(1.1)**	**(1.4)**	**(1.3)**	**(1.2)**	**(1.2)**	**(1.0)**
Total Net Flux	**(6.7)**	**(3.1)**	**(3.7)**	**(3.6)**	**(3.5)**	**(3.4)**	**(3.2)**

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 carbon that remains is effectively removed from the carbon 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 carbon in landfills can increase, with the net effect being removal of carbon from the atmosphere. Estimates of the net carbon flux resulting from landfilled yard trimmings and food scraps were developed by estimating the change in landfilled carbon stocks between inventory years and uses a country-specific methodology based on the methodology for estimating the amount of harvested wood products stored in solid waste disposal systems that is provided in 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 carbon resulting from yard trimmings and food scraps discarded in a given year; adding the accumulated landfilled carbon from previous years; and subtracting the mass of carbon that was landfilled in previous years and has since decomposed and been emitted as CO_2 and CH_4.

To determine the total landfilled carbon stocks for a given year, the following data and factors were assembled:

(1) The composition of the yard trimmings (i.e., the proportion of grass, leaves and branches);

(2) The mass of yard trimmings and food scraps discarded in landfills;

(3) The carbon storage factor of the landfilled yard trimmings and food scraps; and

(4) The rate of decomposition of the degradable carbon.

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 carbon storage factor (i.e., based on differences in moisture content and carbon 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 through 2022 were unavailable, landfilled material generation, recovery, and disposal data for 2019 through 2022 were proxied equal to 2018 values.

The amount of carbon 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) carbon 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 carbon contents and the carbon storage factors were determined by Barlaz (1998, 2005, 2008).

The amount of carbon remaining in the landfill for each subsequent year was tracked based on a simple model of carbon fate based on a laboratory experiment simulating decomposition of landfilled biogenic materials by methanogenic microbes (Barlaz 1998, 2005, 2008). Carbon remaining in landfilled materials is expressed as a proportion of initial carbon content, shown in the row labeled "C Storage Factor, Proportion of Initial C Stored (%)" in Table 6-133.

The modeling approach applied to simulate U.S. landfill carbon flows builds on the findings of Barlaz (1998, 2005, 2008). The proportion of carbon 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.[99] The degradable portion of the carbon is assumed to decay according to first-order kinetics. The decay rates for each of the materials are shown in Table 6-133.

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 municipal solid waste (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-related 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 the Waste chapter, Section 7.1 landfills. The component-specific decay rates are shown in Table 6-133.

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

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[99] The CH_4 emissions resulting from anaerobic decomposition of yard trimmings and food scraps in landfills are reported in the Waste chapter, Section 7.1—Landfills.

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 carbon in landfills for any given year is calculated according to Equation 6-2:

Equation 6-2: Total Carbon Stock for Yard Trimmings and Food Scraps in Landfills

$$LFC_{i,t} = \sum_{n}^{t} W_{i,n} \times (1 - MC_i) \times ICC_i \times \left\{[CS_i \times ICC_i] + \left[\left(1 - (CS_i \times ICC_i)\right) \times e^{-k(t-n)}\right]\right\}$$

where,

t = Year for which carbon stocks are being estimated (year),

i = Waste type for which carbon stocks are being estimated (grass, leaves, branches, food scraps),

$LFC_{i,t}$ = Stock of carbon 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 carbon that is stored for waste i (percent),

ICC_i = Initial carbon 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 carbon in landfills ($TLFC_t$) is the sum of stocks across all four materials (grass, leaves, branches, food scraps). The annual flux of carbon in landfills (F_t) for year t is calculated in as the change in carbon stock compared to the preceding year according to Equation 6-3:

Equation 6-3: Carbon Stock Annual Flux for Yard Trimmings and Food Scraps in Landfills

$$F_t = TLFC_t - TLFC_{(t-1)}$$

Thus, as seen in Equation 6-2, the carbon 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 carbon 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 2022, the total food scraps carbon originally disposed of in 1960 had declined to 179,000 metric tons (i.e., virtually all degradable carbon had decomposed). By summing the carbon remaining from 1960 with the carbon remaining from food scraps disposed of in subsequent years (1961 through 2021), the total landfill carbon from food scraps in 2022 was 53.0 million metric tons. This value is then added to the carbon stock from grass, leaves, and branches to calculate the total landfill carbon stock in 2022, yielding a value of 292.6 million metric tons (as shown in Table 6-134). In the same way total net flux is calculated for forest carbon and harvested wood products, the total net flux of landfill carbon for yard trimmings and food scraps for a given year (Table 6-132) is the difference in the landfill carbon stock for the following year and the stock in the current year. For example, the net change in 2022 shown in Table 6-132 (3.2 MMT C with rounding) is equal to the stock in 2023

(295.9 MMT C) minus the stock in 2022 (292.6 MMT C). The carbon stocks calculated through this procedure are shown in Table 6-134.

To develop the 2023 carbon stock estimate, estimates of yard trimming and food scrap carbon stocks were forecasted for 2023, based on data from 1990 through 2022. These forecasted values were used to calculate net changes in carbon stocks for 2022. Excel's FORECAST.ETS function was used to predict a 2023 value using historical data via an algorithm called "Exponential Triple Smoothing." This method determined the overall trend and provided appropriate carbon stock estimates for 2023.

Table 6-133: Moisture Contents, Carbon Storage Factors (Proportions of Initial Carbon 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 6-134: Carbon Stocks in Yard Trimmings and Food Scraps in Landfills (MMT C)

Carbon Pool	1990	2005	2018	2019	2020	2021	2022	2023
Yard Trimmings	**156.0**	**203.1**	**231.6**	**233.9**	**236.1**	**238.4**	**240.6**	**242.8**
Branches	14.6	18.1	20.7	20.9	21.1	21.3	21.6	21.8
Leaves	66.7	87.4	100.4	101.5	102.5	103.6	104.6	105.6
Grass	74.7	97.7	110.5	111.5	112.5	113.5	114.5	115.4
Food Scraps	**17.9**	**33.2**	**46.9**	**48.3**	**49.6**	**50.9**	**52.0**	**53.0**
Total Carbon Stocks	**173.9**	**236.3**	**278.5**	**282.2**	**285.7**	**289.2**	**292.6**	**295.9**

[a] 2023 C stock estimate was forecasted using 1990 to 2022 data.
Note: Totals may not sum due to independent rounding.

Methodological recalculations were applied to the entire time series to ensure time-series consistency from 1990 through 2022. When available, the same data source was used across the entire time series for the analysis. 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 carbon), initial carbon content, moisture content, decay rate, and proportion of carbon stored. The carbon 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 2022. The results of the Approach 2 quantitative uncertainty analysis are summarized in Table 6-135. Total yard trimmings and food scraps CO_2 flux in 2022 was estimated to be between -17.3 and -4.9 MMT CO_2 Eq. at a 95 percent confidence level. This indicates a range of 47 percent below to 58 percent above the 2022 flux estimate of -11.8 MMT CO_2 Eq.

Table 6-135: 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	2021 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	(11.8)	(17.3)	(4.9)	-47%	58%

[a] Range of flux estimates predicted by Monte Carlo stochastic simulation for a 95 percent confidence interval.
Note: Parentheses indicate negative values or net carbon 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.

To ensure consistency across the LULUCF and Waste sectors, and the accuracy of emissions, EPA plans to perform a comparison of the activity data used and carbon inputs between the landfilled yard trimmings and food scraps, and the Waste chapter, Section 7.1—Landfills categories.

Recalculations Discussion

No recalculations were performed for the current *Inventory*.

Planned Improvements

EPA notes the following improvements may be implemented or investigated within the next two or three *Inventory* cycles pending time and resource constraints:

- MSW data more recent than 2018 have not been released through the *Advancing Sustainable Materials Management* reports. EPA will monitor the release schedule for these data and evaluate data for integration into the *Inventory* when released. Six new food waste management pathways were introduced in the 2018 *Advancing Sustainable Materials Management* report. Time series data for all of these pathways are not provided prior to 2018 but EPA plans to investigate potential data sources and/or methods to address time-series consistency and apply these data to the time series.
- EPA has been made aware of inconsistencies in landfilled food scraps data reported to the EPA Greenhouse Gas Reporting Program (GHGRP) and will evaluate changes to how landfilled and energy recovery values for yard trimmings and food scraps are calculated.

EPA notes the following improvements will continue to be investigated as time and resources allow, but there are no immediate plans to implement these improvements until data are available or identified:

- EPA also plans to continue 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 population and climate data changes over time. Currently the inventory calculations use 2010 U.S. Census data, but 2020 U.S. Census data may be available.

- 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.
- EPA will continue to evaluate data from recent peer-reviewed literature that may modify the default carbon storage factors, initial carbon contents, and decay rates for yard trimmings and food scraps in landfills – particularly updates to population precipitation ranges used to calculate k values. Based upon this evaluation, changes may be made to the default values.
- Finally, EPA plans to review available data to ensure all types of landfilled yard trimmings and food scraps are being included in the *Inventory* estimates, such as debris from road construction and commercial food waste not included in other *Inventory* estimates.

6.11 Land Converted to Settlements (CRT 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).[100] 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).

Land use change can lead to large losses of carbon 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 (Tubiello et al. 2015). IPCC (2006) recommends reporting changes in biomass, dead organic matter, and soil organic carbon stocks due to land-use change. All soil organic carbon 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 carbon are reported for forest land converted to settlements and woodlands associated with grasslands converted to settlements, but not for other land-use conversions to settlements.

There are discrepancies between the current land representation (see Section 6.1) and the area data that have been used in the *Inventory* for land converted to settlements. Specifically, this *Inventory* includes all settlements in the conterminous United States and Hawaii, but does not include settlements in Alaska. Areas of drained organic soils in settlements on federal lands are also not included in this *Inventory.* These differences lead to discrepancies between the managed area in land converted to settlements and the settlement area included in the inventory analysis (Table 6-129). 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* (see Planned Improvements section).

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[100] 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.

Forest land converted to settlements is the largest source of emissions from 1990 to 2022, accounting for approximately 76 percent of the average total loss of carbon among all of the land-use conversions in Land Converted to Settlements. Total losses of aboveground and belowground biomass, dead wood and litter carbon losses in 2022 for all conversions are 35.6, 6.2, 6.7, and 9.2 MMT CO_2 Eq., respectively (9.7, 1.7, 1.8, and 2.5 MMT C). Mineral and organic soils also lost 9.2 and 1.3 MMT CO_2 Eq. in 2022 (2.5 and 0.3 MMT C). The total net flux is 68.2 MMT CO_2 Eq. in 2022 (18.6 MMT C), which is a 19 percent increase in CO_2 emissions compared to the emissions in the initial reporting year of 1990 (Table 6-136 and Table 6-137). 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 carbon.

Table 6-136: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes for Land Converted to Settlements (MMT CO_2 Eq.)

	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Settlements	**2.6**	**8.2**	**3.9**	**3.5**	**3.1**	**2.9**	**2.9**
Mineral Soils	2.1	6.9	3.4	2.9	2.6	2.5	2.5
Organic Soils	0.5	1.2	0.6	0.5	0.4	0.4	0.4
Forest Land Converted to Settlements	**49.3**	**53.9**	**58.4**	**58.6**	**58.6**	**58.6**	**58.6**
Aboveground Live Biomass	30.0	32.4	35.0	35.2	35.2	35.2	35.2
Belowground Live Biomass	5.2	5.6	6.1	6.1	6.1	6.1	6.1
Dead Wood	5.5	6.0	6.5	6.6	6.6	6.6	6.6
Litter	7.6	8.2	9.0	9.0	9.0	9.0	9.0
Mineral Soils	1.0	1.5	1.5	1.5	1.5	1.5	1.5
Organic Soils	0.1	0.2	0.2	0.2	0.3	0.3	0.3
Grassland Converted to Settlements	**5.6**	**15.8**	**9.8**	**8.8**	**7.9**	**7.4**	**7.5**
Aboveground Live Biomass	0.4	0.4	0.5	0.5	0.5	0.5	0.5
Belowground Live Biomass	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Dead Wood	0.1	0.1	0.2	0.2	0.2	0.2	0.2
Litter	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Mineral Soils	4.3	13.7	8.2	7.3	6.5	6.0	6.0
Organic Soils	0.5	1.3	0.7	0.6	0.5	0.5	0.6
Other Lands Converted to Settlements	**(0.4)**	**(1.4)**	**(1.1)**	**(1.0)**	**(0.8)**	**(0.8)**	**(0.8)**
Mineral Soils	(0.4)	(1.5)	(1.1)	(1.0)	(0.9)	(0.8)	(0.8)
Organic Soils	+	0.1	+	+	+	+	+
Wetlands Converted to Settlements	**+**	**0.6**	**0.3**	**0.3**	**0.1**	+	**0.1**
Mineral Soils	+	0.1	+	+	+	+	+
Organic Soils	+	0.6	0.3	0.3	+	+	+
Total Aboveground Biomass Flux	**30.4**	**32.8**	**35.5**	**35.6**	**35.6**	**35.6**	**35.6**
Total Belowground Biomass Flux	**5.2**	**5.7**	**6.1**	**6.2**	**6.2**	**6.2**	**6.2**
Total Dead Wood Flux	**5.6**	**6.1**	**6.7**	**6.7**	**6.7**	**6.7**	**6.7**
Total Litter Flux	**7.7**	**8.4**	**9.2**	**9.2**	**9.2**	**9.2**	**9.2**
Total Mineral Soil Flux	**7.0**	**20.7**	**12.0**	**10.8**	**9.8**	**9.2**	**9.2**
Total Organic Soil Flux	**1.2**	**3.4**	**1.8**	**1.6**	**1.3**	**1.2**	**1.3**
Total Net Flux	**57.2**	**77.1**	**71.4**	**70.2**	**68.8**	**68.2**	**68.2**

+ 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 6-137: Net CO_2 Flux from Soil, Dead Organic Matter and Biomass Carbon Stock Changes for Land Converted to Settlements (MMT C)

	1990	2005	2018	2019	2020	2021	2022
Cropland Converted to Settlements	**0.7**	**2.2**	**1.1**	**1.0**	**0.8**	**0.8**	**0.8**
Mineral Soils	0.6	1.9	0.9	0.8	0.7	0.7	0.7
Organic Soils	0.1	0.3	0.2	0.1	0.1	0.1	0.1
Forest Land Converted to Settlements	**13.5**	**14.7**	**15.9**	**16.0**	**16.0**	**16.0**	**16.0**

Aboveground Live Biomass	8.2	8.8	9.6	9.6	9.6	9.6	9.6
Belowground Live Biomass	1.4	1.5	1.7	1.7	1.7	1.7	1.7
Dead Wood	1.5	1.6	1.8	1.8	1.8	1.8	1.8
Litter	2.1	2.2	2.5	2.5	2.5	2.5	2.5
Mineral Soils	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Organic Soils	+	0.1	0.1	0.1	0.1	0.1	0.1
Grassland Converted to Settlements	**1.5**	**4.3**	**2.7**	**2.4**	**2.2**	**2.0**	**2.0**
Aboveground Live Biomass	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Belowground Live Biomass	+	+	+	+	+	+	+
Dead Wood	+	+	+	+	+	+	+
Litter	+	+	0.1	0.1	0.1	0.1	0.1
Mineral Soils	1.2	3.7	2.2	2.0	1.8	1.6	1.6
Organic Soils	0.1	0.3	0.2	0.2	0.1	0.1	0.2
Other Lands Converted to Settlements	**(0.1)**	**(0.4)**	**(0.3)**	**(0.3)**	**(0.2)**	**(0.2)**	**(0.2)**
Mineral Soils	(0.1)	(0.4)	(0.3)	(0.3)	(0.2)	(0.2)	(0.2)
Organic Soils	+	+	+	+	+	+	+
Wetlands Converted to Settlements	**+**	**0.2**	**0.1**	**0.1**	+	+	+
Mineral Soils	+	+	+	+	+	+	+
Organic Soils	+	0.2	0.1	0.1	+	+	+
Total Aboveground Biomass Flux	**8.3**	**8.9**	**9.7**	**9.7**	**9.7**	**9.7**	**9.7**
Total Belowground Biomass Flux	**1.4**	**1.5**	**1.7**	**1.7**	**1.7**	**1.7**	**1.7**
Total Dead Wood Flux	**1.5**	**1.7**	**1.8**	**1.8**	**1.8**	**1.8**	**1.8**
Total Litter Flux	**2.1**	**2.3**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**
Total Mineral Soil Flux	**1.9**	**5.6**	**3.3**	**2.9**	**2.7**	**2.5**	**2.5**
Total Organic Soil Flux	**0.3**	**0.9**	**0.5**	**0.4**	**0.4**	**0.3**	**0.3**
Total Net Flux	**15.6**	**21.0**	**19.5**	**19.1**	**18.8**	**18.6**	**18.6**

+ 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 carbon stock changes for land converted to settlements, including (1) loss of aboveground and belowground biomass, dead wood and litter carbon with conversion to settlements from forest lands and woodlands designated in the grassland, as well as (2) the impact from all land-use conversions to settlements on soil organic carbon 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 carbonstock 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 2023) however there is no country-specific data for settlements so the biomass, litter, and dead wood carbon stocks 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. Details for each of the carbon attributes described below are available in Domke et al. (2022) and Westfall et al. (2023).

If FIA plots include data on individual trees, aboveground and belowground carbon density estimates are based on Woodall et al. (2011) and Westfall et al. (2023). 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 carbon mass is belowground (Smith et al. 2006). Estimates of carbon 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 carbon density is estimated following the basic method applied to live trees (Woodall et al. 2011 and Westfall et al. 2023) with additional modifications for woodland species 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 carbon 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 carbon 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 carbon is the pool of organic carbon (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 carbon. If FIA plots include litter material, a modeling approach using litter carbon measurements from FIA plots is used to estimate litter carbon 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 carbon density estimates for forest land and the compilation system used to estimate carbon stock changes from forest land.

Soil Carbon Stock Changes

Soil organic carbon stock changes are estimated for land converted to settlements according to land use histories recorded in the 2017 USDA NRI survey for non-federal lands (USDA-NRCS 2020) and extended through 2020 using the USDA-NASS Crop Data Layer Product (USDA-NASS 2021; Johnson and Mueller 2010) and National Land Cover Dataset (NLCD) (Yang et al. 2018; Fry et al. 2011; Homer et al. 2007, 2015)). For federal lands, the land use history is derived from land cover changes in the NLCD. The areas have been modified through a process in which the Forest Inventory and Analysis (FIA) survey data are harmonized with the NRI data (Nelson et al. 2020). This process ensures that the land use areas are consistent across all land use categories (see Section 6.1 Representation of the U.S. Land Base for more information). 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 have been incorporated from the NRI into the inventory analysis through 2017 (USDA-NRCS 2020).

NRI survey locations are classified as land converted to settlements in a given year between 1990 and 2020 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.

Soil Carbon Stock Changes for Mineral Soils

An IPCC Tier 2 method (Ogle et al. 2003) is applied to estimate carbon stock changes for mineral soils on land converted to settlements from 1990 to 2020. 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 carbon 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 carbon stock change factors are derived from published literature to determine the impact of management practices on soil organic carbon 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 2017 NRI survey data (USDA-NRCS 2020) 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 carbon with conversion to settlements under the assumption that there are additional soil organic carbon 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 2020 so that changes reflect anthropogenic activity and not methodological adjustments. Soil organic carbon stock changes from 2021 to 2022 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 2020 emissions data, which is a standard data splicing method for imputing missing emissions data in a time series (IPCC 2006). The Tier 2 method described previously will be applied to recalculate the 2021 to 2022 emissions in a future *Inventory*.

Soil Carbon Stock Changes for Organic Soils

Annual carbon 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 carbon 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 2020, 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 2020, and a linear extrapolation method is used to approximate emissions for the remainder of the 2021 to 2022 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 2020 emissions data, and is a standard data splicing method for imputing missing emissions data in a time series (IPCC 2006). Estimates will be recalculated in future *Inventories* when new activity data are incorporated into the analysis.

Uncertainty

The uncertainty analysis for carbon losses with forest land converted to settlements is conducted in the same way as the uncertainty assessment for forest ecosystem carbon 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.

Sources of uncertainty for mineral soil organic carbon stock changes and annual carbon emission estimates from drained organic soils include emission factors and variance associated with the NRI sample. The total uncertainty was quantified with two variance components (Ogle et al. 2010) that 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 the first variance component, a Monte Carlo analysis was used to propagate uncertainties in the Tier 2 methods for the land use area and the country-specific factors or mineral and organic soils. The second variance component is associated with scaling of the data from the NRI survey to the entire area of land converted to settlements, and is computed using a standard variance estimator for a two-stage sample design (Särndal et al. 1992).

Uncertainty estimates are presented in Table 6-138 for each sub-source (i.e., biomass carbon, dead wood, litter, soil organic carbon in mineral soils and organic soils) and the method applied in the inventory analysis (i.e., Tier 2 and Tier 3). Uncertainty estimates are combined from the forest land converted to settlements and other land use conversions to settlements using the simple error propagation methods provided by the IPCC (2006). There are also additional uncertainties propagated through the analysis associated with the data splicing methods applied to estimate soil organic carbon stock changes from 2021 to 2022. The combined uncertainty for total carbon stock changes in land converted to settlements ranges from 36 percent below to 36 percent above the 2022 stock change estimate of 68.2 MMT CO_2 Eq.

Table 6-138: Approach 2 Quantitative Uncertainty Estimates for Soil, Dead Organic Matter and Biomass Carbon Stock Changes occurring within Land Converted to Settlements (MMT CO_2 Eq. and Percent)

Source	2022 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	**2.9**	**1.3**	**4.5**	**-56%**	**56%**
Mineral Soil C Stocks	2.5	0.9	4.1	-64%	63%
Federal Mineral Soil C Stocks	0.0	(0.0)	0.0	-146%	146%
Organic Soil C Stocks	0.4	0.1	0.7	-80%	80%
Forest Land Converted to Settlements	**58.6**	**35.3**	**81.9**	**-40%**	**40%**
Aboveground Biomass C Stocks	35.2	13.3	57.1	-62%	62%
Belowground Biomass C Stocks	6.1	2.3	9.9	-62%	62%
Dead Wood	6.6	2.5	10.6	-62%	62%
Litter	9.0	3.4	14.7	-62%	62%
Mineral Soil C Stocks	1.5	1.2	1.7	-19%	19%
Federal Mineral Soil C Stocks	0.0	0.0	0.0	0%	0%
Organic Soil C Stocks	0.3	0.1	0.4	-70%	70%
Grassland Converted to Settlements	**7.4**	**5.4**	**9.5**	**-27%**	**27%**
Aboveground Biomass C Stocks	0.5	0.2	0.8	-62%	60%
Belowground Biomass C Stocks	0.1	0.0	0.1	-45%	66%
Dead Wood	0.2	0.1	0.3	-51%	70%
Litter	0.2	0.1	0.3	-61%	57%
Mineral Soil C Stocks	6.0	4.1	7.9	-32%	32%
Federal Mineral Soil C Stocks	0.0	(0.0)	0.0	-194%	194%
Organic Soil C Stocks	0.5	(0.0)	1.1	-108%	108%
Other Lands Converted to Settlements	**-0.8**	**(1.1)**	**(0.4)**	**-44%**	**44%**
Mineral Soil C Stocks	-0.8	(1.1)	(0.5)	-38%	38%
Federal Mineral Soil C Stocks	0.0	(0.2)	0.1	-738%	738%
Organic Soil C Stocks	0.0	(0.1)	0.1	-511%	511%
Wetlands Converted to Settlements	**0.1**	**(0.3)**	**0.3**	**-557%**	**533%**
Mineral Soil C Stocks	0.0	0.0	0.1	-69%	69%
Federal Mineral Soil C Stocks	0.0	0.0	0.0	0%	0%
Organic Soil C Stocks	0.0	(0.3)	0.3	-1,269%	1,214%
Total: Land Converted to Settlements	**68.2**	**43.5**	**92.9**	**-36%**	**36%**
Aboveground Biomass C Stocks	**35.6**	**13.3**	**57.1**	**-62%**	**62%**
Belowground Biomass C Stocks	**6.2**	**2.3**	**9.9**	**-62%**	**62%**
Dead Wood	**6.7**	**2.5**	**10.6**	**-62%**	**62%**
Litter	**9.2**	**3.4**	**14.7**	**-62%**	**62%**
Mineral Soil C Stocks	**9.2**	**6.6**	**11.7**	**-28%**	**28%**
Organic Soil C Stocks	**1.2**	**(6.6)**	**9.1**	**-625%**	**625%**

+ Does not exceed 0.05 MMT CO_2 Eq.

[a] Range of C stock change estimates is 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 2022 on biomass, dead wood and litter carbon stocks in forest land converted to settlements and woodland conversion associated with grassland converted to settlements. Additional recalculations are associated with incorporating new USDA-NRCS NRI data through 2017 and extending the time series using CDL and NLCD for grassland converted to settlements, cropland converted to settlements, other land converted to settlements and wetlands converted to settlements. As a result, land converted to settlements has an estimated smaller carbon loss of 7.7 MMT CO_2 Eq. on average over the time series. This represents a 19 percent decrease in carbon stock changes for land converted to settlements compared to the previous *Inventory.*

Planned Improvements

A key improvement is to develop an inventory of mineral soil organic carbon stock changes in Alaska and losses of carbon from drained organic soils in federal lands. These improvements will resolve most of the differences between the managed land base for land converted to settlements and amount of area currently included in the *Inventory* for land converted to settlements (see Table 6-139).

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 carbon losses associated with drained organic soils in settlements occurring on federal lands.

These improvements will be made pending prioritization of resources to expand the inventory for this source category.

Table 6-139: Area of Managed Land in Land Converted to 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	2,865	2,865	1
1991	3,213	3,213	1
1992	3,573	3,573	1
1993	4,138	4,138	1
1994	4,703	4,702	1
1995	5,262	5,261	1
1996	5,833	5,832	1
1997	6,409	6,408	1
1998	6,929	6,928	1
1999	7,446	7,446	1
2000	7,952	7,952	1
2001	8,362	8,361	1
2002	8,696	8,695	1
2003	8,705	8,704	1
2004	8,710	8,708	2

2005	8,727	8,724	2
2006	8,691	8,688	3
2007	8,672	8,668	3
2008	8,501	8,497	4
2009	8,309	8,305	5
2010	8,130	8,124	5
2011	7,930	7,925	6
2012	7,717	7,711	6
2013	7,325	7,318	6
2014	6,942	6,935	7
2015	6,530	6,523	7
2016	6,112	6,105	7
2017	5,715	5,708	7
2018	5,201	5,194	7
2019	4,696	4,689	7
2020	4,175	4,168	7
2021	3,771	*	*
2022	3,437	*	*

NRI data have not been incorporated into the *Inventory* after 2020, designated with asterisks (*).

6.12 Other Land Remaining Other Land (CRT 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 carbon pools in this land use. Until such time that reliable and comprehensive estimates of carbon 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 (CRT 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 carbon across other land remaining other land and land converted to other land. Until such time that reliable and comprehensive estimates of carbon 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.