QUANTIFYING GREENHOUSE GAS FLUXES IN AGRICULTURE AND FORESTRY: METHODS FOR ENTITY-SCALE INVENTORY

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Executive Summary

Background

Provisions of Section 2709 of the Food, Conservation, and Energy Act of 2008 direct the U.S. Department of Agriculture (USDA) to prepare technical guidelines and science-based methods to measure environmental service benefits from conservation and land management activities, initially focused on carbon. The methods contained in this document address greenhouse gas (GHG) emissions and removals from agricultural and forestry activities.

Through the development of this report, USDA has prepared two primary products:

1. A comprehensive review of techniques currently in use for estimating GHG emissions and removals from agricultural and forestry activities; and
2. A technical report outlining the preferred science-based approach and specific methods for estimating GHG emissions at the farm or forest scale (i.e., this document).

Uses of the Report and Methods:

- Estimating increases and decreases in GHG emissions and carbon sequestration resulting from current and future conservation programs and practices;
- Providing methods suitable for GHG inventory efforts at the entity, farm, or forest scale, with possible implications for regional and national scale assessments as well; and
- Estimating increases and decreases in GHG emissions and carbon sequestration associated with changes in land management.

Purpose of the Report

The objective for this report is to create a standard set of GHG estimation methods for use by USDA, landowners, and other stakeholders to assist them in evaluating the GHG impacts of their management decisions. The methods presented in the report address GHG emissions and carbon sequestration for the entire entity or operation and also provide the opportunity to assess individual practices or management decisions. Therefore, ease of use is critical.

A co-objective is to demonstrate capacity within USDA, establishing a standardized, consensus set of methods that become the scientific basis for entity-scale estimation of the GHG impacts of landowner management decisions. Therefore, scientific rigor and transparency are also critical.

Because the report is intended as a means of evaluating management practices across the full scope of the farm, ranch, and forest management system, the methods in the report need to be as comprehensive as possible. Research and data gaps exist that result in some management practices not being accounted for or are reflected in higher levels of estimate uncertainty. Completeness is important, though, and the report attempts to identify the most significant research gaps and data needs.

This report will be used within USDA and by farmers, ranchers, and forest landowners, and will be made publicly available. These methods are designed to:

1. Provide a scientific basis for methods that can be used by landowners and managers, USDA, and other stakeholders to estimate changes in GHG emissions and removals at the local entity scale;
2. Create a standard set of GHG quantification guidelines and methods for use by stakeholders;
3. Quantify all significant emissions and removals associated with specific source categories;
4. Quantify emissions from land-use change and carbon sequestration from land management practices and technologies; and
5. Support the development of entity-, farm-, or forest-scale GHG inventories that will facilitate the participation of landowners in public and private environmental market registries and reporting systems.

The report also serves as input into the development of a USDA GHG Estimation Tool. The report and the methods are not intended as an addition to or replacement of any current Federal GHG reporting systems or requirements.

Process for the Development of the Report

This report was developed by three author teams (i.e., working groups) under the direction of one lead author for each team (plus one co-lead author for the forestry chapter). The lead authors were chosen based on their experience with GHG inventories and accounting methodologies and their professional research experience. With input from each lead author, USDA chose 8 to12 working group members per team to write the report. These working group members each had different backgrounds that fit with the anticipated content of the document and also had experience with GHG accounting and/or field research that was unique and addressed one or more of the niche methods that were essential for ensuring the comprehensiveness of the methods for each sector. The author teams were provided with a preliminary outline of their chapters and with two background reports developed as part of the project. One background report was an analysis of the scientific literature related to rates of carbon sequestration or emissions reduction resulting from various management practices and technologies (Denef et al., 2011). The other report was a compilation of all of the available tools, protocols, and models, with basic information on each one (Denef et al., 2012).

The methods were developed according to several criteria in order to maximize their usefulness. In particular, the methods must:

1. Stand on their own, independent of any other accounting system, yet maintain consistency with other accounting systems to the maximum extent possible;
2. Be scalable for use at entity-scale sites across the United States, with applicability at county and/or State levels as well;
3. Facilitate use by USDA in assessing the performance of conservation programs;

4. Provide a broad framework to assess management practices to evaluate the GHG aspect of production sustainability;
5. Maintain maximum applicability for use in environmental markets, including possible future Federal, State, or local GHG offsets initiatives;
6. Be scientifically vetted through USDA, U.S. Government and academic expert review, and public comment;
7. Provide reliable, real, and verifiable estimates of onsite GHG emissions, carbon storage, and carbon sequestration (the methods will be designed so that over time they can be applied to quantify onsite GHG reductions and increases in carbon storage due to conservation and land management activities); and
8. Provide a basis for consistency in estimation and transparency in reporting.

Development of the report has been iterative as various drafts of the document have been put through several review stages, including a USDA intra-agency technical review, a Federal interagency technical review, a scientific expert review, and a public comment period.

Overview of Recommended GHG Estimation Methods in the Report

This section provides an overview of the current estimation methods or approaches an entity could use to estimate GHG emissions and sinks on his or her property. This overview is followed by a summary of each sector's proposed methodologies for entity GHG estimations.

There are several approaches that a farmer, rancher, or forest landowner can use to estimate GHG emissions at an entity scale, and each approach gives varying accuracy and precision. The most accurate way of estimating emissions is through direct measurement, which often requires expensive equipment or techniques that are not feasible for a single landowner or manager. On the other hand, lookup tables and estimation equations alone often do not adequately represent local variability or local conditions. This report attempts to delineate methods that balance user-friendliness, data requirements, and scientific rigor in a way that is transparent and justified.

The following approaches were considered for these guidelines:

- Basic estimation equations (cf., IPCC [Intergovernmental Panel on Climate Change] Tier 1)—involve combinations of activity data[1] with parameters and default emission factors.[2] Any default parameters or default emission factors (e.g., lookup tables) are provided in the text, or if substantial in length, in an accompanying compendium of data.
- Models (cf., IPCC Tier 3)—use combinations of activity data with parameters and default emission factors. The inputs for these models can be ancillary data[3] (e.g., temperature, precipitation, elevation, and soil nutrient levels that may be pulled from an underlying source), biological variables (e.g., plant diversity) or site-specific data (e.g., number of acres,

[1] Activity data is defined as data on the magnitude of human activity resulting in emissions or removals taking place during a given period of time (IPCC, 1997).
[2] Emission factor is defined as a coefficient that quantifies the emissions or removals of a gas per unit of activity. Emission factors are often based on a sample of measurement data, averaged to develop a representative rate of emission for a given activity level under a given set of operating conditions (IPCC, 2006).
[3] Ancillary data is defined as additional data necessary to support the selection of *activity data* and *emission factors* for the estimation and characterization of emissions. Data on soil, crop or animal types, tree species, operating conditions, and geographical location are examples of ancillary data.

number of animals). The accuracy of the models is dependent on the robustness of the model and the accuracy of the inputs.

- Field measurements—actual measurements that a farmer or landowner would need to take to more accurately estimate the properties of the soil, forest, or farm or to estimate actual emissions. Measuring actual emissions on the land requires special equipment that monitors the flow of gases from the source into the atmosphere. This equipment is not readily available to most entities, so field measurements are more often incorporated into other methods described in this section to create a hybrid approach. A field measurement such as a sample mean tree diameter could be incorporated into other models or equations to give a more accurate input.
- Inference (cf., IPCC Tier 2)—uses State, regional, or national emissions/sequestration factors that approximate emissions/sequestration per unit of the input. The input data is then multiplied by this factor to determine the total onsite emissions. This factor can have varying degrees of accuracy and often does not capture the mitigation practices on the farm or the unique soil conditions, climate, livestock diet, livestock genetics, or any farm-specific characteristics, although they can be developed with specific soil types, livestock categories, or climactic regions.
- Hybrid estimation approach (cf., IPCC Tier 2 or IPPC Tier 3)—an approach that uses a combination of the approaches described above. The approach often uses field measurements or models to generate inputs used for an inference-based approach to improve the accuracy of the estimate.

The types of approaches that the authors recommended in this report include basic estimation equations with default emission factors (cf., IPCC Tier 1); geography-, crop-, livestock-, technology-, or practice-specific emission factors (cf., IPCC Tier 2); and modified IPCC/empirical and/or process-based modeling (cf., IPCC Tier 2 or IPCC Tier 3).[4] Table ES-1 categorizes the sources of emissions with the types of approaches that are recommended in this report.

Table ES-2 summarizes the sources of agricultural and forestry GHG emissions and removals discussed in this report, the recommended method for estimating emissions and removals for each source category, and the reference(s) used for the development of the method.

[4] A tier represents a level of methodological complexity. Usually three tiers are provided. Tier 1 is the basic method, Tier 2 intermediate, and Tier 3 most demanding in terms of complexity and data requirements. Tiers 2 and 3 are sometimes referred to as *higher tier* methods and are generally considered to be more accurate (IPCC, 2006).

Table ES-1: Summary of the Sources of Emissions and Types of Approaches in this Report

Source	Basic Estimation Equation (cf., IPCC Tier 1)	Inference (cf., IPCC Tier 2)	Modified IPCC or Empirical Model (cf., IPCC Tier 2 or IPPC Tier 3)	Processed-Based Model (cf., IPPC Tier 3)
Croplands/Grazing Lands	▪ Direct N_2O Emissions from Drainage of Organic Soils ▪ CH_4 Emissions from Rice Cultivation ▪ CO_2 from Urea Fertilizer Application	▪ Soil Organic Carbon Stocks for Organic Soils ▪ CO_2 from Liming ▪ N_2O Emissions from Rice Cultivation ▪ Non-CO_2 Emissions from Biomass Burning ▪ Indirect N_2O Emissions	▪ Biomass Carbon Stock Changes ▪ CH_4 Uptake by Soils ▪ Direct N_2O Emissions from Mineral Soils	▪ Soil Organic Carbon Stocks for Mineral Soils
Wet-lands	—	—	—	▪ Biomass Carbon ▪ Soil C, N_2O, and CH_4
Animal Production[5]	▪ Enteric CH_4 from Swine ▪ Enteric CH_4 from Other Animals (Goats, American Bison) ▪ CH_4 from Poultry Housing	▪ CH_4 from Dairy Cattle, Beef Cattle, and Swine 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 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 ▪ CH_4 and N_2O from Anaerobic Lagoon, Runoff Holding Pond, Storage Tanks ▪ CH_4 and N_2O from Combined Aerobic Treatment Systems ▪ CH_4 from Anaerobic Digester	—
Forestry	—	—	▪ Establishing, Re-establishing, and Clearing Forest ▪ Harvested Wood	▪ Forest Carbon Accounting ▪ Forest Management ▪ Urban Forests

[5] Ammonia (NH_3), as an important precursor to GHGs, is included in the animal production systems discussion where necessary, but is not of primary focus. If readers are interested in more technical information, methods for estimating NH_3 emissions can be found in Appendix 5-C.

Source	Basic Estimation Equation (cf., IPCC Tier 1)	Inference (cf., IPCC Tier 2)	Modified IPCC or Empirical Model (cf., IPCC Tier 2 or IPPC Tier 3)	Processed-Based Model (cf., IPPC Tier 3)
			Products	▪ Natural Disturbance—Wildfire and Prescribed Fire
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	—	—	—

Organization of the Report

The report is largely organized by sector, with each chapter providing an overview of management practices and resulting GHG emissions and removals. For each sector, background and information on management practices are presented first, followed by the detailed methods proposed for estimating emissions and removals for those practices.

- Chapter 1 provides an overview of the report, report objectives, contents of the report, and uses and limitations of the report.
- Chapter 2 describes the linkages and cross-cutting issues relating to sector-specific and entity-scale estimation of GHG emissions and removals.
- Chapter 3 describes the GHG emissions from crop and grazing land systems. The chapter presents methods for estimating the influence of land use and management practices on GHG emissions (and removals) in crop and grazing land systems. Methods are described for estimating biomass and soil carbon stocks changes, direct and indirect soil nitrous oxide (N_2O) emissions, methane (CH_4) and N_2O emissions from wetland rice, CH_4 uptake in soils, carbon dioxide (CO_2) emissions or removals from liming, non-CO_2 GHG emissions from biomass burning, and CO_2 emissions from urea fertilizer application.
- Chapter 4 provides guidance for estimation of carbon stock changes and CH_4 and N_2O emissions from actively managed wetlands.
- Chapter 5 describes on-farm GHG emissions from the production of livestock and manure management. The chapter presents GHG estimation methods appropriate to the production of each common livestock sector (beef, dairy, sheep, swine, and poultry), with methods related to manure management combined for all livestock types.
- Chapter 6 provides guidance on estimating carbon sequestration and GHG emissions from managed forest systems. The chapter is organized to provide an overview of the elements of forest carbon accounting, including definitions of the key carbon pools and basic methods for their estimation.

- Chapter 7 provides guidance on estimating the net GHG emissions and removals resulting from changes between land types—i.e., conversions into and out of cropland, wetland, grazing land, or forest land—at the entity scale.
- Chapter 8 presents the approach for accounting for the uncertainty in the estimated net emissions based on the methods presented in this report. A Monte Carlo approach was selected as the method for estimating the uncertainty around the outputs from the methodologies in this report as it is currently the most comprehensive, sound method available to assess the uncertainty at the entity scale.

Summary

In developing this report, the authors have sought to outline the most state-of-the art and suitable science-based approaches and specific methods for estimating farm- or forest-scale GHG emissions (see Table ES-2). In some cases, the proposed methods have not previously been applied in specifically the way that is proposed. For example, the forestry systems chapter describes the integration of the Forest Vegetation Simulator (FVS) within other estimation tools for forest carbon accounting. This application of FVS, while technically sound, will require additional effort to implement. In other cases, the authors have proposed new methods that build on or enhance previously used methods. For example, a new hybrid approach is proposed for estimating direct soil N_2O emissions from mineral soils on croplands and grazing lands. The hybrid approach uses models to derive expected emission rates at the typical fertilization rate for the major soil textures, weather patterns, and crop rotation systems in each USDA Land Resource Region and uses a meta-analysis of empirical studies to develop emission scaling factors for cropland and grazing land systems. The method also applies practice-based scaling factors derived from a meta-analysis of the most recent data. This hybrid approach is the result of a workshop held in February 2012 that convened experts on N_2O emissions from croplands in order to develop estimation methods that were inclusive and best met the objectives of USDA.

In addition to proposing science-based methods, the authors also acknowledge that for certain practices and technologies, adequate data do not currently exist to accurately estimate GHG emissions and/or carbon sequestration. In each sector chapter, the authors have included a discussion of research gaps or priority areas for future data collection that are important in order to improve the completeness and accuracy of the estimation methods put forth in this report. Estimation of GHG emissions from managed wetland systems is a good example. While a method is put forward that reflects the best currently available science, the authors state in Section 4.3 that the methods for these lands are not as well developed as for other sectors. Later in that same section there is text discussing the considerable limitations to estimating GHG fluxes from these systems and the large levels of uncertainty around flux estimates. In Section 4.4, the authors outline a significant list of research and data priorities that would help to refine and strengthen the estimation methods.

In the continual effort to advance the science and improve the understanding of these complex and dynamic systems, this report provides the foundation for entity-level tools to quantify the GHG benefits from conservation and land management activities. The report also identifies priorities for future effort in order to broaden the scope of entity-scale GHG flux estimation and reduce estimation uncertainties.

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

Source	Methodology Approach	Potential Management Practices	Source of Emission Factors	Improvements Compared to Other Greenhouse Gas Methodologies
Croplands/Grazing Lands				
Biomass Carbon Stock Changes	Herbaceous biomass is estimated with an empirical method using entity specific data as input into the IPCC[6] equations developed by Lasco et al. (2006) and Verchot et al. (2006). Woody plant growth and losses in agroforestry or perennial tree crops are estimated with a simulation model (DAYCENT) using entity input.	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. Yield in units of dry matter can be estimated by the entity, or average values from USDA-Natural Agricultural Statistics Service statistics can be used.	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.

[6] IPCC = Intergovernmental Panel on Climate Change

Source	Methodology Approach	Potential Management Practices	Source of Emission Factors	Improvements Compared to Other Greenhouse Gas Methodologies
Soil Organic Carbon stocks for Mineral Soils	The DAYCENT model is used to estimate the soil organic carbon at the beginning and end of the year for mineral soils. The stocks are entered into the IPCC equations developed by Lasco et al. (2006) and Verchot et al. (2006) to estimate carbon stock changes.	Addition of carbon in manure and other organic amendments; tillage intensity; residue management (retention in field without incorporation; retention in the 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).	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.
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 developed by Aalde et al. (2006) and region-specific emission factors from Ogle et al. (2003).	Cropland drainage	Emission factors are from Ogle et al. (2003) and are region-specific based on typical drainage patterns and climatic controls (e.g., temperature/precipitation) on decomposition rates.	Uses entity-specific annual data as input into the equation used in the U.S. Inventory.

Source	Methodology Approach	Potential Management Practices	Source of Emission Factors	Improvements Compared to Other Greenhouse Gas Methodologies
Direct N_2O Emissions from Mineral Soils	Direct N_2O methods are estimated with a hybrid estimation method. For major commodity crops, (e.g., corn, cotton, alfalfa) a combination of experimental data and process-based modeling using DAYCENT[7] and DE nitrification-decomposition (DNDC)[8] are used to derive expected base emission rates for different soil texture classes in each USDA Land Resource Region. For minor commodity crops (e.g., barley, oats, peanuts) and in cases where there are insufficient empirical data to derive a base emission rate, the base emission rate is based on the IPCC default factor (i.e., 0.01) multiplied by the agronomic nitrogen input (de Klein et al., 2006). These emission rates are scaled with practice-based scaling factors to estimate the influence of management changes such as application of nitrification inhibitors or slow-release fertilizers.	Nitrogen application to crops. In addition, specific management practices are included as scaling factors that influence a portion or the entire pool of mineral nitrogen.[9] 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/paddock Management practices that influence the entire pool of mineral nitrogen include: ▪ Tillage	The base emission factors are adjusted by scaling factors related to specific crop management practices that are derived from experimental data.	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.[10]

[7] The version of DAYCENT coded and parameterized for the most recent U.S. national GHG inventory (U.S. EPA, 2013) was used to derive expected base emission rates.
[8] DNDC9.5 compiled on Feb 25, 2013 was used to derive expected base emission rates.
[9] Practice-based emission scaling factors (0 to 1) are used to adjust the portion of the emission rate associated with slow release fertilizers, nitrification inhibitors, and pasture/range/paddock (PRP) manure nitrogen additions. The slow-release fertilizer, nitrification inhibitor, and PRP manure scaling factors are weighted so that their effect is only on the amount of nitrogen influenced by these practices relative to the entire pool of nitrogen (i.e., the amount of slow-release fertilizer, fertilizer with nitrification inhibitor or PRP manure nitrogen added to the soil). In contrast, scaling factors for tillage are used to scale the entire emission rate under the assumption that this practice influences the entire pool of mineral nitrogen.
[10] A full description of the method is included in Chapter 3 and its appendix. Supplemental data outputs from the model runs will be available online to download.

Source	Methodology Approach	Potential Management Practices	Source of Emission Factors	Improvements Compared to Other Greenhouse Gas Methodologies
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., IPCC Tier 1) method (de Klein et al., 2006).	Drainage of organic soils.	Emission rate for cropped histosols based on an IPCC Tier 1 emission factor of 0.008 tonnes N_2O-nitrogen ha^{-1} $year^{-1}$.	Uses entity specific annual data as input into the equation used in the USDA Inventory (USDA, 2011).
Indirect N_2O Emissions	Indirect soil N_2O emissions are estimated with an inference (cf., IPCC Tier 2) based on IPCC methodology (de Klein et al., 2006).	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.	This method uses entity-specific seasonal data on nitrogen management practices.
Methane Uptake by Soils[11]	Methane uptake 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 (cf., IPCC Tier 2 or IPPC Tier 3).	Land management including cultivation for crop production, grazing in grasslands, forest harvest, grassland, or forest fertilization.	Annual average CH_4 oxidation emissions and removals are from the data set used by Del Grosso et al. (2000).	This newly developed methodology makes use of recent U.S.-based research that is not addressed by IPCC or the U.S. Inventory. The method incorporates entity specific annual data.

[11] Methane uptake by soils is a natural process in undisturbed soils. Processes for restoring methanotrophic activity are not well understood, and require decades to develop. A method is outlined in this report, but additional data and understanding are required prior to use or implementation in quantification tools.

Source	Methodology Approach	Potential Management Practices	Source of Emission Factors	Improvements Compared to Other Greenhouse Gas Methodologies
Methane and Nitrous Oxide Emissions from Rice Cultivation	A basic estimation equation (cf., IPCC Tier 1) is used to estimate CH_4, and an inference (cf., IPCC Tier 2) method is used for N_2O emissions from flooded rice production (Akiyama et al., 2005; de Klein et al., 2006; Lasco et al., 2006; USDA, 2011).	CH_4: 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 (e.g., compost, farmyard manure). N_2O: additions from mineral fertilizers, organic amendments, and crop residues.	CH_4: the baseline emission factor or typical daily rate at which CH_4 is produced per unit of land area represents fields that are continuously flooded during the cultivation period, not flooded at all during the 180 days prior to cultivation and receive no organic amendments. CH_4 scaling factors to account for water regimes come from Lasco et al. (2006). N_2O: emission factors rely on Lasco et al. (2006) and the scaling factor to account for drainage effects; comes from Akiyama et al. (2005; USDA, 2011).	The N_2O method uses the IPCC (2006) equation with the addition of a scaling factor for drainage from Akiyama et al. (2005). The method for methane emissions uses entity-specific annual data as input into the equation and is consistent with U.S. Inventory method.
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 emissions factors (adapted from West and McBride, 2005).	The amount of lime, crushed limestone, or dolomite applied to soils.	U.S.-specific emissions factors (West and McBride, 2005).	Uses U.S.-specific emission factors as annual input into the IPCC equation, which is consistent with the U.S. Inventory.
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 2) 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.	Uses entity-specific annual data as input into the IPCC equation.

Source	Methodology Approach	Potential Management Practices	Source of Emission Factors	Improvements Compared to Other Greenhouse Gas Methodologies
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.	Uses entity-specific annual data as input into the IPCC equation, which is used for the U.S. Inventory.
Wetlands				
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 (FVS) model and lookup tables for dominant shrub and grassland vegetation types found in the Cropland and Grazing Land Chapter. If there is a land-use change, methods for cropland herbaceous biomass are suggested.	*Forested Wetlands*: Same as those described for upland forests in Section 6.2.3. *Shrub and Grassland Vegetation*: Same as those described for total biomass carbon stock changes presented in the Cropland and Grazing Land Chapter, Section 3.5.1.	*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 Vegetation:* Same as the Croplands and Grazing Lands Chapter, Section 3.5.1.	Uses entity-specific seasonal data. No IPCC methodologies currently exist for this source; hence, this is a newly developed method.
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 emissions factors are used in this method.	This method leverages the DNDC model to simulate soil carbon, N_2O, and CH_4 emissions from wetlands on a seasonal timescale.

Source	Methodology Approach	Potential Management Practices	Source of Emission Factors	Improvements Compared to Other Greenhouse Gas Methodologies
Animal Production Systems				
Enteric Fermentation				
Mature Dairy Cows	Mits3 equation developed by Mills et al. (2003) and further utilized by DairyGEM (Rotz et al., 2011). Mits3 equation is based primarily on metabolizable energy intake. Dry matter intake (DMI), starch, acid detergent fiber, crude protein, and total digestible nutrients provide the inputs for the equation.	*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.	Emission factors calculated with approach developed by Mills et al. (2003) and Rotz et al. (2011).	Use of the DairyGEM/Mits3 equation is recommended over the IPCC Tier 2 equation (2006) because it has proven to be more accurate, in general, for dairy cows.
Beef Cow-Calf and Bulls	IPCC Tier 2 approach (2006). 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.	Emission factors are determined with the IPCC Tier 2 equation (2006). Methane conversion factor (Ym) based on animal-specific guidance in U.S. EPA (2013).	The equations utilized are the same as existing inventory methods; however, the methods utilize farm-specific feed types and utilize monthly, rather than annual, level data (i.e., account for seasonal variation in forage quality).
Stockers	IPCC Tier 2 approach (2006). 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.	Emission factors are determined with the IPCC Tier 2 equation (2006) on an entity-by-entity basis. Ym based on animal-specific guidance in U.S. EPA (2013).	The equations utilized are the same as existing inventory methods; however, the methods utilize farm-specific feed types and utilize monthly, rather than annual, level data (i.e., account for seasonal variation in forage quality).

Source	Methodology Approach	Potential Management Practices	Source of Emission Factors	Improvements Compared to Other Greenhouse Gas Methodologies
Feedlot Cattle	IPCC Tier 2 approach (2006). 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.	Emission factors are determined with the IPCC Tier 2 equation (2006). Ym based on guidance developed by Hales (2012).	The calculation considers weight, weight gain, mature weight, pregnancy, lactation, other activity (grazing, confined, daily work), and the energy content of the animals' diets.
Sheep	Howden equation (Howden et al., 1994), 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 not utilized.	This method uses actual monthly estimates of DMI, rather than head count, as utilized by the IPCC Tier 1 equation (2006).
Swine	IPCC Tier 1 approach (2006).	None.	Utilizes IPCC Tier 1 emission factor (IPCC, 2006).	None.
Other Animals (Goats, American Bison)	IPCC Tier 1 approach for American bison (based on buffalo, modified by average animal weight) and goats (IPCC, 2006).	None.	Utilizes IPCC Tier 1 emission factors(IPCC, 2006).	None.
Housing				
Methane Emissions from Manure on Barn Floors for Dairy Cattle	DairyGEM (a subset of the Integrated Farm Systems Model) is used to estimate CH_4 emissions.	None.	Empirical relationship as provided in Chianese et al. (Chianese et al., 2009).	Utilizes climate and entity characteristics.
Methane Emissions from Dairy Cattle, Beef Cattle, and Swine Housing	IPCC Tier 2 approach.	Type and duration of manure storage.	Utilizes a combination of IPCC and U.S. EPA Inventory emission factors.	None.

Source	Methodology Approach	Potential Management Practices	Source of Emission Factors	Improvements Compared to Other Greenhouse Gas Methodologies
Nitrous Oxide Emissions from Dairy Cattle, Beef Cattle, Swine, and Poultry Housing	IPCC Tier 2 approach, using American Society of Agricultural Engineers (ASAE) equations to estimate nitrogen excretion and default values for ammonia losses to account for nitrogen balance.	Animal diets and type of manure storage.	Utilizes IPCC emission factors (IPCC, 2006) and ammonia losses from Koelsh and Stowell (2005).	Uses nitrogen balance approach to adjust nitrogen in housing to account for ammonia losses.
Methane Emissions from Poultry Housing	IPCC Tier 1 approach.	None.	Utilizes IPCC emission factors that vary by temperature and whether manure is managed as dry manure or as a liquid (IPCC, 2006).	Of the models evaluated for poultry, an estimate of confidence for output was only available for the IPCC Tier 1 approach. Specific to estimates of poultry, on manure CH_4 emissions, the uncertainty was less than 20% (Little et al., 2008).
Manure Storage and Treatment				
Solid Manure Storage and Treatment - Temporary Stack and Long-Term Stockpile				
Methane Emissions	IPCC Tier 2 approach using IPCC and U.S. EPA Inventory emission factors, utilizing monthly data on volatile solids and dry manure.	Animal diets.	Utilizes a combination of IPCC and U.S. EPA Inventory emission factors.	Uses U.S.-specific emission factors and takes into account diet characterization.
Nitrous Oxide Emissions	IPCC Tier 2 approach using U.S. EPA Inventory emission factors and monthly data on total nitrogen, and dry manure.	Duration of manure storage and animal diets.	Utilizes emission factors from U.S. EPA Inventory.	Uses U.S.-specific emission factors and takes into account diet characterization.
Manure Storage and Treatment-Composting				
Methane Emissions	IPCC Tier 2 approach utilizing monthly data on volatile solids and dry manure.	Configuration of storage unit (e.g., composting in-vessel, static pile, intensive windrow, passive windrow) and animal diets.	Utilizes emission factors from IPCC.	Takes into account diet and climate characteristics.

Source	Methodology Approach	Potential Management Practices	Source of Emission Factors	Improvements Compared to Other Greenhouse Gas Methodologies
Nitrous Oxide 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.	Utilizes emission factors from IPCC.	Takes into account diet and climate characteristics.
Liquid Manure Storage and Treatment – Aerobic Lagoon				
Methane Emissions	The methane correction factor for aerobic treatment is negligible and was designated as 0% in accordance with the IPCC.	Not applicable.	Utilizes emission factors from IPCC.	Not estimated.
Nitrous Oxide Emissions	IPCC Tier 2 method.	Configuration of storage (e.g., volume of lagoon), natural or forced aeration, and animal diets.	Utilizes emission factors from IPCC.	None.
Liquid Manure Storage and Treatment – Anaerobic Lagoon, Runoff Holding Pond, Storage Tanks				
Methane Emissions	Sommer Model (Sommer et al., 2004) is used with degradable and non-degradable fractions of volatile solids from Møller et al. (2004).	Configuration of storage unit (e.g., covered or uncovered storage, presence or absence of crust) and animal diets.	Parameters for estimation from Sommer et al. (2004).	Takes into account diet and storage temperature characteristics.
Nitrous Oxide Emissions	Emissions are a function of the exposed surface area and U.S.-based emission factors.	Configuration of storage unit (e.g., surface area of manure).	Utilizes emission factors from Rotz et al. (2011a).	Utilizes U.S.-specific emission factors.
Liquid Manure Storage and Treatment – Anaerobic Digestion with Biogas Utilization				
Methane 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).	Takes into account system design and diets.
Combined Aerobic Treatment Systems				

Source	Methodology Approach	Potential Management Practices	Source of Emission Factors	Improvements Compared to Other Greenhouse Gas Methodologies
Methane Emissions	Assumed to be 10 percent of the emissions resulting from method to estimate emissions from Liquid Manure Storage and Treatment – Anaerobic Lagoon, Runoff Holding Pond, Storage Tanks.	Configuration of storage unit (e.g., covered or uncovered storage, presence or absence of crust) and animal diets.	Parameters for estimation from Sommer et al. (2004).	Takes into account diet and storage temperature characteristics.
Nitrous Oxide Emissions	Assumed to be 10 percent of the emissions resulting from method to estimate emissions from Liquid Manure Storage and Treatment – Anaerobic Lagoon, Runoff Holding Pond, Storage Tanks.	Configuration of storage unit (e.g., surface area of manure).	Utilizes emission factors from Rotz et al. (2011a).	Uses U.S.-specific emission factors.
Liquid Manure Storage and Treatment – Sand/Manure Separation	No method provided as GHG emissions are negligible. However, resulting volatile solids, total nitrogen, organic nitrogen, and manure temperature of the separated liquid manure should be measured and used as the inputs to estimate emissions of GHGs for subsequent storage and treatment operations.	Not applicable.	Not applicable.	Not applicable.
Liquid Manure Storage and Treatment – Nutrient Removal	Not estimated due to limited quantitative information on GHGs from nitrogen removal processes.	Not applicable.	Not applicable.	Not applicable.

Source	Methodology Approach	Potential Management Practices	Source of Emission Factors	Improvements Compared to Other Greenhouse Gas Methodologies
Liquid Manure Storage and Treatment – Solid/Liquid Separation	No method provided as GHG emissions are negligible. Efficiency factors for different mechanical solid-liquid separation systems provided. However, resulting volatile solids, total nitrogen, organic nitrogen, and manure temperature of the separated liquid manure should be measured and used as the inputs to estimate emissions of GHGs for subsequent storage and treatment operations.	Not applicable.	Not applicable.	Not applicable.
Liquid Manure Storage and Treatment – Constructed Wetlands				
GHG Removals	Currently no method is provided, although GHG removals are noted to likely be greater than CH_4 and N_2O emissions, which are considered negligible.	Not applicable.	Not applicable.	Not applicable.
Solid Manure Storage and Treatment – Thermo-Chemical Conversion	Not estimated as CH_4 and N_2O emissions considered negligible.	Not applicable.	Not applicable.	Not applicable.
Manure Application				

Source	Methodology Approach	Potential Management Practices	Source of Emission Factors	Improvements Compared to Other Greenhouse Gas Methodologies
Solid Manure Application Systems (manure handling prior to land application)	Not estimated due to limited quantitative information on GHGs from manure mixing and removal from storage systems or during transport to fields where manure is land applied.	Not applicable.	Not applicable.	Not applicable.
Liquid Manure Application Systems (manure handling prior to land application)	No method is provided as CH_4 and N_2O GHG emissions are negligible; however, CO_2 emissions would result from the operation of equipment.	Not applicable.	Not applicable.	Not applicable.
Forestry				
Forest Carbon	Methods include: (1) FVS model with Fire and Fuels Extension module (FVS-FFE) with Jenkins et al. (2003) allometric equations; and (2) default look up tables.	FVS-FFE models hundreds of management practices (thinning from below/above/evenly through a stand, thinning with species preference, conditional thinning/planting/ regeneration, piling of surface fuels and prescribed fires, salvage operations, mastication treatments, insect/disease management, etc.)	Allometric equations are from Jenkins et al. (2003); default look up tables from Smith et al. (2006).	The method allows large landowners to estimate base year carbon stocks from field surveys and repeat the field survey at recommended intervals (e.g., 5-year, 10-year) depending on the region/forest type group. Small landowners estimate carbon stocks from lookup tables based on USDA Forest Inventory and Analysis program data, which is comparable to other GHG methodologies (e.g., Section 1605(b) Guidance).

Source	Methodology Approach	Potential Management Practices	Source of Emission Factors	Improvements Compared to Other Greenhouse Gas Methodologies
Establishing, Re-establishing, and Clearing Forest	IPCC equations developed by Aalde et al. (2006); with Jenkins et al. (2003) allometric equations.	Planting trees on previously unforested lands; replanting trees on previously forested lands; and permanently clearing trees from forested lands.	Allometric equations are from Jenkins et al. (2003)	This method allows large landowners to estimate base year carbon stocks from field surveys and repeat the field survey at recommended intervals (e.g., 5-year, 10-year) depending on the region/forest type group. The National Inventory Report (NIR) uses a carbon stock change method, which explicitly includes the establishment, re-establishment, and clearing of forests.
Forest Management	Methods include: (1) FVS-FFE with Jenkins et al. (2003) allometric equations and (2) default lookup tables of management practice scenarios.	Stand density management; site preparation techniques; vegetation control; planting; natural regeneration; fertilization; selection of rotation length; harvesting and utilization techniques; fire and fuel load management; reducing risk of emissions from pests and disease; short-rotation woody crops.	Default lookup tables of carbon stocks over time by region, forest type categories, including species group (e.g., hardwood, softwood, mixed); regeneration (e.g., planted, naturally regenerated); management intensity (e.g., low, moderate, high, very high) and site productivity (e.g., low, high), to be developed as a supporting product using FVS.	This method provides a consistent and comparable set of carbon stocks for each region, forest type group, management intensity, and site productivity over time, under management scenarios common to the forest types and management intensities.

Source	Methodology Approach	Potential Management Practices	Source of Emission Factors	Improvements Compared to Other Greenhouse Gas Methodologies
Harvested Wood Products	U.S.-specific harvested wood products tables developed by Skog (2008), taking the estimated average amount of harvested wood product carbon from the current year's harvest that remains stored in end uses and landfills over the next 100 years.	The approach models various management practices including the disposition of each primary product (e.g., lumber, structural panels) to major end uses (e.g., percentage of product going to residential housing, non-residential housing, manufacturing (furniture)), and percentage going to exports; with decay functions indicating how quickly products go out of use for each end use; fraction of material going out of use that goes to landfills; fraction of material in landfills that does not decay, and the decay rate for material in landfills that does decay.	WOODCARB II model used to estimate annual change in carbon stored in products and landfills (Skog, 2008).	Provides a method that is suitable to count the average amount of carbon stored in products in use and in landfills, and the underlying model is the same used for the National Inventory Report (NIR) (i.e., The NIR also uses WOODCARB II model to estimate annual change in carbon stored in products and landfills). The harvested wood product tables (Skog, 2008) provide annual values for zero to 10 years after production and 5-year intervals for 10 to 100 years after production.
Urban Forests	Methods include: (1) Field Data Method using i-Tree Eco (formerly UFORE) model; and (2) Aerial Method using i-Tree Canopy model with aerial tree cover estimates and look up tables.	Maintenance (use of vehicles, chain saws, etc.) and altering building energy use (use of trees for shading and wind breaks); quantitative methods for estimating emissions from these management practices are included for information purposes only.	i-Tree Eco model; i-Tree Canopy model.	This method provides a range of options dependent on the data availability of the entities' urban forest land. The NIR uses equations based on look up tables and average tree canopy values.
Natural Disturbance—Wildfire and Prescribed Fire	Methods include: (1) First Order Fire Effects (FOFEM) model entering measured biomass; and (2) FOFEM model using default values generated by vegetation type.	Fire and fuel load management.	FOFEM (Reinhardt et al., 1997).	This method provides a range of options dependent on the data availability of the entities' disturbed forest land. The use of a U.S.-specific fire and fuel load management model is an improvement compared to the NIR, which uses equations based on IPCC (2006).

Source	Methodology Approach	Potential Management Practices	Source of Emission Factors	Improvements Compared to Other Greenhouse Gas Methodologies
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).	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 (Aalde et al., 2006) and are a basic estimation equation.	Land conversion.	IPCC 2006 Guidelines (Aalde et al., 2006).	Uses entity-specific annual data as input into the equation and is consistent with IPCC 2006 guidance.

IPCC= Intergovernmental Panel on Climate Change

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