Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry:

METHODS FOR ENTITY-SCALE INVENTORY

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Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory

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Executive Summary

The U.S. Department of Agriculture (USDA) published its first version of *Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory* in 2014, as directed by Section 2709 of the Food, Conservation, and Energy Act of 2008. In this updated version, USDA has revised the report to reflect the latest science-based methods for estimating greenhouse gas (GHG) emissions and removals from agricultural and forestry activities.

This report has several important purposes, including the following:

- Enables landowners and others to estimate entity-scale GHG fluxes and impacts (including fluxes associated with different management practices) using the most accurate science-based methods currently available.
- Allows USDA to estimate GHG fluxes from current and future conservation programs and practices and assess the performance of conservation and renewable energy programs using the most accurate science-based methods currently available given agency objectives and available resources. Note that the intensity metrics of GHGs (i.e., emissions per production unit) are not explicitly addressed in this guidance.
- Provides a basis for updating USDA's GHG flux estimation tools, including COMET-Planner and COMET-Farm (see box 1-2).
- Informs GHG estimates for other programs. For example, this report may inform emerging methods that underlie voluntary GHG registries, facilitate regional GHG markets, and provide technical inputs for future GHG reporting programs.

This report was developed by authors that have expertise in GHG accounting specific to agriculture and forestry. The authors were chosen based on their experience with GHG inventories and accounting methodologies and their professional research experience. The authors worked in teams under the direction of one lead author for each team (plus one co-lead author for the forestry chapter).

Summary of GHG Flux Sources and Approaches

There are several approaches to GHG emissions estimation at an entity scale, and each approach gives varying accuracy and precision. For some agricultural sectors, direct measurement may be the most accurate way of estimating emissions, however, this often requires expensive equipment or techniques that are not feasible for a single landowner or manager. However, simple lookup tables and estimation equations alone often do not adequately represent local variability or conditions. This report aims to provide methods that balance straightforward approaches, practical data requirements, and appropriate scientific rigor in a way that is transparent and justified.

The authors evaluated updated sources to reflect current science, including the Intergovernmental Panel on Climate Change (IPCC) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The types of approaches that the authors recommended in this report include multiple levels, or tiers, of complexity and accuracy, based on the best available data and methods, similar to the methodological tiers developed by the IPCC, which are based on the complexity of different approaches for estimating GHG emissions (see box ES-1).

Box ES-1. IPCC Tiers

- Tier 1 represents the simplest methods, using default equations and emission factors provided in the IPCC guidance.
- Tier 2 uses default methods, but emission factors that are specific to different regions.
- Tier 3 uses country-specific estimation methods, such as a process-based model.

The methods range from the simple Tier 1 approaches to the most complex Tier 3 approaches. Higher-tier methods, particularly Tier 3 methods, are expected to reduce uncertainties in the GHG estimates if sufficient activity data are available and the methods are well developed (Ogle et al., 2019a).

The methods described in this report fall into the following categories:

- Basic estimation equations use default equations and emission factors, such as IPCC Tier 1 methods.
- Inference uses geography-, crop-, livestock-, technology-, or practice-specific emission factors to approximate emissions/removal factors. This approach is similar to an IPCC Tier 2 method and is more accurate, more complex, and requires more data inputs than the basic estimation.
- Modified IPCC/empirical and/or process-based modeling, comparable to IPCC Tier 2 or IPCC Tier 3 methods. These methods are the most demanding in terms of complexity and data requirements and produce the most accurate estimates.

Table ES-1 categorizes the GHG flux sources with the types of approaches that are recommended in this report.

Table ES-1: Summary of the Sources of GHG Fluxes and Types of Approaches in This Report

Source	Basic Estimation Equation	Inference	Modified IPCC or Empirical Model	Processed-Based Model
Croplands/Grazing Lands	▪ CH_4 Emissions From Rice Cultivation[a] ▪ CO_2 From Urea Fertilizer Application ▪ Direct N_2O Emissions From Mineral (Other Crops) and Organic Soils[a] ▪ Indirect N_2O Emissions From Mineral Soils ▪ Biomass Carbon Stock Changes (Other Woody) ▪ CH_4 Flux for Organic Soils ▪ Non-CO_2 Emissions From Biomass Burning	▪ Soil Organic Carbon Stocks for Organic Soils ▪ CO_2 From Liming ▪ CH_4 Emissions From Rice Cultivation[a] ▪ Biomass Carbon Stock Changes (Herbaceous)	▪ Biomass Carbon Stock Changes (Woody) ▪ CH_4 Flux for Mineral Soils ▪ Soil Organic Carbon Stocks for Mineral Soils (Other Crops)[a]	▪ Soil Organic Carbon Stocks for Mineral Soils (Most Crops)[a] ▪ Direct N_2O Emissions From Mineral Soils (Most Crops and Grazing Lands)[a]
Animal Production	▪ Enteric CH_4 From Swine ▪ Enteric CH_4 From Other Animals (American Bison, Llamas, Alpacas, and Managed Wildlife) ▪ CH_4 and N_2O From Other Animals Housing[a]	▪ CH_4 From Dairy Cattle, Beef Cattle, Swine, and Poultry Housing ▪ CH_4 and N_2O From Aerobic Lagoons ▪ CH_4 and N_2O From Temporary Stack and Long-Term Stockpile ▪ CH_4 and N_2O From Composting ▪ Enteric CH_4 From Other Animals (Goats) ▪ CH_4 and N_2O From Other Animals Housing[a]	▪ Enteric CH_4 From Dairy Cattle, Sheep, Beef Cow-Calf, Bulls, Stockers, Feedlot Cattle ▪ CH_4 From Manure From Barn Floors—Dairy Cattle ▪ N_2O From Dairy Cattle, Beef Cattle, Swine, and Poultry Housing[c] ▪ CH_4 and N_2O From Anaerobic Lagoon, Runoff Holding Pond, Storage Tanks ▪ CH_4 From Anaerobic Digester	—

Source	Basic Estimation Equation	Inference	Modified IPCC or Empirical Model	Processed-Based Model
Forestry	—	—	▪ Silvicultural Practices (Reforestation; Extended Rotation; Avoided Deforestation) ▪ Fuels and Management/ Avoided Wildfire (Natural Disturbances) ▪ Urban Forest Management ▪ Harvested Wood Products	▪ Urban Forest Management ▪ Fuels and Management/ Avoided Wildfire (Natural Disturbances) ▪ Silvicultural Practices (Reforestation; Extended Rotation; Avoided Deforestation)
Wetlands	—	—	—	▪ Biomass Carbon ▪ Soil Carbon, N_2O, and CH_4
Land-Use Change	▪ Annual Change in Carbon Stocks in Dead Wood and Litter Due to Land Conversion ▪ Change in Soil Organic Carbon Stocks for Mineral Soils ▪ Annual Change in Carbon Stocks in Biomass Due to Land Conversion	—	—	—

[a] Tier used is dependent on data availability (e.g., soil and crop conditions).

Overview of Recommended GHG Estimation Methods

This report includes the most appropriate science-based approaches and specific methods for estimating farm- or forest-scale GHG emissions. For each source of GHG fluxes, table ES-2 provides a summary of the report methods, including:

- A description of the chosen methodology.
- A list of the management practices that impact GHG fluxes. For this report, management practices are defined as activities undertaken by the entity that can affect GHG emissions and removals. Examples of management practices include (but are not limited to) irrigation, tillage, and residue management for croplands.
- Emission factors used in the methodology; an emission factor is a coefficient that quantifies the emissions or removals of a gas per unit of activity.
- A brief explanation of how the methods have changed since the 2014 report. In some cases, the proposed methods have not previously been applied in specifically the way that is proposed. In other cases, the authors have proposed updated methods that reflect new science since the last report (for example, methods and data published in *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*). While the effect of these updates on emissions cannot by quantified or generally qualified as an increase or decrease because the effect is dependent on certain activity or ancillary data (e.g., animal diet), the updates are meant to offer increased accuracy.
- A description of why the chosen methodology is an improvement over other GHG estimation methodologies.

In addition to the changes in methods listed in table ES-2, the global warming potential (GWP) values used in the calculations are updated in this report. GWP values correlate to how much heat the GHG molecules absorb in the atmosphere. Table 2-1, in chapter 2, presents the GWPs used in this report.

Table ES-2: Summary of Source Categories, Recommended Methods, and Emission Factors in This Report

Source	Methodology Approach	Management Practices	Source of Emission Factors	Update Since 2014 Methods Report	Improvements Compared to Other Greenhouse Gas Methodologies
Croplands/Grazing Lands					
Biomass Carbon Stock Changes	Herbaceous biomass and woody biomass are estimated with an empirical method using entity-specific data as input into the IPCC equations (McConkey et al., 2019; Ogle et al., 2019b). Woody biomass from trees uses allometric equations and entity-measured data (Chojnacky et al., 2014).	Changes in the estimated biomass carbon stock for cropland and grazing land if there is a land-use change or a change in the crop or forage species.	U.S.-specific default values (West et al., 2010) are used for estimating biomass carbon for annual crops and grazing lands. The IPCC default is proposed for estimating the carbon fraction value. Estimate yield (in units of dry matter) or use average values from USDA, National Agricultural Statistics Service statistics.	Updated reference to IPCC (McConkey et al., 2019; Ogle et al., 2019b)) for herbaceous biomass though the equation/methods stay the same. For woody biomass, method updates allow for a combination of Tier 1 and Tier 3.	This method was chosen because it captures the influence of land-use change and changes in crop or forage species on biomass carbon stocks by using U.S.-specific default values where entity-specific data are not available.
Soil Organic Carbon Stocks for Mineral Soils	Ogle et al. (2019a) provide the stock difference approach to estimate soil organic carbon at the beginning and end of the year for mineral soils.	Addition of carbon in manure and other organic amendments; tillage intensity; residue management (retention in field without incorporation; retention in field with incorporation; and removal with harvest, burning, or grazing); influence of bare and vegetated fallows; irrigation effects on decomposition in cropland and grazing land systems; setting aside cropland from production; influence of fire on oxidation of soil organic matter; and woody plant encroachment, agroforestry, and silvopasture effects on carbon inputs and outputs.	The DayCent model (Parton et al., 1987) or country-specific stock change factors depending on the crop and soil conditions (U.S. EPA, 2020; Ogle et al., 2019b).	Biochar amendments to soil are specifically addressed with updates provided in Ogle et al. (2019a) and described in Woolf et al. (2021).	The DayCent model has been demonstrated to represent the dynamics of soil organic carbon and estimate soil organic carbon stock change in cropland and grasslands (Parton et al., 1993). There have been uncertainties noted in the model in Ogle et al. (2007). The model captures soil moisture dynamics, plant production, and thermal controls on net primary production and decomposition with a time step of a month or less.

Source	Methodology Approach	Management Practices	Source of Emission Factors	Update Since 2014 Methods Report	Improvements Compared to Other Greenhouse Gas Methodologies
Soil Organic Carbon Stocks for Organic Soils	CO_2 emissions from drainage of organic soils (i.e., histosols) are estimated with an inference method (cf., IPCC Tier 2) using the IPCC equation (Ogle et al., 2019a).	Cropland drainage	Emission factors are from U.S. GHG Inventory (U.S. EPA 2020) and are region-specific based on typical drainage patterns and climatic controls (e.g., temperature/ precipitation) on decomposition rates.	Updated to reference IPCC (2019) though the methods remained the same (Ogle et al., 2019a).	Uses entity-specific annual data as input into the equation used in the U.S. GHG Inventory (U.S. EPA, 2020).
Direct N_2O Emissions From Mineral Soils	Use the DayCent model for major commodity crops, (e.g., corn, cotton, alfalfa). Use a modified IPCC Tier 1 (Hergoualc'h et al., 2019) with scaling factors and in cases where there are insufficient empirical data to derive a base emission rate.	Nitrogen application to crops. In addition, specific management practices are included as scaling factors. Management practices that influence a portion of the emission rate include: ▪ Use of slow-release formulation ▪ Nitrification inhibitor application Manure nitrogen directly deposited on pasture range or paddock management practices that influence the entire pool of mineral nitrogen include: ▪ Tillage ▪ Biochar amendments	For Tier 1, adjust the base emission factors with scaling factors related to specific crop management practices. Scaling factors determined from IPCC (Drösler et al., 2013; Hergoualc'h et al., 2019) or management practice scaling factors from the published literature or an analysis by the authors.	Some soil conditions updated to a Tier 1 approach.	The method is based on using results from process-based models and measured N_2O emissions in combination with scaling factors based on U.S.-specific empirical data on a seasonal timescale.
Direct N_2O Emissions From Drainage of Organic Soils	Direct N_2O emissions from drainage of organic soils, i.e., histosols, are estimated with a basic estimation equation (cf., modified IPCC Tier 1) method (Hergoualc'h et al., 2019).	Drainage of organic soils.	Emission factors are from IPCC (Drösler et al., 2013; Hergoualc'h et al., 2019) or management practice scaling factors from published literature.	Updated to reference IPCC (2019) equations but the methods remained the same (Drösler et al., 2013; Hergoualc'h et al., 2019).	Uses entity-specific annual data as input into the equation used in the U.S. GHG Inventory (U.S. EPA, 2020).

Source	Methodology Approach	Management Practices	Source of Emission Factors	Update Since 2014 Methods Report	Improvements Compared to Other Greenhouse Gas Methodologies
Indirect N_2O Emissions	Indirect soil N_2O emissions are estimated with an inference (cf., IPCC Tier 1) based on IPCC methodology (Hergoualc'h et al., 2019).	Irrigation.	IPCC defaults are used for estimating the proportion of nitrogen that is subject to leaching, runoff, and volatilization. Where cropping systems with leguminous and non-leguminous winter cover crops are grown, a U.S.-specific emission factor is provided.	Updated to reference IPCC (2019) equations but the methods remained the same (Hergoualc'h et al., 2019).	This method uses entity-specific seasonal data on nitrogen management practices.
CH_4 Flux for Nonflooded Soils	CH_4 flux by soil is estimated with an equation that uses average values for methane oxidation in natural vegetation—whether grassland, coniferous forest, or deciduous forest—attenuated by current land use practices. This approach is an empirical model (IPCC Tier 3).	Land management including cultivation for crop production, grazing in grasslands, forest harvest, grassland, or forest fertilization.	Annual average CH_4 flux emissions and removals are from a meta-analysis by the authors. Emission factors for drained organic soil from Drösler et al. (2013).	Updates address mineral and drained organic soils.	CH_4 emissions from nonflooded mineral soils are not addressed by IPCC and are not included in the U.S. GHG Inventory (U.S. EPA, 2020). The method incorporates entity-specific annual data.
CH_4 Emissions From Flooded Rice Cultivation	Either IPCC Tier 1 or 2 estimation equation, depending on the rice production region (Ogle et al., 2019b).	Scaling factors are differentiated by hydrological context (e.g., irrigated, rain fed, upland (i.e., dry soil)—all rice fields in the United States are irrigated), cultivation period flooding regime (e.g., continuous, multiple aeration), time since last flooding (prior to cultivation; e.g., more than 180 days, less than 30 days) and type of organic amendment	Linquist et al. (2018) provide emission factors specific to the California and Mid-South regions. Otherwise, default IPCC factors are available.	Updated to include IPCC Tier 2 equation for certain regions. Region-specific emission factors are built on scaling factors, amount of clay soil present, and cultivation period, among other variables.	Provides U.S.-specific considerations, including region-specific distinctions.

Source	Methodology Approach	Management Practices	Source of Emission Factors	Update Since 2014 Methods Report	Improvements Compared to Other Greenhouse Gas Methodologies
		(e.g., compost, farmyard manure).			
CO_2 From Liming	An inference (cf., IPCC Tier 2) method is used to estimate CO_2 emissions from application of carbonate limes (de Klein et al., 2006) with U.S.-specific emission factors (adapted from West and McBride, 2005).	The amount of lime, crushed limestone, or dolomite applied to soils.	U.S.-specific emission factors (West and McBride, 2005).	No change from the previous methods.	Uses U.S.-specific emission factors as annual input into the IPCC equation, which is consistent with the U.S. GHG Inventory (U.S. EPA 2020).
Non-CO_2 Emissions From Biomass Burning	Non-CO_2 GHG emissions from biomass burning of grazing land vegetation or crop residues are estimated with an inference (cf., IPCC Tier 1) method (Aalde et al., 2006).	Area burned.	Emission factors are from values in the IPCC guidelines (Aalde et al., 2006) and West et al. (2010) for the residue:yield ratios.	No change from the previous methods.	Uses entity-specific annual data as input into the IPCC equation.
CO_2 From Urea Fertilizer Application	CO_2 emissions from application of urea or urea-based fertilizers to soils are estimated with a basic estimation equation (cf., IPCC Tier 1) method (de Klein et al., 2006).	The amount of urea fertilizer applied to soils.	Emission factors are from values in the IPCC guidelines (de Klein et al., 2006). This method assumes that the source of CO_2 used to manufacture urea is fossil fuel CO_2 captured during NH_3 manufacture.	No change from the previous methods.	Uses entity-specific annual data as input into the IPCC equation.
Animal Production Systems					
Enteric Fermentation					
Dairy Cattle	Adopted from Niu et al. (2018) equation for lactating cows and Moraes et al. (2014) for	Dietary changes: increasing DMI, using fibrous concentrate rather than starch concentrate, feeding rapidly degraded starch	Emission factors needed for nonlactating and heifer populations from Moraes et al. (2014).	Updated to equations that perform best for North America, as compared to other	Niu et al. (2018) equation contained the most prediction variables and had the highest prediction

Source	Methodology Approach	Management Practices	Source of Emission Factors	Update Since 2014 Methods Report	Improvements Compared to Other Greenhouse Gas Methodologies
	both nonlactating and heifer populations. Inputs include milk fat, body weight, and dietary intake and composition.	(such as barley), and addition of dietary fat. Feeding 3-NOP, nitrates, or lipid supplementation is also included.		known sources/equations.	accuracy, similarly Moraes at al. (2014) had the highest prediction accuracy for simple models based on GEI.
Nongrazing Beef Cow-Calf, Bulls, and Stockers	IPCC (2019) Tier 2 approach. The calculation considers weight, weight gain, mature weight, pregnancy, lactation, other activity (grazing, confined, daily work), and the energy content of the animals' diets.	*Dietary changes:* considerations for additions of ionophores, supplementary fat content, changes to grain type or processing within the diet, and/or impacts of using fibrous concentrate rather than starch concentrate, feeding rapidly degraded starch (such as barley)	Emission factors are determined with the IPCC (2019) Tier 2 equation. Methane conversion factor (Y_m) based on animal-specific guidance in the U.S. GHG Inventory (U.S. EPA 2020).	Updated to reference IPCC (2019) but the equations remained the same (Gavrilova et al., 2019).	The equations utilized are the same as existing inventory methods; however, the methods use farm-specific feed types and monthly, rather than annual, data (i.e., account for seasonal variation in forage quality).
Grazing Beef Cow-Calf, Bulls, and Stockers	Modified IPCC (2019) Tier 2 approach.	*Dietary changes:* increasing DMI or methane yield dependent on feed quality. *Activity changes:* confining currently grazing animals, fewer work hours per day.	Modified IPCC (2019) equation to determine emission factor.	Updated to IPCC (2019) Tier 2 equation and default IPCC (2019) values (Gavrilova et al., 2019).	
Feedlot Cattle	IPCC (2019) Tier 2 approach. The calculation considers weight, weight gain, mature weight, pregnancy, lactation, other activity (grazing, confined, daily work), and the energy content of the animals' diets.	*Dietary changes:* increasing DMI, using fibrous concentrate rather than starch concentrate, feeding rapidly degraded starch (such as barley), and addition of dietary fat. *Activity changes:* confining currently grazing animals, fewer work hours per day, fewer days on feed prior to slaughter.	Correction factor to Y_m developed based on up-to-date research. See appendix 4-B.2.3.	Updated to reference IPCC (2019) though the equations remained the same. Updated the correction factor to Y_m.	The method provided accounts for changes in enteric CH_4 related to changes in diet or management, which Gavrilova et al. (2019) does not currently offer for default methods.

Source	Methodology Approach	Management Practices	Source of Emission Factors	Update Since 2014 Methods Report	Improvements Compared to Other Greenhouse Gas Methodologies
Sheep, When DMI Is Known	Howden et al. (1994) equation based on dietary DMI	Dietary changes, but no well-developed research due to difficulty of obtaining accurate feed-intake estimates for grazing sheep.	The equation from Howden et al. (1994) estimates emissions based solely on DMI; hence, emission factors are not utilized.	No change from the previous methods.	This method uses actual monthly estimates of DMI, rather than head count, as utilized by the IPCC (2019) Tier 1 equation.
Sheep, When DMI is Unknown	IPCC (2019) Tier 2 equation	None.	Uses IPCC (2019) default Y_m if unknown.	New method since the last version of the report. Provided to increase usability for users less familiar with diet (as compared to Howden et al. (1994) equation.)	None.
Swine	IPCC (2006) Tier 1 approach (Dong et al., 2006).	None.	Uses IPCC (2006) Tier 1 emission factor.	No change from the previous methods.	None.
Other Animals (Goats)	IPCC (2019) Tier 2 equation	None.	Uses IPCC (2019) default Y_m.	Updated to reference IPCC (2019) but the equations remained the same.	None.
Other Animals (American Bison, Llamas, Alpacas, Managed Wildlife)	IPCC Tier 1 approach for American bison (based on buffalo, modified by average animal weight), deer, llamas, and managed wildlife.	None.	Uses IPCC (2019) Tier 1 emission factors.	Updated to reference IPCC (2019) though the equations remained the same. However, Gavrilova et al. (2019) provided some updates to emission factors or other activity data.	None.
Housing					
CH_4 Emissions From Dairy Manure on Freestall Barn Floors	Empirical model by Chianese et al. (2009) For barn floors and IPCC (2019) Tier 2 for other dairy housing.	None.	Empirical relationship as provided in Chianese et al. (2009).	No updates for emissions from barn floors. Other housing updated to reference IPCC (2019), though the	Utilizes climate and entity characteristics.

Source	Methodology Approach	Management Practices	Source of Emission Factors	Update Since 2014 Methods Report	Improvements Compared to Other Greenhouse Gas Methodologies
or Other Housing				equations remained the same. However, Gavrilova et al. (2019) provided some updates to emission factors or other activity data.	
N_2O Emissions From Dairy Cattle Housing	IPCC (2019) Tier 2 approach with the amount of nitrogen excreted determined by equations from Reed et al. (2015).	Animal diets and type of manure storage.	Uses available emission factors and ammonia losses from Koelsch and Stowell (2005), Voglmeier et al. (2018); Sommer et al., (2019); Adhikari et al. (2020); Fischer et al. (2015); and IPCC (2019).	Updated to reference IPCC (2019) but the equations remained the same (Gavrilova et al., 2019). Emission factors or other activity data may have been updated, including the equations to determine nitrogen excreted.	Uses nitrogen balance approach to adjust nitrogen in housing to account for ammonia losses.
CH_4 Emissions From Beef Cattle, Swine Housing, and Poultry Housing	IPCC Tier 2 approach.	Type and duration of manure storage.	Uses a combination of IPCC (2019) and U.S. EPA (2020) Inventory emission factors.	Updated to reference IPCC (2019) though the equations remained the same (Gavrilova et al., 2019).	None.
N_2O Emissions From Beef Cattle	IPCC (2019) Tier 2 approach with the amount of nitrogen excreted determined by equations from Dong et al. (2014).	Animal diets.	For feedlot cattle use Dong et al. (2014) equation to determine nitrogen excretion.	Updated to reference IPCC (2019) but the equations remained the same. Emission factors or other activity data may have updated, including the equations to determine nitrogen excreted.	Uses nitrogen balance approach to adjust nitrogen in housing to account for ammonia losses.
N_2O Emissions From Swine,	IPCC Tier 2 approach including updated nitrogen excreted	Animal diets and type of manure storage.	Uses IPCC (2019) emission factors and ammonia losses from Koelsh and Stowell	Updated to reference IPCC (2019) though the equations remained the	Uses nitrogen balance approach to adjust nitrogen in housing to

Source	Methodology Approach	Management Practices	Source of Emission Factors	Update Since 2014 Methods Report	Improvements Compared to Other Greenhouse Gas Methodologies
		(e.g., compost, farmyard manure).			
CO_2 From Liming	An inference (cf., IPCC Tier 2) method is used to estimate CO_2 emissions from application of carbonate limes (de Klein et al., 2006) with U.S.-specific emission factors (adapted from West and McBride, 2005).	The amount of lime, crushed limestone, or dolomite applied to soils.	U.S.-specific emission factors (West and McBride, 2005).	No change from the previous methods.	Uses U.S.-specific emission factors as annual input into the IPCC equation, which is consistent with the U.S. GHG Inventory (U.S. EPA 2020).
Non-CO_2 Emissions From Biomass Burning	Non-CO_2 GHG emissions from biomass burning of grazing land vegetation or crop residues are estimated with an inference (cf., IPCC Tier 1) method (Aalde et al., 2006).	Area burned.	Emission factors are from values in the IPCC guidelines (Aalde et al., 2006) and West et al. (2010) for the residue:yield ratios.	No change from the previous methods.	Uses entity-specific annual data as input into the IPCC equation.
CO_2 From Urea Fertilizer Application	CO_2 emissions from application of urea or urea-based fertilizers to soils are estimated with a basic estimation equation (cf., IPCC Tier 1) method (de Klein et al., 2006).	The amount of urea fertilizer applied to soils.	Emission factors are from values in the IPCC guidelines (de Klein et al., 2006). This method assumes that the source of CO_2 used to manufacture urea is fossil fuel CO_2 captured during NH_3 manufacture.	No change from the previous methods.	Uses entity-specific annual data as input into the IPCC equation.
Animal Production Systems					
Enteric Fermentation					
Dairy Cattle	Adopted from Niu et al. (2018) equation for lactating cows and Moraes et al. (2014) for	Dietary changes: increasing DMI, using fibrous concentrate rather than starch concentrate, feeding rapidly degraded starch	Emission factors needed for nonlactating and heifer populations from Moraes et al. (2014).	Updated to equations that perform best for North America, as compared to other	Niu et al. (2018) equation contained the most prediction variables and had the highest prediction

Source	Methodology Approach	Management Practices	Source of Emission Factors	Update Since 2014 Methods Report	Improvements Compared to Other Greenhouse Gas Methodologies
		diets.			
N_2O Emissions	IPCC Tier 2 approach utilizing data on total initial nitrogen and dry manure.	Manure handling (i.e., no mix or active mix) and animal diets.	Uses emission factors from IPCC.	Updated to IPCC (2019) though the equations remained the same (Gavrilova et al., 2019).	Considers diet and climate characteristics.
Liquid Manure Storage and Treatment—Aerobic Lagoon					
CH_4 Emissions	The methane correction factor for aerobic treatment is negligible and was designated as 0 in accordance with the IPCC.	Not applicable.	Uses emission factors from IPCC.	No change from the previous methods.	Not estimated.
N_2O Emissions	IPCC Tier 2 method.	Configuration of storage (e.g., volume of lagoon), natural or forced aeration, and animal diets.	Uses emission factors from IPCC.	Updated to IPCC (2019) but the equations remained the same (Gavrilova et al., 2019).	None.
Liquid Manure Storage and Treatments—Anaerobic Lagoon, Runoff Holding Pond, Storage Tanks					
CH_4 Emissions	IPCC (2019) Tier 2 method.	Configuration of storage unit (e.g., covered or uncovered storage, presence or absence of crust) and animal diets.	Uses "MCF Calculations Example Spreadsheet" from IPCC (2019).	Updated from the Sommer et al. (2004) model.	Considers diet and storage temperature characteristics.
N_2O Emissions	Emissions are a function of the exposed surface area and U.S.-specific emission factors.	Configuration of storage unit (e.g., surface area of manure).	Uses emission factors from Rotz et al. (2011).	No change from the previous methods.	Utilizes U.S.-specific emission factors.
Liquid Manure Storage and Treatment—Anaerobic Digestion With Biogas Utilization					
CH_4 Emissions	Leakage from anaerobic digestion system is estimated using IPCC Tier 2 approach and system- specific emission factors.	Configuration of digester (e.g., steel or lined concrete or fiberglass digesters) and animal diets.	Utilizes emission factors from CDM (CDM, 2012).	Updated to reference IPCC (2019) but the equations remained the same (Gavrilova et al., 2019).	Considers system design and diets.
N_2O	Not estimated due to	Not applicable.	Not applicable.	No change from the	Not applicable.

Source	Methodology Approach	Management Practices	Source of Emission Factors	Update Since 2014 Methods Report	Improvements Compared to Other Greenhouse Gas Methodologies
Emissions	negligible GHG emissions.			previous methods.	
Forestry					
Silviculture Practices and Improved Forest Management	Methods include: (1) Excel workbook-facilitated emissions estimates, with or without changing practices overtime; (2) user-specified or site-specific removal or emission factors; or (3) using forest vegetation simulator (FVS) modeling with Forest Inventory Analysis (FIA) data.	Type of management (forest maintenance, reforestation, extending rotation, or avoiding deforestation), and years before harvest.	FIADB (Burrill et al., 2021) data used in creating lookup tables for nonuser specified data.	Creation of an accompanying Excel workbook to simplify calculations for users. Basis of allometric equations updated from only Jenkins et al. (2003) to considerations from Chojnacky et al. (2014) and Woodall et al. (2011).	Gain-loss approach used aligns with other GHG inventories.
Harvested Wood Products	Method is an Excel workbook facilitated carbon stocks and emissions estimation for products in use and in landfills, as well as potential substitution benefits.	Type of management (avoided deforestation, extended rotation, harvest), and harvest volume.	Various regional factors from Smith et al. (2006).	Creation of an accompanying Excel workbook to simplify calculations for users. Updated from referencing the WOODCARB II model to improve calculations with other known data sources [Smith et al. (2006), Skog (2008), McKeever (2009) and McKeever and Howard (2011)].	Builds on WOODCARB II to adhere to the IPCC production approach. Aims to provide a novel cradle to grave approach.
Urban Forests	Methods include: (1) Field Data Method using i-Tree Eco, i-Tree MyTree, i-Tree Design;	Maintenance (use of vehicles, chain saws, etc.) and altering building energy use (use of trees for shading and wind	i-Tree Eco model; i-Tree Canopy model.	Additional i-Tree tools were identified for use and varying levels of user technical ability as	This method provides a range of options dependent on the data availability of the entities'

Source	Methodology Approach	Management Practices	Source of Emission Factors	Update Since 2014 Methods Report	Improvements Compared to Other Greenhouse Gas Methodologies
	(2) Aerial Method using i-Tree Canopy model with aerial tree cover estimates and look up tables; and (3) Online Geospatial Database Method using i-Tree Landscape.	breaks); quantitative methods for estimating emissions from these management practices are included for information purposes only.		well as data access.	urban forest land.
Wildfire and Prescribed Fire	Methods include: (1) Excel workbook-facilitated emissions estimates for certain fire scenarios (2) Inventory data combined with model simulations- e.g., First Order Fire Effects Model (FOFEM) or FVS with the Fire and Fuels Extension (FFE).	Fire and fuel load management.	Simulations using FIADB data as input to the FFE-FVS.	Creation of an accompanying Excel workbook to simplify calculations for users.	This method provides a range of options dependent on the data availability of the entities' disturbed forest land.
Wetlands					
Biomass Carbon in Wetlands	Methods for estimating forest vegetation and shrub and grassland vegetation biomass carbon stocks use a combination of the FVS model and lookup tables for dominant shrub and grassland vegetation types found in the Cropland and Grazing Land Chapter (chapter 3). If there is a land-use change, methods for cropland herbaceous biomass are suggested.	Forested Wetlands: Same as those generally described in chapter 5. Shrub and Grassland Vegetation: Same as those described for total biomass carbon stock changes presented in chapter 3.	Forest Wetlands: 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, and the regional variants include many wetland tree species. However, if a species-specific curve is not available, then a default function is used to estimate carbon stock changes. Shrub and Grassland	No revisions in this report update.	Uses entity-specific seasonal data. No IPCC methodologies currently exist for this source; hence, this is a newly developed method.

Source	Methodology Approach	Management Practices	Source of Emission Factors	Update Since 2014 Methods Report	Improvements Compared to Other Greenhouse Gas Methodologies
			Vegetation: Same as chapter 3.		
Soil Carbon, N_2O, and CH_4 in Wetlands	The DeNitrification-DeComposition (DNDC) process-based biogeochemical model is the method used for estimating soil carbon, N_2O, and CH_4 emissions from wetlands.	Vegetation management, water management regime, soil management, fertilization practices, and land-use history.	Process based model is used; hence, no emission factors are used in this method.	No change from the previous methods.	This method leverages the DNDC model to simulate soil carbon, N_2O, and CH_4 emissions from wetlands on a seasonal timescale.
Land-use Change					
Annual Change in Carbon Stocks in Dead Wood and Litter Due to Land Conversion	A basic estimation equation (cf., IPCC Tier 1) is used to estimate change in carbon stocks in dead wood and litter (Aalde et al., 2006).	Land conversion.	IPCC 2006 Guidelines (Aalde et al., 2006).	No change from the previous methods.	Uses entity-specific annual data as input into the equation and is consistent with IPCC 2006 guidance.
Change in Soil Organic Carbon Stocks for Mineral Soils	The methodologies to estimate soil carbon stock changes for organic soils and mineral soils are adopted from IPCC (Ogle et al., 2019a) and are a basic estimation equation.	Land conversion.	IPCC 2019 Refinements (Ogle et al., 2019a).	Updated to IPCC (2019) though the equations remained the same (Ogle et al., 2019a).	Uses entity-specific annual data as input into the equation and is consistent with IPCC 2019 refinements.
Annual Change in Biomass Carbon Stocks Due to Land Conversion	A basic estimation equation is used to estimate the change in carbon stocks in biomass due to land conversion (Aalde et al., 2006).	Land conversion.	IPCC 2006 Guidelines (Aalde et al., 2006)	New method since the last version of the report.	None.

Executive Summary References

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