Chapter 7
Quantifying Greenhouse Gas Sources and Sinks From Land-Use Change

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Acronyms, Chemical Formulae, and Units

C	carbon
CH_4	methane
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalents
DOM	Dead organic matter
GHG	greenhouse gas
ha	hectare
IPCC	Intergovernmental Panel on Climate Change
N_2O	nitrous oxide
PRISM	Parameter-Elevation Regressions on Independent Slopes Model
SOC	soil organic carbon
SSURGO	Soil Survey Geographic Database
USDA	U.S. Department of Agriculture
U.S. EPA	U.S. Environmental Protection Agency

7. Quantifying Greenhouse Gas Sources and Sinks From Land-Use Change

This chapter provides methodologies and guidance on estimating the net greenhouse gas (GHG) flux resulting from changes between land-use types—i.e., conversions into and out of cropland, wetland, grazing land, or forestland—at the entity scale:

- Section 7.1 provides a brief overview of land use.
- Section 7.2 provides the methods for estimating emissions or annual carbon stock changes for land-use change.

The appendixes that accompany this chapter are:

- Appendix 7-A provides the rationale for the methods.

Table 7-1 describes the sources covered in this chapter, along with the corresponding GHGs. As needed, refer to chapter 2 for land use background or definitions.

Table 7-1. Overview of Land-Use Change Sources and Associated GHGs

Section	Source	Method for GHG Estimation			Description
		CO_2	N_2O	CH_4	
7.2.1	Annual change in biomass carbon stocks due to land conversion	✓			Live biomass carbon stocks constitute a significant carbon sink in many forest and some agricultural lands.
7.2.2	Annual change in carbon stocks in dead wood and litter due to land conversion	✓			Dead organic matter (DOM) carbon stocks occur in dead wood and litter, and may constitute a significant carbon sink, particularly in forest lands.
7.2.3	Change in SOC stocks for mineral soils and organic soils due to land use conversion	✓			Soil organic carbon (SOC) stocks are influenced by land-use change (Aalde et al., 2006). The most significant changes in SOC occur with land-use conversions to croplands, due to changes in the disturbance regimes and associated effects on soil aggregate dynamics (Six et al., 2000), or due to drainage of the soil if previous land use was a wetland.

7.1 Overview

In many cases, the methods for estimating GHG flux resulting from land-use change are the same as those used to estimate carbon stock changes in the chapters on cropland and grazing land, forestry, and wetlands (chapters 3, 5, and 6 respectively). This chapter provides additional guidance on those methods and, in some cases, this chapter also provides guidance on reconciling carbon stock estimates between discrete data sets and estimation methods (e.g., reconciling forest soil carbon estimates and cropland soil carbon estimates for land-use change from forest land to cropland). Table 7-2 presents the methodologies for each source and indicates their section.

Table 7-2. Overview of Land-Use Change Sources, Methods, and Sections

Section	Source	Proposed Method
7.2.1	Annual change in carbon stocks in biomass due to land conversion	The change in carbon stocks in biomass due to land conversion is estimated as the difference in carbon stocks in the current and previous land-use categories applied in the year of the conversion (carbon losses) or distributed uniformly over the transition period (carbon gains) (Aalde et al., 2006).
7.2.1	Annual change in carbon stocks in dead wood and litter due to land conversion	The change in carbon stocks in dead wood and litter due to land conversion is estimated as the difference in carbon stocks in the current and previous land-use categories applied in the year of the conversion (carbon losses) or distributed uniformly over the transition period (carbon gains) (Aalde et al., 2006).
7.2.3	Change in SOC stocks for mineral soils	The methodologies to estimate soil carbon stock changes for organic soils and mineral soils are adopted from methods created by the Intergovernmental Panel on Climate Change, or IPCC (Ogle et al., 2019a).

7.2 Estimation Methods

The methods provided in this chapter are strictly for portions of an entity's operation that have undergone a land-use change during the 20 years before the reporting year. The reporting convention is that all carbon stock changes associated with a land-use change are reported in the new land-use category. For example, in the case of conversion of forest land to cropland, both the initial carbon stock changes associated with the clearing of the forest and any subsequent carbon stock changes that result after the conversion are reported under cropland for 20 years following the conversion (IPCC, 2006).

As shown in equation 7-1, the change in C stocks associated with land-use change on a land parcel is the sum of the carbon stock changes in the individual pools, including biomass, DOM, and SOC.

Equation 7-1: Annual Carbon Stock Changes for a Land-Use Change as a Sum of Changes in Each Carbon Pool

$$\Delta C_{LUC_{PQ}} = (\Delta C_{Biomass_{PQ}} + \Delta C_{DOM_{PQ}} + \Delta C_{SOC_{PQ}}) \times CO_2MW$$

Where:

$\Delta C_{LUC_{PQ}}$ = carbon stock changes for land-use change from previous land use P to current land use Q (metric tons CO_2-eq/year)

$\Delta C_{Biomass_{PQ}}$ = annual change in biomass carbon stocks for land-use change from previous land use P to current land use Q (metric tons C/year)

$\Delta C_{DOM_{PQ}}$ = annual change in carbon stocks in dead wood or litter for land-use change from previous land use P to current land use Q (metric tons C/year)

$\Delta C_{SOC_{PQ}}$ = annual change in carbon stocks in soil organic carbon for land-use change from previous land use P to current land use Q (metric tons C/year)

CO_2MW = ratio of molecular weight of CO_2 to C = 44/12 (metric tons CO_2/metric tons C)

PQ = change from previous land use P to current land use Q (e.g., forest land converted to cropland, where forest land is the previous land-use category and cropland is the current land-use category)

In the case of conversion of forest land to cropland or grazing land, assess the carbon stock changes associated with each of the forest carbon pools plus harvested wood products.

7.2.1 Carbon Pools in Biomass

Method for Estimating Carbon Pools in Biomass

- The change in carbon stocks in live biomass due to land conversion is estimated as the difference in carbon stocks in the previous and current land-use categories applied in the year of the conversion (for biomass carbon losses) or distributed uniformly over the length of the transition period (for soil carbon stock changes and biomass carbon gains after the land use change).

7.2.1.1 Description of Method

Live biomass constitutes a significant carbon pool in many forests, and in some croplands and grazing lands. Following land-use conversion, use the sector-specific methods for estimating the biomass carbon stocks—detailed in the individual sector chapters—when estimating the previous and current biomass C stocks.

Equation 7-2 provides the conceptual approach to estimating changes in carbon stocks in biomass carbon pools (adapted from Aalde et al., 2006). Estimate the difference in biomass carbon stocks in the previous and current land use categories that occur at the time of the conversion ($\Delta C_{conversion}$), and also additional annual changes in biomass C stocks that occur in the current land use over the 20 years following conversion.

Equation 7-2: Annual Change in Carbon Stocks in Biomass Due to Land Conversion

$$\Delta C_{Biomass_{PQ}} = \left(\Delta C_{Biomass_Q} + \Delta C_{conversion_{PQ}}\right) \times A \div T$$

Where:

$\Delta C_{Biomass_{PQ}}$ = annual change in biomass carbon stocks for land-use change from land use P to land use Q (metric tons C/year)

$\Delta C_{Biomass_Q}$ = annual change in biomass carbon stocks for the current land use Q, which are based on the specific methods for the land use in other chapters of this report (metric tons C/ha)

$\Delta C_{conversion_{PQ}}$ = initial change in biomass carbon stocks due to conversion from previous land use P to current land use Q (metric tons C/ha)

A = area of the land parcel (ha)

T = time period of this estimation, which is 1 year for this equation (year)

PQ = change from previous land use P to current land use Q (e.g., forest land converted to cropland, where forest land is the previous land-use category and cropland is the current land-use category)

Q = current land use category

Note: $\Delta C_{conversion_{PQ}}$ is set to 0 after the first year following the conversion.

The initial change in biomass C stocks that occurs during the year of the conversion is estimated using equation 7-3 and addresses any biomass that stays on the land during the land-use conversion; for example, when forest is converted to grasslands, some trees may be left to provide shade for grazing livestock.

Equation 7-3: Initial Change in Biomass Carbon Stocks Due to Land Conversion

$$\Delta C_{conversion_{PQ}} = B_{After} - B_{Before}$$

Where:

$\Delta C_{conversion_{PQ}}$	=	initial change in biomass C stocks due to conversion of the previous land use to the current land use (metric tons C/ha)
B_{After}	=	biomass C stock remaining from the previous land use P after conversion (metric tons C/ha)
B_{Before}	=	biomass C stock in the previous land use P before the land-use conversion (metric tons C/ha)
PQ	=	change from previous land use P to current land use Q (e.g., forest land converted to cropland, where forest land is the previous land-use category and cropland is the current land-use category)

The change in biomass C stocks for the new land-use change category Q following conversion are estimated with equations found in the other chapters of this report. Notably, the change associated with harvested woody products has not been included here but may be estimated with methods outlined in chapter 5, associated with clearing/harvest of the forest biomass.

7.2.2 Carbon Pools in Dead Organic Matter

Method for Estimating Carbon Pools in Dead Organic Matter

- The change in carbon stocks in dead wood and litter due to land conversion is estimated as the difference in carbon stocks in the previous and current land-use categories applied in the year of the conversion (carbon losses) or distributed uniformly over the length of the transition period (carbon gains).

7.2.2.1 Description of Method

Equation 7-4 provides the conceptual approach to estimating changes in carbon stocks in dead wood and litter pools. Estimate the difference in carbon stocks in the previous and current land-use categories, then apply this change in the year of the conversion (i.e., there is a net loss in carbon stocks with conversion from land use P to land use Q) or distribute it uniformly over the length of the 20-year transition period (i.e., there is a gain in carbon stocks with conversion from land use P to land use Q).

Equation 7-4: Annual Change in Carbon Stocks in Dead Wood and Litter Due to Land Conversion

$$\Delta C_{DOM_{PQ}} = \left(C_{DOM_Q} - C_{DOM_P}\right) \times A \div T$$

Where:

$\Delta C_{DOM_{PQ}}$	=	annual change in carbon stocks in dead wood or litter for a land use change from previous category P to current category Q (metric tons C/year)
C_{DOM_Q}	=	dead wood/litter stock, under the current land-use category Q (metric tons C/ha)
C_{DOM_P}	=	dead wood/litter stock, under the previous land-use category P (metric tons C/ha)
A	=	area of the land parcel (ha)
T	=	time period of this estimation; the default is 20 years for carbon stock increases and one year for carbon losses (year)
PQ	=	change from previous land use P to current land use Q (e.g., forest land converted to cropland, where forest land is the previous land-use category and cropland is the current land-use category)

7.2.3 Changes in Soil Carbon

Method for Estimating Changes in Soil Carbon

- The methodologies to estimate soil carbon stock changes for organic soils and mineral soils are adopted from IPCC (Aalde et al., 2006, Ogle et al., 2019a).

SOC stocks are influenced by land-use change (Aalde et al., 2006) due to changes in productivity that influence carbon inputs, as well as changes in soil management that influence carbon outputs (Davidson and Ackerman, 1993; Ogle et al., 2005; Post and Kwon, 2000). For all land-use changes—and especially conversion to croplands—the most significant changes in SOC are due to changes in the soil disturbance regimes and associated effects on soil aggregate dynamics (Six et al., 2000).

While estimates should be made separately for each parcel of land that undergoes a change in land use, the stock changes will only be reported as a land-use change effect for a 20-year transition period, as noted above. For time series consistency, the method described in this section should be applied for the entire 20-year transition period to eliminate errors associated with changing the methods (i.e., changes in the stock due to a method changes rather than the anthropogenic activity).

7.2.3.1 Description of Method

Models have been adopted from the IPCC methods to estimate SOC stock change (Aalde et al., 2006, Ogle et al., 2019a). For mineral soils, use equation 7-6 to estimate carbon stocks at the beginning and end of the year. Emissions occur in organic soils following drainage due to the conversion of an anaerobic environment with a high-water table to aerobic conditions (Armentano and Menges, 1986), resulting in a significant loss of carbon to the atmosphere (Ogle et al., 2003). Emission estimation methods from organic soils should be consistent with the appropriate sector methodologies (i.e., forestry, croplands, grazing lands, or wetlands).

The total change in SOC stocks is estimated by summing the change in mineral and organic soils for the entity using equation 7-5.

Equation 7-5: Annual Change in SOC Stocks Due to Land Conversion

$$\Delta C_{SOC_{PQ}} = \Delta C_{mineral\,PQ} + \Delta C_{organic_{PQ}}$$

Where:

$\Delta C_{SOC_{PQ}}$	=	annual change in carbon stocks in soil organic carbon for land-use change from previous land use P to current land use Q (metric tons C/year)
$\Delta C_{mineral\,PQ}$	=	annual change in mineral soil organic carbon stock for land-use change from previous land use P to current land use Q (metric tons C/year)
$\Delta C_{organic_{PQ}}$	=	annual change in carbon stocks from drained organic soils for land-use change from previous land use P to current land use Q (metric tons C/year)
PQ	=	change from previous land use P to current land use Q (e.g., forest land converted to cropland, where forest land is the previous land-use category and cropland is the current land-use category)

Mineral Soils

The methods for estimating changes in SOC stocks for mineral soils has been adopted from the IPCC method (Ogle et al., 2019a). Estimate the change separately for each parcel in the entity's operation that has a land-use change. Use equation 7-6 (same as equation 3-8) to estimate the change in stocks for each area over 20-year intervals for the entire reporting time series.

Equation 7-6: Change in SOC Stocks for Mineral Soils Due to Land Conversion

$$\Delta C_{mineral\,PQ} = \left[\left(SOC_Q - SOC_P\right) \div t\right] \times A$$

Where:

$\Delta C_{mineral\,PQ}$	=	annual change in mineral soil organic carbon stock for land-use change from previous land use P to current land use Q (metric tons C/year)
SOC_Q	=	mineral soil organic carbon stock for the current land use Q (metric tons C/ha)
SOC_P	=	mineral soil organic carbon stock for the previous land use P (metric tons C/ha)
t	=	time period over which the land use, management and input factors quantify the change in SOC stocks, which is 20 years for this equation (year)
A	=	area of the parcel (ha)
PQ	=	change from previous land use P to current land use Q (e.g., forest land converted to cropland, where forest land is the previous land-use category and cropland is the current land-use category)

Estimate the SOC stock with country-specific factors using equation 3-8 from Chapter 3, copied here as equation 7-7.

Equation 7-7: SOC Stock for Mineral Soils

$$SOC = SOC_{ref} \times F_{LU} \times F_{MG} \times F_I$$

Where:

SOC	=	soil organic carbon stock on mineral soils for land use P or Q (metric tons C/ha)

SOC_{ref}	=	reference SOC stocks for United States agricultural lands in long-term cultivation (metric tons C/ha)
F_{LU}	=	stock change factor for land use (dimensionless)
F_{MG}	=	stock change factor for management regime (dimensionless)
F_I	=	stock change factor for the input of organic matter (dimensionless)

The stock change factors (F_{LU}, F_{MG}, F_I) and reference carbon stocks (SOC_{REF}) are country-specific values developed for the United States (Ogle et al., 2003, 2006). The reference stocks are based on the SOC stocks in croplands (table 7-3), while the land-use factors represent the relative change in SOC between cropland and grazing lands, forest land, and set-aside cropland (table 7-4). The management factors represent the influence of tillage in croplands and grassland conditions in grazing lands. The input factors represent the influence of changing plant productivity on carbon input to soils. Management and input factors are not needed for forest lands (i.e., factors are set to a value of one). See section 3.2.3.1 for more information about the classification of management and input for cropland and grazing lands.

Table 7-3. Reference Carbon Stocks and 95-Percent Confidence Intervals for the United States (Metric Tons C/ha)

IPCC Soil Categories	USDA Taxonomic Soil Orders	Cold Temperate, Dry	Cold Temperate, Moist	Warm Temperate, Dry	Warm Temperate, Moist	Sub-Tropical, Dry	Sub-Tropical, Moist
High-clay-activity mineral soils	Vertisols, Mollisols, Inceptisols, Aridisols, and high-base-status Alfisols	42 (±2.7)	65 (±2.2)	37 (±2.2)	51 (±2.0)	42 (±5.1)	57 (±25.5)
Low-clay-activity mineral soils	Ultisols, Oxisols, acidic Alfisols, and many Entisols	45 (±5.9)	52 (±4.5)	25 (±2.7)	40 (±2.4)	39 (±9.4)	47 (±27.2)
Sandy soils	Any soils with greater than 70% sand and less than 8% clay (often Entisols)	24 (±9.4)	40 (±7.3)	16 (±4.7)	30 (±3.9)	33 (±3.7)	50 (±15.5)
Volcanic soils	Andisols	124 (±22.3)	114 (±32.7)	124 (±22.3)	124 (±22.3)	124 (±22.3)	128 (±29.4)
Spodic soils	Spodosols	86 (±12.7)	74 (±13.3)	86 (±12.7)	107 (±16.3)	86 (±12.7)	86 (±12.7)
Aquic soils	Soils with aquic suborder	86 (±22.3)	89 (±7.1)	48 (±7.1)	51 (±3.5)	63 (±3.7)	48 (±16.5)

Source: Inventory Annex Table A-203, U.S. EPA, 2020.

Stocks represent the amount of SOC with long-term cultivation of the land parcel. The values in parentheses are 95-percent confidence intervals based on a normal distribution that can be used to quantify uncertainty and propagate error through the analysis.

Table 7-4. Land-Use, Management, and Input Factors and 95-Percent Confidence Intervals for the United States

Factor	Subtropical Moist and Warm Moist Climate	Subtropical Dry and Warm Dry Climate	Cool Moist Climate	Cool Dry Climate
Land-Use Factors				
Cultivated[a]	1	1	1	1
Wetland rice production factor[b]	2.14±0.13	2.14±0.13	1.85±0.15	1.85±0.15
General uncultivated (i.e., grazing land, forest land, wetlands, perennial crops)	1.58±0.12	1.58±0.12	1.37±0.15	1.37±0.1
Set-asides (e.g., Conservation Reserve Program Lands)	1.18±0.19	1.18±0.19	1.05±0.24	1.05±0.24
Cropland Management Factors				
Full intensive till[a]	1	1	1	1
Reduced till	1.05±0.08	1.00±0.09	1.05±0.08	1.00±0.09
No-till	1.14±0.06	1.09±0.07	1.14±0.06	1.09±0.07
Grazing Land Management Factors[c]				
Native or nominally managed grazing lands[a]	1	1	1	1
Moderately degraded from high-intensity grazing	0.90±0.14	0.90±0.14	0.90±0.14	0.90±0.14
Severely degraded from high-intensity grazing	0.70±0.55	0.70±0.55	0.70±0.55	0.70±0.55
Improved	1.14±0.25	1.14±0.25	1.14±0.25	1.14±0.25
Cropland Input Factors				
Low	0.94±0.02	0.94±0.02	0.94±0.02	0.94±0.02
Medium[a]	1	1	1	1
High	1.07±0.04	1.07±0.04	1.07±0.04	1.07±0.04
High with amendment[c]	1.44±0.19	1.37±0.16	1.44±0.13	1.37±0.16
Grazing Land Input Factors				
Improved with medium input[a]	1	1	1	1
Improved with high input[c]	1.11±0.15	1.11±0.15	1.11±0.15	1.11±0.15

Source: U.S. EPA, 2020.

[a] Uncertainty is not applicable because the uncertainty is already incorporated into the reference carbon stock.

[b] United States-specific factors are not estimated for wetland rice production due to a lack of studies addressing the impacts of wetland rice production on soil organic carbon stocks in the United States. Factors provided by IPCC for the Tier 1 method (Ogle et al., 2019b) are used as the best estimates of these impacts. USDA derived this factor by combining the land-use change factor for general uncultivated cropland (in this table) and the rice cultivation factor from the IPCC guidelines.

[c] United States-specific factors are not estimated for high input with an organic amendment for croplands, or grazing land management, due to a lack of studies addressing the impacts in the United States. Factors provided by IPCC for the Tier 1 method (Ogle et al., 2019b; McConkey et al., 2019) are used as the best estimates of these impacts.

The influence of biochar carbon amendments may also be included in the estimation of mineral SOC stock changes. Use the approach described in section 3.2.3.1 (equation 3-10).

Organic Soils

The methodology for estimating soil carbon stock changes in organic soils has been adopted from IPCC (Aalde et al., 2006; Ogle et al., 2019a) and is described accordingly in chapter 3 (equation 3-12) and copied here as equation 7-8. Chapter 5 recommends soil sampling in cases where there have been significant changes in soil carbon (e.g., land conversion). See for example, the "Level 3" approach for silvicultural practices and improved forest management in section 5.2.1 of chapter 5.

Equation 7-8: Change in SOC Stocks for Organic Soils

$$\Delta C_{organic_{PQ}} = A \times EF$$

Where:

$\Delta C_{organic_{PQ}}$	=	annual change in carbon stocks from drained organic soils in crop and grazing lands (metric tons C/ year)
A	=	area of drained organic soils (ha)
EF	=	annual emission factor (metric tons C/ha)
PQ	=	change from previous land use P to current land use Q (e.g., forest land converted to cropland, where forest land is the previous land-use category and cropland is the current land-use category)

Emission factors have been adopted from the U.S. National GHG Inventory (U.S. EPA, 2020; Ogle et al., 2003) and are region-specific and based on typical drainage patterns and climatic controls on decomposition rates.

Table 7-5. Emission Factors and 95-Percent Confidence Intervals for Organic Soils (i.e., *Histosols*) That Are Drained in Cropland and Grazing Land in the United States

Emission Factor for Drained Organic Soils (metric tons C/ha)	Cool Temperate Climate	Warm Temperate Climate	Subtropical Climate
Cropland	11.2 (±2.5)	14.0 (±2.5)	14.3 (±6.5)
Grazing land	2.8 (±1.3)	3.5 (±1.3)	3.6 (±3.3)

7.2.3.2 Activity Data

Mineral soils require the following activity for croplands:

- Area of land parcel (i.e., field)
- Crop types and rotation sequence
- Residue management, including harvested, burned, grazed, or left in the field
- Mineral fertilization (yes/no)
- Organic amendments (yes/no)

- Tillage implements and number of passes in each operation[1]
- Use of irrigation (yes/no)
- Cover crops (yes/no)

The method for grazing land on mineral soils requires the following management activity data:

- Area of the land parcel (i.e., field)
- Forage type (perennial grass such as cool or warm season grasses, legume, or mixed grass-legume nitrogen-fixing species)
- Mineral fertilization (yes/no)
- Organic amendments (yes/no)
- Use of irrigation (yes/no)
- Current ecological site and the reference condition for the land parcel based on the USDA, Natural Resources Conservation Service (NRCS) ecological state and transition model framework. The reference and alternative states are available through the USDA, NRCS web soil survey[2] (https://websoilsurvey.nrcs.usda.gov/app/).

The activity data are used to classify land-use, management, and input classes. The classifications can be found in chapter 3. Note that the method does not require any management activity data for forest land and wetlands because the method provided here assumes limited influence of forest or wetland management on SOC stock changes (i.e., the land-use change has the largest impact).

The method for organic soils requires the following activity data.

- Area of drained organic soils on the land parcel

7.2.3.3 Ancillary Data

Ancillary data include climate regions and soil types, consistent with the method developed by IPCC (Reddy et al., 2019). Weather data may be based on national datasets such as the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) data (PRISM Climate Group, 2018) and are classified according to the IPCC classification as refined for the United States (table 7-6). Soil data may also be based on national datasets such as the Soil Survey Geographic Database (SSURGO) (Soil Survey Staff, 2019), and are classified according to the IPCC classification (Reddy et al., 2019, Figure 3A.5.3). However, entities may also substitute field-specific soil data, as long as entities characterize the soil pedons necessary for use of the IPCC classifications. These characteristics include sand and clay content, soil order, and suborder (See table 7-3).

[1] Use this information to determine tillage intensity (i.e., intensive till, reduced till, and no-till), using the classification applied in the U.S. National GHG Inventory. See section 3.2.3.2 in chapter 3 for more information about the tillage classification.

[2] If the information is not available through the USDA-NRCS web soil survey, then the entity should contact USDA-NRCS extension office for guidance on identifying the current and reference conditions.

Table 7-6. Climate Classification for the SOC Methods Associated With Land-Use Change

Climate Type	Mean Annual Temperature (°C)	Mean Annual Precipitation (mm)
Cool temperate dry	<10	<Potential evapotranspiration
Cool temperate moist	<10	≥Potential evapotranspiration
Warm temperate dry	10–20	<Potential evapotranspiration
Warm temperate moist	10–20	≥Potential evapotranspiration
Subtropical dry	>20	<1,000
Subtropical moist	>20	1,000–2,000

Source: Reddy et al. (2019), Figure 3A.5.2

7.2.3.4 Limitations and Uncertainty

The limitations of the mineral SOC method include no assessment of the effect of land-use change at deeper depths in the profile (the IPCC method only addresses changes in the top 30 centimeters of the soil profile; Ogle et al. 2019a; Aalde et al., 2006), and no assessment of erosion, transport, and deposition ofcarbon. Uncertainties in the mineral soil methods include imprecision in the emission factors, in addition to uncertainties in the activity and ancillary data. Uncertainty for the emission factors is provided in chapter 3 (Ogle et al., 2003, 2006). Uncertainty in the activity data is based on the entity input, as well as the ancillary data to the extent that this information is provided by the entity. Uncertainties can be combined using a Monte Carlo simulation approach; see chapter 8.

While there is considerable evidence and mechanistic understanding about the influence of land-use change on SOC, there is less known about the effect on soil inorganic carbon. Consequently, current methods do not include impacts on inorganic carbon uncertainty associated with estimates of land use and management impacts on soil carbon stocks.

7.3 Chapter 7 References

Aalde, H., P. Gonzalez, M. Gytarski, T. Krug, W.A. Kurz, R.D. Lasco, D.L. Martino, et al. 2006. Chapter 2: Generic methodologies applicable to multiple land-use categories. In IPCC. *2006 IPCC guidelines for national greenhouse gas inventories, volume 4.* Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/.

Armentano, T.V., and E.S. Menges. 1986. Patterns of change in the carbon balance of organicsoil. *Journal of Ecology,* 74(3): 755–774. https://doi.org/10.2307/2260396.

Davidson, E., and I. Ackerman. 1993. Changes in soil carbon inventories following cultivation of previously untilled soils. *Biogeochemistry*, 20(3): 161–193.

IPCC. 2006. *2006 IPCC guidelines for national greenhouse gas inventories*. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/.

McConkey, B., S.M. Ogle, N. Chirinda, A.W.M. Kishimoto, J. Baldock, A. Trunov, C. Alsaker, et al. 2019. Chapter 6: Grassland. In IPCC. *2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories, volume IV.* Intergovernmental Panel on Climate Change. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html.

Ogle, S.M., F.J. Breidt, M.D. Eve, K. Paustian. 2003. Uncertainty in estimating land use and management impacts on soil organic carbon storage for US agricultural lands between 1982 and 1997. *Global Change Biology*, 9(11): 1521–1542. https://doi.org/10.1046/j.1365-2486.2003.00683.x.

Ogle, S.M., F.J. Breidt, K. Paustian. 2005. Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. *Biogeochemistry*, 72(1): 87–121. https://doi.org/10.1007/s10533-004-0360-2.

Ogle, S.M., F.J. Breidt, K. Paustian. 2006. Bias and variance in model results associated with spatial scaling of measurements for parameterization in regional assessments. *Global Change Biology*, 12: 516–523. https://doi.org/10.1111/j.1365-2486.2006.01106.x.

Ogle, S.M., W.A. Kurz, C. Green, A. Brandon, J. Baldock, G. Domke, M. Herold, et al. 2019a. Chapter 2: General methodologies applicable to multiple land-use categories. In IPCC. *2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories, volume IV.* Intergovernmental Panel on Climate Change. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html.

Ogle, S.M., S.J. Wakelin, L. Buendia, B. McConkey, J. Baldock, H. Akiyama, A.W.M. Kishimoto, et al. 2019b. Chapter 5: Cropland. In IPCC. *2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories, volume IV.* Intergovernmental Panel on Climate Change. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html.

Post, W.M., and K.C. Kwon. 2000. Soil carbon sequestration and land-use change: Processes and potential. *Global Change Biology*, 6: 317–327. https://doi.org/10.1046/j.1365-2486.2000.00308.x.

PRISM Climate Group. 2018. *PRISM climate data.* Oregon State University. http://prism.oregonstate.edu.

Reddy, S., L. Panichelli, R.M. Waterworth, S. Federici, C. Green, I. Jonckheere, S. Kahuri, et al. 2019. Chapter 3: Consistent representation of land. In IPCC. *2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories, volume IV.* Intergovernmental Panel on Climate Change. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html.

Six, J., E.T. Elliot, K. Paustian. 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry*, 32(14): 2099–2103. https://doi.org/10.1016/S0038-0717(00)00179-6.

Soil Survey Staff. 2019. *Gridded soil survey geographic (gSSURGO) database for the conterminous United States.* U.S. Department of Agriculture, Natural Resources Conservation Service. https://gdg.sc.egov.usda.gov/.

U.S. EPA. 2020. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2018. Environmental Protection Agency.

Appendix 7-A: Method Documentation

7-A.1 Rationale for Methods

These methods are based on the IPCC 2006 (Aalde et al., 2006) and refined in the 2019 Guidelines (Ogle et al., 2019a) and represent the most consistent way to estimate emissions from land-use change. Other methods are provided for land parcels that are not undergoing land-use change, and those methods are more comprehensive for estimating emissions for the specific land use. However, it is critical to use a consistent, seamless method for estimating carbon stock changes for an individual land parcel throughout the time series. Otherwise, artificial changes in stocks can be estimated due to a change in the method. Further testing and development will be needed before the more comprehensive methods provided in each land-use section can be integrated into a seamless approach for estimating the carbon stock changes.