Chapter 6
Quantifying Greenhouse Gas Sources and Sinks in Managed Wetland Systems

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This chapter has been minimally updated since the 2014 publication of *Quantifying greenhouse gas fluxes in agriculture and forestry: Methods for entity scale inventory*. Therefore, this chapter does not take into consideration any updated literature or methodologies, notably those available in the *2013 supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: Wetlands* (IPCC 2013). This chapter will be revised in future updates of this report.

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Acronyms, Chemical Formulae, and Units

C	carbon
CH_4	methane
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalents
dbh	diameter at breast height
DNDC	Denitrification-Decomposition
EPA	Environmental Protection Agency
FVS	Forest Vegetation Simulator
GHG	greenhouse gas
ha	hectare
IPCC	Intergovernmental Panel on Climate Change
N	nitrogen
N_2O	nitrous oxide
NO_x	mono-nitrogen oxides
NRCS	USDA Natural Resources Conservation Service
P	phosphorous
PRISM	Parameter-Elevation Regressions on Independent Slopes Model
SOC	soil organic carbon
Tg	teragrams
USDA	U.S. Department of Agriculture
USDA-ARS	U.S. Department of Agriculture, Agricultural Research Service

6. Quantifying Greenhouse Gas Sources and Sinks in Managed Wetland Systems

This chapter provides methodologies and guidance for reporting greenhouse gas (GHG) emissions and sinks at the entity scale for managed wetland systems. More specifically, it focuses on methods for managed palustrine wetlands.[1]

- Section 6.1 provides an overview of wetland systems and resulting GHG emissions, system boundaries and temporal scale, and a summary of the selected methods/models and its sources of data.
- Section 6.2 provides the estimation methods for biomass carbon in wetlands and soil carbon, N_2O, and CH_4 emissions and sinks. A single method is provided for each source presented in this chapter (i.e., biomass carbon in forested, shrub, and grass wetlands; soil carbon and CH_4 in wetlands; and direct N_2O emissions in wetlands).
- Appendix 6-A presents the various management practices that influence GHG emissions in wetland systems and land-use change to wetlands.
- Appendix 6-B includes a discussion of research gaps in wetland management.

This chapter and its methods have been minimally updated since the 2014 report. Therefore, this chapter does not take into consideration any updated literature or methodologies, notably those available in the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands* (IPCC 2013). Revisions will be made to this chapter in future report updates. Additional background information on the impact of cropland and grazing land management is available in the 2014 report.

6.1 Overview

Wetlands occur across most landforms, existing as natural unmanaged and managed lands, restored lands following conversion from another use (typically agriculture), and as constructed systems for water treatment, such as anaerobic lagoons. All wetlands sequester carbon and are a source of GHGs. Table 6-1 describes the sources of emissions or sinks and the gases estimated in the methodology.

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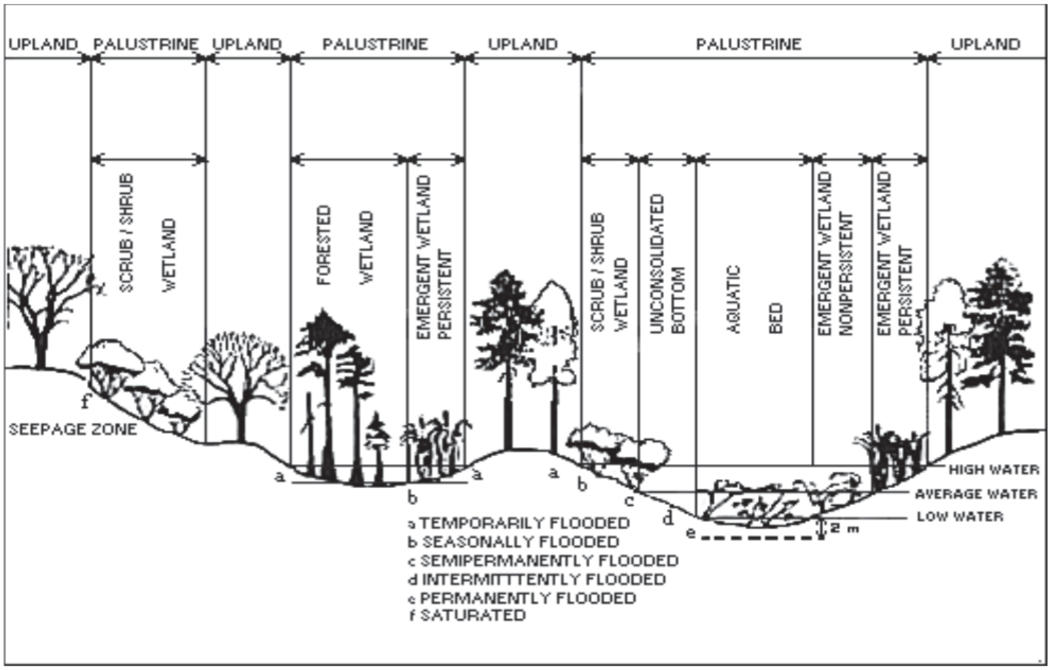
[1] Palustrine wetlands include nontidal and tidal wetlands that are primarily composed of trees, shrubs, persistent emergent, emergent mosses, or lichens, where salinity due to ocean-derived salts is below 0.5 ‰ (parts per thousand). Palustrine wetlands also include those wetlands lacking vegetation that have the following four characteristics: (1) are less than 20 acres; (2) do not have active wave-formed or bedrock shorelines; (3) have a maximum water depth of less than 6.5 ft. at low water; and (4) have a salinity due to ocean-derived salts less than 0.5 percent (Stedman and Dahl, 2008).

Table 6-1. Overview of Wetland Systems Sources and Associated Greenhouse Gases

Source	Method for GHG Estimation			Description
	CO_2	N_2O	CH_4	
Biomass carbon	✓			Provisions for estimating aboveground biomass for wetland forests and above and belowground biomass and carbon are included for shrub and grass wetlands in this chapter. Aboveground biomass for forested wetlands and shrub and grass wetlands includes live vegetation, trees, shrubs, and grasses, standing dead wood (dead biomass), and down dead organic matter—litter layer (dead biomass).
Soil C, N_2O, and CH_4 in wetlands	✓	✓	✓	The production and consumption of carbon in wetland-dominated landscapes are important for estimating the contribution of GHGs, including CO_2, CH_4, and N_2O emitted from those areas to the atmosphere. The generation and emission of GHGs from wetland-dominated landscapes are closely related to inherent biogeochemical processes, which also regulate the carbon balance (Rose and Crumpton, 2006). However, those processes are highly influenced by land use, vegetation, soil organisms, chemical and physical soil properties, geomorphology, and climate (Smemo and Yavitt, 2006).

6.1.1 Description of Sector

The National Wetlands Inventory, available through the U.S. Fish and Wildlife Service, provides information on wetland habitats in the United States via the wetlands geospatial dataset and wetland status and trends reports, both determined via remote sensing technology. Cowardin et al. (1979) defines wetlands and broadly classifies them into five major systems: (1) marine, (2) estuarine, (3) riverine, (4) lacustrine, and (5) palustrine. Four of those systems (marine, estuarine, riverine, and lacustrine) are open-water bodies and are not considered within the methods described in this guidance. Palustrine wetlands encompass the wetland types occurring on the land and are further classified by major vegetative life forms and wetness or flooding regime. Common palustrine wetlands are illustrated in figure 6-1. For example, forested wetlands are often classified as palustrine—forested. Similarly, most grass wetlands are classified as palustrine—emergent, reflecting emergent vegetation (e.g., grasses and sedges). Wetlands also vary greatly with respect to groundwater and surface water interactions that directly influence hydroperiod (i.e., the length of time and portion of the year the wetland holds water), water chemistry, and soils (Cowardin et al., 1979; Winter et al., 1998). All these factors along with climate and land-use drivers influence the overall carbon balance and GHG fluxes.



Source: Cowardin et al. (1979).

Figure 6-1. Palustrine Wetland Classes Based on Vegetation and Flooding Regime

Grassland and forested wetlands are subject to a wide range of land use and management practices that influence the carbon balance and GHG flux (Faulkner et al., 2011; Gleason et al., 2011). For example, forested wetlands may be subject to silvicultural prescriptions with varying intensities of management through the stand rotation; hence, the carbon balance and GHG emissions should be evaluated on a rotation basis, which could range from 20 to more than 50 years. In contrast, grass wetlands may be grazed, hayed, or directly cultivated to produce a harvestable commodity annually. While each management practice may influence carbon sequestration and GHG fluxes, the effect is dependent on vegetation, soil, hydrology, climatological conditions, and management prescriptions. This section focuses on restoration and management practices associated with palustrine wetlands that are typically forested or grassland.

6.1.2 Resulting GHG Emissions

GHG emissions from wetlands are largely controlled by water table depth and duration as well as climate and nutrient availability. Under aerobic soil conditions, which are common in most upland ecosystems, organic matter decomposition releases CO_2, and atmospheric CH_4 can be oxidized in the surface soil layer (Trettin et al., 2006). In contrast, the anaerobic soils that characterize wetlands can produce CH_4 (depending on the water table position) in addition to emitting CO_2. Accordingly, wetlands are an inherent source of CH_4, with globally estimated emissions of 55 to 150 teragrams (Tg) of CH_4 per year (Blain et al., 2006).

Biomass carbon can change significantly with the management of wetlands, particularly in forested wetlands, changes from forest to wetlands dominated by grasses and shrubs, or open water. In forested wetlands, there can also be significant carbon in dead wood, coarse woody debris, and fine litter. Harvesting practices will also influence the carbon stocks in wetlands to the extent the wood is collected for products, fuel, or other purposes.

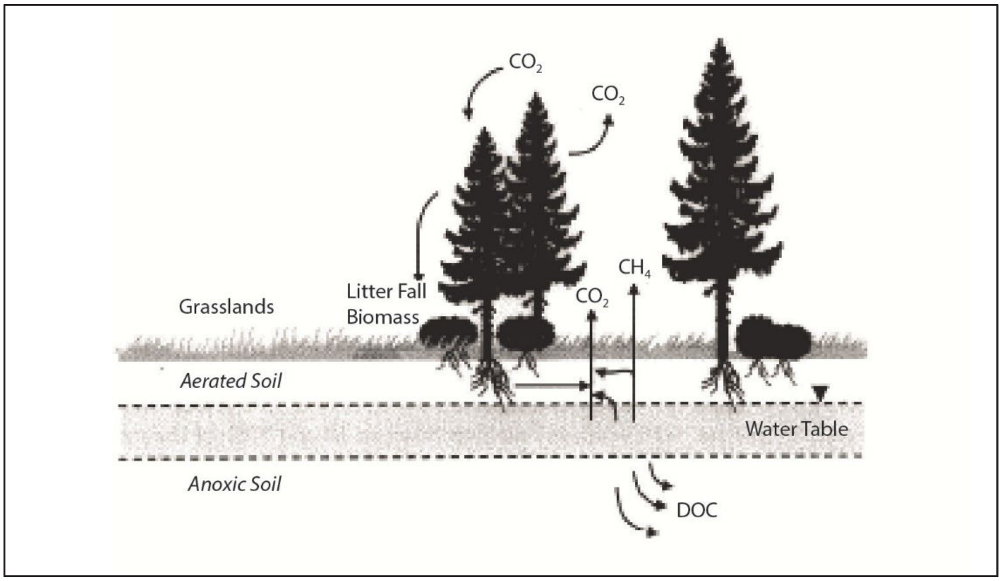
Wetlands are also a source of soil N_2O emissions, primarily because of nitrogen runoff from adjoining uplands and leaching into groundwater from agricultural fields and/or animal production facilities. N_2O emissions from wetlands due to nitrogen inputs from surrounding fields or animal products are considered indirect emissions of N_2O (de Klein et al., 2006). Methodologies for estimating indirect N_2O are provided in the respective source chapter (i.e., chapter 3 or chapter 4). However, direct N_2O emissions occur in wetlands if management practices include nitrogen fertilization, hence, guidance is provided for this source of emissions.

6.1.3 Risk of Reversals

Wetlands inherently accumulate carbon in the soils due to anaerobic conditions, and they are natural sources of CO_2 and CH_4 in the atmosphere. Management may alter conditions that affect both the pools and fluxes. For example, accumulated soil carbon can be returned to the atmosphere if the wetland is drained (Armentano and Menges, 1986). In contrast, silvicultural water management in wetlands can lead to higher biomass production, which may partially offset increased soil organic matter oxidation. Conversely, the soil carbon pool in converted wetlands is typically lower than the unmanaged soil, and restoring wetland conditions may increase carbon storage over time if inherent hydric soil conditions are maintained with consistent organic matter inputs.

Reversals of emission trends can occur if a manager reverts to a prior condition or an earlier practice. For example, an entity may decide to return a wetland that had been drained and cropped back to a forested wetland condition. Another common example would be if a restored forested wetland reverted to agriculture. These reversals do not negate the mitigation of CH_4 or N_2O emissions to the atmosphere that had occurred previously, to the extent that wetland restoration or change in management can reduce or change these emissions. Correspondingly, the starting point from the reversion will determine the effect on carbon sequestration and GHG flux. For example, in a restored forested wetland, reversion of the site to crop production would return carbon sequestered during the restoration period to the atmosphere over time.

There is a trade-off in CH_4 and N_2O emissions with the management of the water table position. Wetlands with anaerobic soil conditions that are persistent near the surface for a longer period during the year will tend to have higher CH_4 emissions and lower emissions of N_2O. N_2O emissions are greatly reduced if soils are saturated because there is little inherent nitrification, and denitrification will lead to N_2 production (Davidson et al., 2000). For example, restoration of wetlands will normally lead to a higher water table for a longer period of the year and thus contribute to higher emissions of CH_4 but lower emissions of N_2O. These trends can be reversed if the water table is lowered through management or drought, which will tend to enhance N_2O emissions if there is a source of nitrate while reducing emissions of CH_4. Figure 6-2 provides an illustration of the carbon cycle typically found in wetland forests and grassland wetlands and represents the scope of the methods presented in this guidance.



Source: Trettin and Jurgensen (2003).

Figure 6-2. Carbon Cycle for Forest and Grassland Wetlands

6.1.4 System Boundaries and Temporal Scale

System boundaries are defined by the coverage, extent, and resolution of the estimation methods. The location of the wetlands may be approximated by use of the National Wetlands Inventory (FWS, 2022), the location of hydric soils as conveyed by the NRCS soils map, or through direct delineation of wetlands. The coverage of the methods can be used to estimate a variety of emission sources, including emissions associated with biomass C, litter C, and soil carbon stock changes and CO_2, CH_4, and N_2O fluxes from soils. System boundaries are also defined by the extent and resolution of the estimation method. The methods provided for wetlands have a spatial extent that would include all wetlands in the entity's operation, with estimation occurring at the resolution of an individual wetland. Emissions are estimated on an annual basis for as many years as needed for GHG emissions reporting.

6.1.5 Summary of Selected Methods

This chapter provides methods for estimating carbon stock changes and CH_4 and N_2O emissions from naturally occurring wetlands and restored wetlands on previously converted wetland sites.[2] Constructed wetlands for water treatment, including detention ponds, are engineered systems that are beyond the scope considered here because they have specific design criteria for influent and effluent loads. In addition, the methods are restricted to the estimation of emissions on palustrine wetlands that are influenced by a variety of management options such as water table management, timber, or other plant biomass harvest, and wetlands that are managed with fertilizer applications. The methods are based on established principles and represent the best available science for estimating changes in carbon stocks and GHG fluxes associated with wetland management activities. However, given the wide diversity of types of wetlands and the variety of management regimes, the basis for the methods provided in this section is not as well-developed as other chapters in this report (i.e., Cropland and Grazing Lands, Animal Production, and Forestry

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[2] Wetlands that are converted to a nonwetland status should be considered in the appropriate chapter (e.g., Cropland and Grazing Lands, Animal Production Systems, and Managed Forest Systems).

Methods). Table 6-2 provides a summary of the methods and their corresponding section for the sources of emissions estimated in this report.

The data required to apply these methods range from basic information on soils, vegetation, weather, land use, and management history to data on fertilization rates or drainage conditions. While some of these data are operation-specific and must be provided by the entity, other data can be obtained from national databases, such as weather data and soil characteristics.

Table 6-2. Overview of Wetland Systems Sources, Method, and Section

Section	Source	Method
6.2.1	Biomass carbon	Methods for estimating forest vegetation and shrub and grassland vegetation biomass carbon stocks use a combination of the Forest Vegetation Simulator (FVS) model and lookup tables for dominant shrub and grassland vegetation types found in chapter 3. If there is a land-use change to agricultural use, methods for cropland herbaceous biomass are provided in chapter 3.
6.2.2	Soil C, N_2O, and CH_4 in wetlands	The Denitrification-Decomposition (DNDC) process-based biogeochemical model is the method used for estimating soil C, N2O, and CH4 emissions from wetlands. DNDC simulates the soil carbon and nitrogen balance and generates emissions of soil-borne trace gases by simulating carbon and nitrogen dynamics in natural and agricultural ecosystems (Li et al., 2000; Miehle et al., 2006; Stang et al., 2000) and forested wetlands (Dai et al., 2011; Zhang et al., 2002), using plant growth estimated as described in section 6.2.1.

6.2 Estimation Methods

Section 6.2.1 provides methods for estimating live and dead biomass in forested, shrub, and grassland wetlands. Section 6.2.2 provides methods for estimating soil C, N_2O, and CH_4 emissions from managed naturally occurring wetlands.

6.2.1 Biomass Carbon in Wetlands

Method for Estimating Live and Dead Biomass Carbon in Wetlands

- Methods for estimating forest vegetation and shrub and grassland vegetation biomass carbon stocks use a combination of the Forest Vegetation Simulator model and the biomass carbon stock changes method in section 3.2.1 of chapter 3. If there is a land-use change to agricultural use, use the chapter 3 methods for cropland herbaceous biomass.

6.2.1.1 Description of Method

Provisions for estimating aboveground biomass for wetland forests and aboveground and belowground biomass and carbon are included for shrub and grass wetlands in this section. Since the vegetative cover on wetlands may vary from natural communities to agricultural crops, cross-references are made to ensure congruity with chapter 3 and chapter 5.

Forest vegetation: Biomass carbon stocks are estimated for forests in wetlands using the methods described in chapter 5. The ‘Level 3’ approach uses the FVS, which is a system of growth and yield models that estimate growth and yield for U.S. forests. FVS is an individual tree model and can estimate biomass carbon stock change for nearly any type of forest stand. The Fire and Fuels Extension to FVS can be used to generate reports of all live and dead biomass carbon pools in addition to harvested wood products. Regional variants are available for FVS that allow for region-specific focus on species and forest vegetation communities. The driver for productivity is the availability of site index curves,[3] and the regional variants include many wetland tree species. Regional variants of FVS may also provide provisions for refining the basis for estimating productivity by classifying the area of interest into ecological units, habitat types, or plant associations. However, if a species-specific curve is not available, then a default function is used to estimate carbon stock changes.

Grassland vegetation: The change in carbon stock for grass wetlands is generally small unless there are drought conditions, or the area is actively managed. However, changes can be significant with a land-use change. Therefore, biomass carbon stock changes can be estimated following a land-use change using the method in section 3.2.1 of chapter 3.

6.2.1.2 Activity Data

Forested wetlands: The data and requirements for estimating the changes in carbon stocks in wetland forests are the same as those described for upland forests in chapter 5.

Grassland vegetation: The data and requirements for estimating the changes in carbon stocks in grassland vegetation are the same as those described for total biomass carbon stock changes presented in chapter 3.

6.2.1.3 Model Output

Changes in aboveground carbon pools associated with wetland forests are provided for live vegetation, standing dead biomass, and down dead biomass. Change in live biomass carbon is also provided for belowground biomass. The units of reporting are metric tonnes/ha CO_2-eq.

6.2.1.4 Limitations and Uncertainty

Estimates of the forest biomass carbon pools in wetlands are constrained by limited data on productivity response to management and are sensitive to the wide array of characteristic vegetative communities and soil types. Although FVS is the most inclusive model available, many results for wetlands will still be based on default model functions, because there is limited data on the growth of specific wetland species under particular management regimes. Accordingly, the results will provide a relative basis for tracking changes over time in biomass carbon. Table 6-3 summarizes additional limitations of the current approach.

Table 6-3. Key Limitations to Estimating Biomass Carbon Pools in Forest Wetland Vegetation

Consideration	Limitation
Ratio for belowground biomass	A ratio is used to estimate belowground biomass in upland and wetland forests based on aboveground biomass. While a common ratio will provide a basis for estimating relative change, it will likely over or underestimate actual stocks in many wetlands.
Response to management or climatic conditions	Wetland vegetation is known to respond to management practices, soil, and climatic conditions. Those relationships are not necessarily reflected in FVS because there is an insufficient basis for generalized assessment purposes. For example, in response to dynamic water-level fluctuations during wet and dry

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[3] Site index is the measure of a forest's potential productivity. The height of the dominant or co-dominant trees at a specified age in a stand are calculated in an equation that uses the tree's height and age. Site index equations differ by tree species and region. Site index curves are constructed by using the tree heights at a base age and an equation is derived from the curves to estimate the site index when an individual tree's age is not the same as the base age (Hanson et al., 2002).

Consideration	Limitation
	cycles, wetlands often exhibit major intra- and interannual shifts in vegetative structure, ranging from open water to emergent herbaceous vegetation. Correspondingly, the altered site conditions under the management regime and the genetic quality of the planted trees may exhibit responses that are not captured by the existing allometric relationships in FVS.

The shrub and herbaceous biomass method is based on the assumptions found in chapter 3.

Major sources of uncertainty include belowground biomass, vegetation response to management, and hydrologic regime (e.g., seasonal hydroperiod). Uncertainty in herbaceous carbon stock changes will result from a lack of precision in crop or forage yields, residue-yield ratios, root-shoot ratios, and carbon and carbon fractions, as well as the uncertainties associated with estimating the biomass carbon stocks for the other land uses.

Measurement, sampling, and regression/modeling errors are all part of the estimation process in FVS. Some similar measure of the representativeness of selected forest inventory and analysis plots to the entities' forests is needed. Uncertainties about carbon conversion factors are also significant in some cases.

6.2.2 Soil C, N_2O, and CH_4 in Wetlands

Method for Estimating Soil C, N_2O and CH_4 in Wetlands

- The DNDC process-based biogeochemical model is the method used for estimating soil C, N_2O, and CH_4 emissions from wetlands.
- DNDC predicts soil carbon and nitrogen balance and the generation and emission of soil-borne trace gases by simulating carbon and nitrogen dynamics in natural and agricultural ecosystems (Li et al., 2000; Miehle et al., 2006; Stang et al., 2000) and forested wetlands (Dai et al., 2011; Zhang et al., 2002), using plant growth estimatedas described in section 6.2.1.

6.2.2.1 Description of Method

The method consists of using the process-based model—DNDC—to estimate the changes in soil organic carbon (SOC) stocks, CH_4, and N_2O emissions, based on the standing biomass and plant growth that are provided by the vegetation method outlined above (section 6.2.1), wetland characteristics, and the planned management activities. The model simulates SOC stocks, CH_4, and N_2O emissions at the beginning of the reporting period based on an assessment of initial conditions at the site; then the model simulates the reporting period based on the current/recent management activity and any changes in the wetland conditions. This information characterizes the physical and chemical soil properties that in turn interact with the climatic regime, management practices, and vegetation response. The reported emissions for the land parcel must reflect the total for the entire land area. Accordingly, the per-unit area emission rates from DNDC are expanded based on the total wetland area for the land parcel to estimate total emissions.

Use equation 6-1, equation 6-2, and equation 6-3 to estimate SOC stock changes, CH_4 emissions, and N_2O emissions from a parcel of land in a wetland, respectively. Global warming potentials are provided in chapter 2.

Equation 6-1: Change in SOC Stocks for Wetlands

$$\Delta C_{soil} = (SOC_t - SOC_{t-1}) \times A \times CO_2MW$$

Where:

ΔC_{soil} = annual change in mineral soil organic carbon stock (metric tons CO_2-eq/year)

SOC_t = soil organic carbon stock at the end of the year (metric tons C/ha)

SOC_{t-1} = soil organic carbon stock at the beginning of the year (metric tons C/ha)

A = area of parcel (ha)

CO_2MW = ratio of molecular weight of CO_2 to C, 44/12 (dimensionless)

Equation 6-2: CH_4 Emissions from Wetlands

$$CH_{4Wetlands} = ER \times A \times CH_4MW \times CH_{4GWP}$$

Where:

$CH_{4Wetlands}$ = total CH_4 emissions from managed wetlands for the parcel (metric tons CO_2-eq/year)

ER = emission rate on a per unit wetland area (metric tons CH4-C/ha/year)

A = area of the parcel (ha)

CH_4MW = conversion of CH_4-C to C, 16/12 (dimensionless)

CH_{4GWP} = global warming potential for CH_4 (metric tons CO_2-eq/metric tons CH_4)

Equation 6-3: N_2O Emissions from Wetlands

$$N_2O_{Wetlands} = ER \times A \times N_2O_{MW} \times N_2O_{GWP}$$

Where:

$N_2O_{Wetlands}$ = total N_2O emissions from managed wetlands for the parcel (metric tons CO_2-eq/year)

ER = emission rate on a per unit land area (metric tons N_2O-N/ha/year)

A = area of the parcel (ha)

N_2O_{MW} = conversion of N_2O-N to N_2, 44/28 (dimensionless)

N_2O_{GWP} = global warming potential for N_2 O (metric tons CO_2-eq/metric tons N_2O)

To estimate the SOC stock changes, CH_4, and N_2O emissions, DNDC requires a considerable amount of information to characterize the plant production (section 6.2.1), wetland characteristics, and management activities. The initial step in applying the method is to parameterize DNDC using the baseline soil conditions, along with the corresponding forest or grassland conditions. For example, if a forest plantation is to be harvested and regenerated during the reporting period, the initial conditions should reflect the preharvest conditions. Based on the initial conditions, the model simulates baseline fluxes and the SOC stock prior to the reporting period for the entity.

Subsequently, the entity specifies the type of management activity(s) changes that occurred during the reporting period (if any occurred). Provisions are available to have multiple management activities on a single tract if there were mixed activities. Climatic factors, especially precipitation, can affect carbon turnover and wetland conditions. Consequently, weather data are a key input to DNDC, and will be provided from a climatological data set.

The simulation output at the end of each year is used to estimate the change in SOC stocks and the total amount of CH_4 and N_2O emissions for the year. Annual changes in SOC can be estimated based on the difference between years, and the total change in emissions can be estimated by combining the changes in SOC pools with the annual CH_4 and N_2O flux.

6.2.2.2 Activity Data

Activity data for the application of DNDC are summarized in table 6-4. Vegetation management information affects the amount of organic matter that is available for decomposition processes. Water management information conveys how the drainage system affects the soil water table dynamic as compared to an undrained condition. Soil tillage information is used to convey when the surface soil is disturbed, or its elevation changed because of the associated effects on decomposition. The fertilization information is needed because the addition of nitrogen greatly affects decomposition and N_2O production. In addition, land-use history influences the amount of soil organic carbon. If an entity is composed of different wetland types, it is recommended that separate estimates be prepared because the carbon turnover rate and GHG emissions can vary widely depending on hydric soil properties and the type of vegetation.

Table 6-4. Activity Data for Application of DNDC

Category	Management Practice	Data
Vegetation management	Grazing or management events should be included to capture the influence on carbon input to soils and subsequent effects on the soil carbon stocks.	▪ Harvesting: date, harvest, or cut fraction ▪ Understory thinning or chopping: date, chopped fraction ▪ Prescribed fire: date, the proportion of forest floor, and understory consumed ▪ Tree planting: date, species, density
Water management regime	Water table response to the drainage system, daily data.	▪ Drainage system: date, controlled water table elevation
Soil management	Application of soil amendments or site preparation practices for tree planting.	▪ Type of site preparation
Fertilization practices	Applications of mineral or organic nitrogen fertilizers will be needed to simulate the effect on N_2O emissions.	▪ Fertilization frequency, date, application rate (N, P kg/ha)

Category	Management Practice	Data
Land-use history	Summary of land-use practices over the past 5 years. For assessing if prior use affects parameterization. The time since a change in land management practice for assessing effects on decomposition.	▪ Fertilization regimes, drainage regimes, cropping, or forest management history.

6.2.2.3 Ancillary Data

The DNDC model requires relatively detailed information about the site (table 6-5). While default values are available for most parameters, some entity-specific data are needed to produce reasonable estimates. Most of the required soil input data are available from the national soils database (NCSS, 2022). Similarly, climate data are available from the Parameter-Elevation Regressions on Independent Slopes Model, or PRISM (PRISM Climate Group, 2018).

Table 6-5. Input Information Needed for the Application of DNDC

Category	Data
Climate	Daily maximum and minimum temperature, daily rainfall; nitrogen deposition in rainfall, or use the default value.
Vegetation	Standing biomass and biomass and detrital inputs are provided in section 6.2.1; belowground biomass is estimated based on aboveground biomass.
Soil	Hydraulic parameters and physical and chemical components, including thickness; layers; hydraulic conductivity; porosity; field capacity; wilting point; carbon content; pH; organic matter fractions; content of stone, sand, silt, and clay; and bulk density for major soil layers.
Hydrology	The water table below the surface is the daily input or starting position and DNDC can estimate GHG emissions and sinks using empirical functions.

6.2.2.4 Model Output

Model output includes annual estimates of CH_4, N_2O emissions, and changes in soil organic carbon stocks. The units of reporting are metric tons CO_2-eq/ha.

6.2.2.5 Limitations and Uncertainty

The models to estimate biomass carbon stock change in vegetation are robust with respect to species and community composition. However, uncertainties may be higher than for uplands because of limited background information. The merit of the recommended approach is that it ensures consistency for estimating changes in the vegetative carbon pool among land types and uses by using common methods as described in section 6.2.1. However, this approach complicates the application of DNDC for estimating changes in soil carbon pools and fluxes because it contains provisions for sequestering carbon in crops, grasslands, and forest vegetation. Accordingly, DNDC would have to undergo substantial revisions to accommodate the vegetative component as an input variable because the vegetation growth functions are integral to the consideration of hydrologic processes (especially evapotranspiration) and biogeochemical processes. The DNDC model could be used as a stand-alone tool for wetlands, but unfortunately, the production or biomass carbon functions have not been validated for many of the wetland plant communities.

The availability of water table data is essential to modeling the carbon cycle in wetland soils. Since the lack of site-specific water table data for a sufficient period is likely a constraint for most entities, an approach incorporating a hydrologic module or look-up table is needed. Hydrologic models that provide information on water table dynamics are inherently complex, but they can be effective (Dai. et al., 2010). Accordingly, the development of characteristic water table conditions for a range of climatological and soil settings would be a viable approach that can also incorporate water management effects (e.g., Skaggs et al., 2011).

Tidal freshwater forested wetlands, which occur to a limited extent along the Atlantic, Gulf, and Pacific coasts, are a special case. The tidal influence on water table dynamics can make characterizing the water table regime of such sites more difficult. For DNDC to simulate the carbon dynamics would require detailed data on daily water table dynamics, and such detailed data are unavailable.

While the effects of the various management regimes on soil carbon pools and GHG fluxes have not been widely studied, this is more of a consideration with respect to uncertainties in the estimates as opposed to a limitation to its application. The DNDC framework is robust because it is a process-based model that has been validated in a wide variety of wetland types and soils. However, it has not been extensively tested on Histosols or peat soils, especially with respect to changes in soil carbon stocks. The model was validated successfully for estimating CH_4 from microtopographic positions in a peatland (Zhang et al., 2002), but additional work is needed to better address the wide array of managed Histosols that exist across the country.

Similarly, this method is not applicable to constructed wetlands, impoundments, or shallow reservoir systems that have extended periods of ponding; those sites would tend to have dynamics more similar to a lake or pond as opposed to a terrestrial ecosystem.

Concerning the forest model, the accuracy of the estimates is dependent on the applicability of the available site index curves. While the general curves are available for all species, they may not accurately represent the site or the entity's management regime. Provisions are included within FVS for customizing the tree site index curves, which could be important for an entity, especially if genetically improved planting stock and fertilization regimes are employed.

Detrital organic matter is the source of decomposition processes. The effect of vegetation on wetland carbon dynamics is promulgated through the amount of organic matter and the water regime (e.g., evapotranspiration). Accordingly, the accuracy of the vegetation productivity and turnover will affect the estimates of the soil carbon pools and GHG flux.

Water table position is the most critical factor affecting CH_4 and N_2O flux from the wetland soil (Trettin et al., 2006). Accordingly, considerations to improve that estimate as discussed in section 6.2.2 will improve the estimates of GHG emissions from the soil. There are other uncertainties in the activity and ancillary data, as well as a model structure that can create bias and imprecision in the resulting estimates. Wetlands typically exist in a mosaic with upland forests, grasslands, and cultivated lands. Accordingly, the accuracy of partitioning the entity into upland (agriculture, forest) and wetlands will affect the accuracy of the estimates.

6.3 Chapter 6 References

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Appendix 6-A: Method Documentation

6-A.1 Biomass Carbon in Wetlands

6-A.1.1 Rationale for Method

Various approaches are used for estimating tree biomass carbon, but ultimately each relies on allometric relationships developed from a characteristic subset of trees. The FVS is offered for the "Level 3" approach to estimate tree biomass. FVS is model-based approach that is specific to United States conditions and a Tier 3 method as defined by the IPCC. The simulator is the most complete model in the United States to estimate tree biomass. Regional versions of FVS have been refined based on large databases developed from many years of data collection on forest stands throughout the United States, thereby providing improved estimates while requiring few input parameters from the user.

Both IPCC (Ogle et al., 2019) and the U.S. EPA (2020) consider herbaceous biomass carbon stocks to be ephemeral and recognize that there are no net emissions to the atmosphere following crop growth and senescence during one annual crop cycle (West et al., 2011). However, with respect to changes in land use (e.g., forest to cropland), IPCC (Ogle et al., 2019) recommends that cropland biomass be counted in the year that land conversion occurs, and the same assumption also applies for grassland (McConkey et al., 2019). According to IPCC, estimating the herbaceous biomass carbon stock during changes in land use is necessary to quantify the influence of herbaceous plants on CO_2 uptake from the atmosphere and storage in the terrestrial biosphere. However, this method does not recognize changes in herbaceous biomass that occur with changes in crop rotations, nor does it recognize long-term increases in annual crop yields. The method in this chapter is considered a Tier 2 method as defined by IPCC because it incorporates factors that are based on United States-specific data and differs from the methodology in U.S. EPA (2020) because of this.

The methods presented in this section are based on the following definitions.

- *Live vegetation biomass:* Live vegetation includes trees, shrubs, and grasses. The tree carbon pool includes aboveground and belowground carbon mass of live trees, and the aboveground biomass of the forest understory is defined in section 5.1.3. The methods to estimate full-tree and aboveground biomass for trees greater than one inch in diameter at breast height (dbh) are based on the models provided in the forest section.

The forest understory vegetation includes all biomass of undergrowth plants in a forest, including woody shrubs and trees less than one inch in dbh.

- *Standing dead wood (dead biomass)*: The carbon pool of standing deadwood in a forested wetland is defined and estimated according to the methods in chapter 5.
- *Down dead organic matter—litter* layer *(dead biomass)*: Down dead organic matter includes the litter layer composed of small pieces of dead wood, branches, leaves, and roots in various stages of decay. This layer is typically designated as the organic layer of the soil. This pool also includes logs in various stages of decay that lie on the soil surface (e.g., down-dead wood, forest floor or litter).

6-A.2 Soil C, N2O, and CH_4 in Wetlands

6-A.2.1 Rationale for Method

The production and consumption of carbon in wetland-dominated landscapes are important for estimating the contribution of GHGs, including CO_2, CH_4, and N_2O emitted from those areas to the atmosphere. The generation and emission of GHGs from wetland-dominated landscapes are closely related to inherent biogeochemical processes that also regulate the carbon balance (Rose and Crumpton, 2006). However, those processes are highly influenced by the land use, vegetation, soil organisms, chemical and physical soil properties, geomorphology, and climate (Smemo and Yavitt, 2006).

Given this complexity, a process-based modeling approach is desirable because these approaches typically account for more of the variability than simpler emission factor methods (IPCC, 2006). However, few process-based models have been tested sufficiently to be used for operational reporting of GHG emissions. One of the more widely tested models for estimating GHG fluxes from wetlands is the DNDC model. DNDC is a process-based biogeochemical model that is used to predict plant growth and production, carbon and nitrogen balance, and generation and emission of soil-borne trace gases by means of simulating carbon and nitrogen dynamics in natural and agricultural ecosystems (Li et al., 2000; Miehle et al., 2006; Stang et al., 2000) and forested wetlands (Zhang et al., 2002). The model is designed to explicitly consider anaerobic biogeochemical processes, which are fundamental to addressing soil carbon dynamics and trace GHG dynamics in wetlands (Trettin et al., 2001). It integrates decomposition, nitrification–denitrification, photosynthesis, and hydro-thermal balance within the ecosystem. These components are mainly driven by environmental factors, including climate, soil, vegetation, and management practices.

DNDC has been tested and used for estimating GHG emissions from forested ecosystems in a wide range of climatic regions, including boreal, temperate, subtropical, and tropical (Kesik et al., 2006; Kiese et al., 2005; Kurbatova et al., 2008; Li et al., 2004; Stang et al., 2000; Zhang et al., 2002), and similarly for grasslands and cultivated wetlands (Giltrap et al., 2010; Rafique et al., 2011).

Appendix 6-B: Summary of Research Gaps for Managed Wetland Systems.

Wetland management, and its influence on GHG emissions, is not as well studied as some of the other management practices in this report, such as tillage in croplands or forest harvesting practices in uplands. There is the potential for improving the estimation of GHG emissions associated with different management practices in the future if there are monitoring activities and studies to fill information gaps. A select number of information needs and research gaps are identified here.

- The 2013 Supplement to the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines provide new guidance for estimating emissions from drained inland organic soils, rewetted organic soils, coastal wetlands, inland wetland mineral soils, and constructed wetlands for wastewater treatment (Blain et al., 2013). These newly developed guidelines will be compared to the technical methods provided in this report.
- Water table position is the principal factor affecting carbon dynamics in wetlands; unfortunately, while estimates of water table depth are provided in the Web Soil Survey, there is a lack of long-term data, which is needed to characterize the water table response to a management regime and to provide a basis for validating assessment tools. Establishment of a network of water table monitoring sites within selected USDA, Forest Service experimental forests and ranges and USDA, Agricultural Research Service (ARS) experiment stations could provide the continuity in measurements and linkages with common management practices to represent the major soil and climatic condition in the United States.
- Improving modeling capabilities that integrate surrounding areas with the wetlands that receive surface and subsurface drainage waters will allow for modeling the flows of nutrients and organic matter into wetlands and subsequent losses to other wetlands beyond the entity's operation. This type of assessment framework is used in several established spatially explicit hydrologic models; the need is to integrate the biogeochemistry. Linked models can be used at present; but development of a functionally integrated system is needed to support broad-based applications.
- While the National Range and Pasture Handbook provides methods for determining and estimating site-specific biomass, there is a need, generally, for improved information on biomass production and allocation in managed wetlands. These data could be obtained through a coordinated monitoring program employing USDA, Forest Service experimental forests and ranges, USDA, ARS experiment stations, and U.S. Department of the Interior wildlife refuges to monitor production of key species or vegetation types in association with common management prescriptions. There is also need for more detailed mechanistic research to provide information on energy, water, and GHG dynamics on selected managed sites; this information is critical for validating process-based models.
- Field-based studies are needed to develop more complete databases that provide ancillary data for GHG estimation, particularity CH_4 emissions for DNDC or similar process-based models, rather than relying on entity input, which will likely be challenging. A key attribute of this work should be the consideration of the inherent spatial and temporal variability within a site.
- Further quantification of the controlling and threshold parameters and associated uncertainty within DNDC or similar process-based models to estimate trace gas emissions is

warranted. This work could also suggest a path towards development of an assessment tool that was not reliant on a wide array of parameters to effectively simulate the GHG dynamics of the site.

- A more robust and extensive database on GHG emissions from freshwater tidal (salinity <0.5 percent) palustrine wetlands is needed to more fully understand the drivers of emissions, in addition to providing a more complete dataset for parameterization and evaluation of process-based models.
- Studies on individual sites and meta-analyses of existing data are needed to fully evaluate the net GHG flux for CH_4, N_2O, and soil carbon. Most studies only consider one of the GHGs and may mask some of the differences in fluxes among the GHGs associated with a management activity.

This list is not exhaustive but is intended to provide some direction for improving the estimation methods for GHG emission from wetlands.