Review of Agricultural Greenhouse Gas Emissions and Sequestration in Vermont: Inventory Tools and Methodological Recommendations

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Contents

1. Introduction

Development of robust agricultural greenhouse gas (GHG) emissions and sequestration inventories requires meticulous selection of appropriate activity data, emissions factors, tools, and models in order to realistically reflect the impact of regional variation and practice implementation. This task is particularly crucial when the objective is to monitor changes in emissions and sequestration over time and quantify the benefits of conservation practice adoption.

This report evaluates the existing Vermont Greenhouse Gas Emissions Inventory and Forecast, existing GHG accounting tools, and datasets to ultimately offer recommendations for optimizing GHG inventory practices within Vermont's agricultural sector. To achieve this objective, the report is structured into seven main sections, and appendices, each contributing to the overarching goal of refining GHG accounting methodologies.

The sources of agricultural GHG emissions were considered during this review process to identify the largest opportunities for enhanced reporting. In 2020, Vermont's agricultural inventory profile included 48% of all emissions from enteric fermentation, 26% from manure management, 23% from managed agricultural soils, and 2% from liming and urea fertilization. Carbon fluxes also occurred from agricultural soils from cropland and managed grassland. Due to Vermont's large dairy market, it was noted that a considerable portion of agricultural GHG emissions result from livestock husbandry, particularly from the enteric fermentation and manure management categories, as opposed to emissions from agricultural soils and crop production. These considerations were integrated into the review of tools, activity data, and other inventory components.

A primary consideration in this analysis is the pivotal role of conservation practices, often referred to as climate-smart agricultural practices, in mitigating GHG emissions and enhancing carbon sequestration in the agricultural sector. Recognizing the multitude of practices and their varying definitions, the report provides a comprehensive overview of these practices, their definitions, and the potential climate change impacts associated with their adoption. This section is later used in the evaluation of tools for the Intergovernmental Panel on Climate Change (IPCC) Agriculture category to determine the most appropriate tool to quantify GHG emissions/sequestration for each category.

The subsequent section delves into a detailed examination of existing agricultural tools and models available for generating GHG inventories, with a focus on their compatibility with Vermont's objectives, adherence to IPCC Guidance for the Agriculture, Forestry, and Other Land Use (AFOLU) sector, ease of use, completeness, and ability to account for the impacts of management practices in the State of Vermont.

Moreover, the report offers insights into available activity data sources that could bolster Vermont's agricultural GHG inventory, highlighting both strengths and limitations. Recommendations pertaining to data sourcing and potential areas for further research are also provided.

Further, emission source-specific reviews are conducted to propose inventory enhancements, including suggestions for refined activity data collection and model utilization. These recommendations are derived from a comprehensive review of existing inventories, assessed against the U.S. Environmental Protection Agency's (EPA) State Inventory Tool (SIT) modules, IPCC guidelines, and available activity data.

Lastly, all analyses and recommendations are synthesized into final conclusions, providing a roadmap for Vermont to enhance its agricultural GHG inventory practices. Through this structured approach, the report aims to support Vermont in its pursuit of accurate and informed GHG accounting, facilitating effective climate action within the agricultural sector.

2. Management Practices

Several agricultural conservation practices that are commonly implemented in the State of Vermont were assessed to identify the practices' effect on climate change mitigation. Based on the current Vermont GHG inventory, the list of climate smart practices currently adopted in Vermont and the climate mitigation potential of each of the practices, ICF ranked the practices in order of the most to least useful in reducing Vermont's agricultural GHG emissions. The practice name, the definition of each practice, and the climate change impact of each practice is provided in **Appendix 7.**[1]

3. Model and Tool Review

Seven agricultural GHG quantification tools and two agricultural GHG models as well as one set of disaggregated state-level inventory results were reviewed for the Agency of natural Resources (ANR), through direct tool use where possible, and a literature review of relevant literature and tool user resources (e.g., guides). Assessment of the tools included entering realistic test data and generation of emission results. The primary purpose of testing tools in this way was to assess their ability to estimate GHG impacts from various management practices that might be of interest to the State of Vermont and determine how these estimates may be incorporated into an official inventory report as the basis for emission mitigation strategy development and related decision making.

The following tools, models, and modeling efforts were reviewed:

1. DeNitrification-DeComposition (DNDC) model,
2. DAYCENT: Daily timestep model,
3. APEX: Agricultural Policy / Environmental eXtender,
4. CarbOn Management & Emissions Tool – Planner (COMET-Planner),
5. Integrated Farm Systems Model (IFSM),
6. Holos,
7. United States Environmental Protection Agency's State Inventory Tool (SIT),
8. EX-Ante Carbon-balance Tool Farm Energy Analysis Tool (EX-Act),
9. The Farm Energy Analysis Tool (FEAT), and
10. The state level inventory data from the U.S. EPA GHG Inventory of Sources and Sinks.

[1] All practice definitions are from the U.S. Department of Agriculture Natural Resources Conservation Service unless otherwise note (U.S. Department of Agriculture, n.d.).

The following factors were assessed:

- Whether the tool / model is current: Published date and ongoing maintenance,
- Model type: From IPCC Tier 3 processed-based modelling to Tier 1 emission-factor based calculations;
- Fit for purpose: Regional scale, scope of emission sources, ability to capture the effects of management practices and mitigation;
- Complexity: Technical expertise required and level of effort to use tool / model;
- Alignment with IPCC: Methodology, parameters and EF's, and overall level (Tiers 1– 3);
- User experience: Data and other inputs required, software/user interface, and outputs;
- Cost; and
- Use among peers.

3.1 Tool Comparison

3.1.1 Agricultural Policy Environmental eXtender (APEX)

Description: The Agricultural Policy eXtender (APEX) Model is designed for watershed management. APEX models carbon and nitrogen cycling from the watershed management lens however was not designed with a primary objective of GHG estimation and only two GHGs are simulated, CO_2 and N_2O (Texas A&M, n.d.). APEX simulates weather, hydrology, erosion and sedimentation, nutrient cycling, pesticide fate, crop growth, soil temperature, tillage, plant growth dynamics and economics. The most important of these processes for inventorying processes is biogeochemical (nutrient) cycling. Nutrient cycling is modelled using a process-based method. APEX does require input data on manure and manure management activities, however further data transformation would be required to estimate GHG emissions from manure management and manure deposited onto pasture by grazing livestock. Additionally, APEX requires input data on livestock population, type and some management practices such as grazing, however does not estimate GHG emissions from enteric fermentation (not the objective of the model) and it is highly likely further data collection and compilation would be needed in addition to data transformation to generate estimates of CH_4 from enteric fermentation, which would be done outside the APEX model (e.g., in another spreadsheet or GHG estimation tool).

Carbon cycling relative to nitrogen in soils is based on the soil organic model developed for the Environmental Policy Integrated Climate (EPIC) model. Williams et al., (2023) highlight some key differences for carbon and nitrogen cycling compared to the CENTURY model, which is the foundational model for DAYCENT, including of leaching equations in APEX to simulate nutrient travel to subsurface layers, use of EPIC to calculate temperature and water controls, omission of a passive compartment for surface litter fraction which is included in CENTURY, and lignin content modelling.

The following direct N_2O sources are modelled as one N_2O output (requiring further data processing for IPCC alignment):

- N_2O from nitrification and denitrification processes of overall N soil inputs, including crop residues, fertilizer (organic and inorganic) and
- N_2O from N mineralization.

Alignment with IPCC and Reporting Tier: Denitrification in APEX is a function of temperature and soil water content. N_2O cannot be apportioned to specific emission source categories as defined by the IPCC (e.g., attributed to application of synthetic fertilizer as opposed to organic / manure fertilizer application, etc.). A similar method used to apportion N_2O to the respective IPCC emission source categories as is used for DAYCENT modelling in the U.S. National GHG Inventory could theoretically be used for APEX, however, could be problematic as different location and management system data in input into each model, and so navigation of the allocation of emissions across IPCC source would be handled slightly differently. Additionally, indirect N_2O from leaching and volatilization processes are estimated. Like direct N_2O, this would not be attributable to specific IPCC emissions source categories. APEX was not designed to estimate GHG emissions, and carbon and nitrogen cycling modelling does not provide estimates of GHG emissions associated with each IPCC agriculture emission source. With further processing of model outputs, these as they are based on process based modelling, could be considered Tier 3 estimates however the estimates would be incomplete as APEX does not model CH_4 emissions from manure management, enteric fermentation, or rice cultivation (not relevant for Vermont), and the livestock sources are key agricultural emission sources for Vermont.

Cost: APEX is free.

Scale: APEX operates on a daily timestep and can be used internationally.

Use: The primary uses of APEX have been for dairy cattle system watershed management (Williams et al., 2023).

Activity Data and Coverage of Management Practices: Management practice inputs for APEX include irrigation type, drainage, inclusion of buffer strips, terraces, waterway management, fertilization practices, manure management, lagoons, reservoirs, crop rotation and selection, pesticide application, grazing, and tillage (Williams et al., 2023).

Other Considerations: APEX does not model key agricultural CH_4 emission sources including CH_4 from enteric fermentation and manure management. Apex is freely available and extensive user resources are available.

APEX summary remarks: APEX emission categories are not aligned with the IPCC emissions source categories, and it may be problematic to crosswalk between APEX outputs and IPCC emission source categories. Further, APEX does not model key agricultural CH_4 emission sources. If ANR would like to align state level reporting with IPCC guidance, APEX is not the best model of those reviewed to achieve this objective. However, APEX provides unique insight into nutrient cycling relative to freshwater management, and ANR might justify its use because of other modelling outputs. At the very least, APEX cannot be used in isolation to generate state level agricultural GHG emissions estimates.

3.1.2 COMET-Planner

Note – Much of this model review was performed on Version 3.0 of COMET-Planner. In December 2023, Version 3.1 was released, which includes "major changes to Woody Plantings system types and woody biomass carbon emission reduction estimates." It implemented a new estimation method based on guidance from the updated Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory by the United States Department of Agriculture (USDA), which has not yet been *released. The authors noted that soil carbon and soil N_2O estimates were not changed in this update, and that a detailed methods white paper will be released in the future* (U.S. Department of Agriculture & Colorado State University, n.d.). *Please see the [companion report for COMET-Planner Version 3.1](#) for more information.*

Description: COMET-Planner estimates emissions and removals attributable crop and livestock GHG emission sources, as well as soil carbon fluxes. It is an online conservation planning tool for estimating the GHG impact of implementing USDA Natural Resources Conservation Service (NRCS) practices. The tool does not provide site specific GHG estimates (for which COMET-Farm would be more appropriate). COMET-Planner employs both modelling and empirical GHG estimation methods, further outlined in Appendix 2. Types of empirical estimation methods that are used include basic estimation equations (IPCC Tier 1 activity data, parameters and emission factors), models, field measurements, inference and hybrid combinations of these methods. COMET-Planner uses emission reduction coefficients (ERCs) as relative to a baseline or business as usual scenario to determine the change in GHG emissions associated with changes in management (specifically aligned with the USDA NRCS practices). The baseline typically represents standard management practices and includes minimal conservation practice implementation (Eve et al., 2014).

Alignment with IPCC and Reporting Tier: COMET emissions sources estimated are aligned with IPCC emission source categories. As mentioned above IPCC methods of varying tiers are used. IPCC tier 1 activity data and in some cases tier 1 or 2 emissions factors are employed. COMET-Planner employs activity data, emission factors, methods of inference from state, regional and national data, model-based estimation methods and hybrid estimation approaches meaning that the results span IPCC Tiers 1-3 depending on the emission source.

Cost: COMET-Planner is free.

Scale: The GHG estimation methods used in COMET-Planner are suitable for GHG inventory efforts at entity scale, as well as use in regional and national scale assessments.

Use: COMET-Planner has a wide range of users, including educational institutions, businesses, state and federal programs and individual farmers (Haley Nagle, personal communication, December 5, 2023). Specific uses include the USDA Partnerships for Climate Smart Commodities Program, which uses COMET-Planner to compare GHG benefits among funded projects (U.S. Department of Agriculture, 2023). Additionally, COMET-Planner is used as an optional tool within Field to Market: The Alliance for Sustainable Agriculture's Fieldprint Platform 4.0 tool to evaluate options for management practices and to document the impacts of these practices on soil carbon (Field to Market, 2021). Finally, the American Farmland Trust's CaRPE Tool utilizes the ERCs from COMET-Planner; this tool allows users to quantify and visualize GHG mitigation potentials based on the adoption of various conservation practices (Moore & Manter, 2022). Using COMET-Planner ERCs, the CaRPE Tool provides estimates at the county level that can be scaled to state, regional, and national levels (Moore & Manter, 2022).

Activity Data and Coverage of Management Practices: COMET-Planner estimates emission reductions using the following general equation:

$$\text{Emission reduction} = \text{Area (acres)} \times \text{Emission Reduction Coefficient}$$

In version 3.1 of COMET-Planner, ERCs are derived using a sample based approach and model runs from COMET-Farm, including underlying DAYCENT modelling, and additional empirical methods as outlined by emission source by (Eve et al., 2014) and updated to align with new IPCC Guidance (Calvo et al., 2019). Soil carbon and direct N_2O emissions from soils, for example, are both modeled using DAYCENT (Haley Nagle, personal communication, December 5, 2023). All new modelled ERCs were compared against literature as version 1 ERCs were developed through meta-analyses and literature reviews and differentiated by IPCC's broad climate zones (Swan et al., 2022). Methods and modelling are further outlined in Appendix 1, Table 1 and Table 2 as adapted from (Eve et al., 2014).

To capture management practices, a COMET-Planner user activity data entry requirements include:

- Livestock population and physiological characteristics (age, breed, gestating etc.)
- Cover crops: type, dates, yield in bushels per acre, percentage of residue removal;
- Grazing management: dates, rest period in days and percentage of land parcel utilized;
- Tillage: dates of planting and implementation pass;
- Fertilizer: type, dates, total fertilizer amount, equivalent amount of N applied, ammonium percent;
- Manure: type, dates, amount applied, moisture content, total nitrogen, ammonium nitrogen, C/N ratio;
- Irrigation: yes or no, method;
- Liming: type, dates, amount;
- Burning: whether before or after harvest (VT indicated this is not relevant).

COMET-Planner is unique in its ability to capture interactions and synergies of and between various land management practices when complete system data is entered. Crop and grazing management practices for example interact in a complex manner, in some cases enhancing or downscaling the effect on GHG emissions observed in the emission source of interest. COMET-Planner requires a comprehensive and complete system description of management practices to pre-populate underlying assumptions about each management practice's effect on other management practices as described in full by (Eve et al., 2014).

Other Considerations: COMET-Planner is designed for entity scale analysis and is not typically used for larger-area emission inventories due to the comprehensive data entry requirements, nor is it used for site-specific analyses for which COMET-Farm is more appropriate.

COMET-Planner summary remarks: COMET-Planner uses current scientific emission estimation methods, accounts for complete system GHG emissions and removals and complex interactions and synergies between management practices occurring in the system area being modelled. It requires most technical expertise throughout the activity data collection process, but otherwise is a relatively simple tool to learn and use. There are extensive user resources available including transparent documentation of the GHG estimation methods that COMET-Planner employs, dedicated staff that maintain the tool, host training sessions and are available to respond to user queries via email.

COMET-Planner, to ICF's knowledge, has not been employed at a larger regional or state level for inventorying purposes. However, it has available-to-download data that includes ERCs for different management practices that are representative of regional averages (i.e., averages for country-rectified USDA Major Land Resource Areas) (Haley Nagle, personal communication, December 5, 2023) (U.S. Department of

Agriculture and Colorado State University, n.d.). It may therefore be possible for ANR to extract these ERCs from COMET-Planner and apply them to acreage data for different cropland management practices in Vermont to obtain state-specific mitigation estimates for each practice. ANR could then choose to integrate these mitigation estimates into the cropland emissions portion of the state inventory; if this approach is taken, careful attention should be paid to ensure that management practices are not being double counted across different tools.

3.1.3 DAYCENT

Description: DAYCENT (Daily CENTURY) is a process-based biogeochemical model that simulates carbon, nitrogen, and other nutrient fluxes in agroecosystems over long time scales. DAYCENT therefore models emissions and removals attributable crop emission sources, including soil carbon fluxes but not livestock emissions sources. This model differs from the original CENTURY model in that it calculates fluxes a daily time step. When modelling fluxes DAYCENT considers parameters such as soil processes, management practices, and climate. Key drivers of GHG emissions estimates include temperature, soil moisture, soil texture, management practices (such as tillage, fertilization, and crop rotation), and climate variables (such as temperature, precipitation, and solar radiation).

Alignment with IPCC and Reporting Tier: In the context of IPCC reporting tiers, DAYCENT generates Tier 3 emission estimates when calibrated for a specific region and verified using local measurement data. Emissions are modelled so a comparison of whether there is alignment of emission estimation methods and emissions factors does not apply.

Cost: DAYCENT is free to use for access to the academic version by request from the developer, Colorado State University (CSU) Natural Resources Ecology Lab (NREL). Additionally, a version designed to be used by inventory compilers is set for release in 2024 with an expected licensing fee of $100,000 per annum.

Complexity: DAYCENT requires a model expert and generating sufficient number of model runs for GHG Inventorying purposes may require a very high level of effort.

Scale: The DAYCENT model was developed to run at both regional and site-specific scales. At the field scale, DAYCENT can be used to model net primary production (NPP), nutrient cycling, and GHG emissions at the plot scale at the level of detail that can account for the impacts of management practices, climate variations, and crop type at that specific location. Using the DAYCENT model version designed for regional modelling assess trends at the landscape scale, rather than the specific dynamics of a location.

Use: The DAYCENT model was originally developed as a refinement of the CENTURY model on a daily timestep in order to more accurately model nitrogen cycling in agroecosystems. This model is widely used amongst U.S. government and research institutions to quantify GHG emissions, nutrient cycling, yields, and net primary productivity (NPP) on both the landscape and farm scales, including 1) quantification of soil organic carbon and GHG emissions on croplands and grasslands in the Inventory of U.S. Greenhouse Gas Emissions and Sinks and 2) as the underlying model used to generate estimates of GHG reductions and/or carbon sequestration in both the COMET-Farm and COMET-Planner tools.

DAYCENT is also widely used in academic research both domestically and internationally.

Activity data and Coverage of Management Practices: Running DAYCENT requires activity data on management practices, including data on tillage practices, mineral fertilization, manure amendments, cover crop management, planting/harvest dates, and climate data (e.g. daily min/max temperature). The U.S. GHG Inventory uses data from the USDA-NRCS Conservation Effects and Assessment Project (CEAP). CEAP data is assigned to Natural Resources Inventory (NRI) survey locations (all non-federal land) which have "expansion factors" that indicate the total area of land with the same land-us/management history.

Finally, agricultural GHG inventories require activity data on crop residues (to estimate crop residue N) and N mineralized from soil organic matter. The DAYCENT model internally generates the decomposition, N fixation and mineralization processes and therefore does not require input data on crop residues nor N mineralization (EPA, 2023).

DAYCENT additionally includes input parameters for grazing events. Fertilization data inputs ensure that DAYCENT model outputs accommodate manure deposited on pasture, range and paddock (included in N_2O estimates on grasslands and managed pasture). Additional livestock management practices which result in altered GHG emissions include manure management strategies, and feeding strategies or rumen manipulation are not included in DAYCENT-modelled outputs as DAYCENT models N_2O emissions from agricultural soils and soil organic carbon.

Modelling: Insight into the process and level of technical expertise that would be required to model N_2O emissions, and soil organic carbon fluxes at a state level for Vermont can be gleaned by studying the application of DAYCENT at the national level. The application of DAYCENT at the national level also provides insight into the methods that underpin the EPA's State Inventory Module, which was used to estimate Vermont's previous GHG inventory.

To model direct **N_2O emissions from agricultural soils**, the U.S. GHG Inventory uses the following process:

a) NRI data is combined with crop specific National Agricultural Statistics Service (USDA-NASS) land-use history and fertilization data.
b) DAYCENT is run for specific crops including alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, lentils, oats, onions, peanuts, peas, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, sweet potatoes, tobacco, tomatoes, and wheat.
    - The DAYCENT model simulates interactions with weather and environmental factors relevant to specific locations (e.g. freeze-thaw effects that generate N_2O pulses) using climate and soil data. DAYCENT does not assume all potential N_2O is emitted in a single year, and results include legacy effects of previous years (N_2O not yet emitted).

DAYCENT is not used at the national level for some emission sources (e.g., cobbly, gravelly, and shaley mineral soils, direct N_2O from animals grazing on federal lands, among others) due to the model not yet being calibrated for these situations and or data limitations (U.S. Environmental Protection Agency, 2023).

At a high level, to model emissions from **mineral cropland and grassland soils**, the U.S. GHG Inventory uses the following inputs and process:

c) CEAP trends in management practices over the inventory time series (1990 – present year) are determined by combining CEAP data with several other national datasets, determining the likely management practice(s) at a given NRI location using a machine learning technique known as gradient boosting, and assigning certain management practices from CEAP to NRI locations using predictive mean matching.

a) Additional Fertilization Data for mineral fertilization and manure amendments data from the Agricultural Resource Management Surveys (ARMS) and the USDA-NASS is combined with CEAP data.
b) Additional Tillage Data from Conservation Technology Information Center (CTIC) data and OpTIS data is combined with CEAP data.
c) Additional Cover Crop Data from OpTIS and USDA-NASS data is combined with CEAP data.
d) Using the above inputs, the DAYCENT model is run from 1990 to 2020 and a linear extrapolation method using linear regression is used for 2021 to approximate emissions given data for the most recent inventory year is not yet available at the time model runs occur in order to meet international inventory reporting deadlines.

To model emissions from mineral cropland soils using DAYCENT, Vermont might consider combining relevant state specific data with national datasets, or in some cases supplanting national data. A similar process as outlined above would be required, including estimating levels of and trends for key management practices, and additional steps for model calibration (which have been done at the national level). Model validation is necessary and achieved by comparing independent data with model results to determine the model's predictive ability. Calibration is required for a subset of the more than 1000 parameters in DAYCENT (Hartman et al., 2018) and DAYCENT developers recommend model outputs are validated for soil water content, crop yields, plant growth rates, soil organic carbon levels, and nitrogen flows, in order. Vermont should consider availability of independent datasets for model calibration and validation.

Other Considerations: N_2O emission results that are generated by DAYCENT model runs cannot be partitioned into the activities responsible for them, i.e., N_2O emissions from synthetic fertilizer applied to agricultural soils cannot be separated from the N_2O emissions from manure applications (U.S. Environmental Protection Agency, 2023). The U.S. GHG inventory reports N_2O emissions by source by determining the average proportion of specific N from for example, synthetic fertilizer, and dividing this by the total mineral N in the soil. The proportion is then multiplied by total N_2O emissions to estimate source specific N_2O emissions. If Vermont were to use DAYCENT for state level modelling, a similar process and set of assumptions could be made to allocate emissions to specific sources.

DAYCENT Summary Remarks: For Vermont to determine whether it would be worthwhile to run DAYCENT to model direct and indirect N_2O emissions, and emissions from mineral soils (grassland and cropland), Vermont should consider the following:

- A comparative assessment of CEAP, ARMS, USDA-NASS, CTIC and OpTIS data against the State's available and representative data on fertilization, tillage and cover crop practices and whether there are any indications that Vermont's state specific data varies significantly from data presented in the national datasets,
- Available resources to compile and interpret state specific data, and input data into a State specific calibration of the DAYCENT Model, and
- Technical expertise available to interpret and input data and calibrate DAYCENT before generating model results to ensure that the results are representative.

3.1.4 DNDC

Description: The Denitrification-Decomposition (DNDC) model is a process based biogeochemical model focused on nitrogen (N) and carbon (C) biogeochemical cycling in agricultural systems (*DNDC Scientific Basis and Processes Version 9.5*, 2017). DNDC therefore models emissions and removals attributable crop GHG emission sources, as well as soil carbon fluxes. The original DNDC model does not inherently estimate livestock GHG emissions, so the Manure-DNDC model was developed, which estimates CH4, N2O and NH3 emissions occurring from the manure organic matter turnover processes it models, including decomposition and nitrification etc.

In DNDC, the primary drivers effecting GHG emissions are climate inputs (e.g. rainfall and min/max temperatures), soil, vegetation, and management practices, which in turn determine the soil environmental conditions and the resulting GHG emissions, yields, and carbon sequestration by pool. Nitrification, denitrification, and fermentation sub-models predict emissions of CO_2, N_2O, CH_4, NH_3, NO, and N_2.

Cost: ReGrow Ag holds the exclusive commercial rights to DNDC, and the costs for calibration are significant. ICF has engaged in conversations with ReGrow Ag to determine estimated costing for production of State level inventories and costs are yet unclear. They believe that they could produce Tier 3 state level inventory outputs within 6 months of a contract being initialized. Older versions of DNDC are publicly available via the University of New Hampshire website.

Complexity: DNDC requires a model expert and is expected to require a very high level of effort.

IPCC Alignment and Reporting Tier: In the context of IPCC reporting tiers, DNDC generates Tier 3 emission estimates when calibrated for a specific region and verified using local measurement data. Emissions are modelled so a comparison of whether there is alignment of emission estimation methods and emissions factors does not apply.

Scale: The model can be run in either regional or site mode. In the regional model the model utilizes a GIS database with the necessary environmental and land management data to produce more generalized results for a large land area (e.g. a county). Site mode offers the ability to tailor many more parameters in the general user interface (GUI) and produces Monte Carlo uncertainty analyses (Approach 2 per IPCC Guidance) are only possible at a site scale.

Use: The model was originally developed for quantification of GHG's from crop cultivation in the U.S., with special focus on quantification of nitrogen-based emissions in the mid-west. DNDC has since been further modified in the following, to list a few:

- NZ DNDC: adapted for New Zealand conditions and to model intensive grassland systems (Saggar et al., 2004, 2007)
- DNDCv.CAN: Canadian version of DNDC best suited to cold temperate climates
- Manure-DNDC: estimates GHG and ammonia emissions from manure systems (Li et al., 2012)
- Forest-DNDC: estimates forest production, carbon sequestration, and trace gas emissions in forests
- Rice DNDC: estimates GHG emissions from rice paddy fields
- UK-DNDC: modified for UK conditions and used for the UK GHG inventory estimates of direct N_2O from agricultural soils (Brown et al., 2002; Cardenas et al., 2013)

DNDC has been extensively used in Australia, Canada, China, Europe, India, New Zealand, the U.K., and the U.S. Due to independent academic developments, a single complete list on use of DNDC models and combinations of models exists, however the model can be calibrated to the Vermont system (interview with ReGrow).

Additionally, results from DNDC were used by the IPCC in generating the default emission factor for $EF_{3PRP,CPP}$ (emission factor for cattle, swine and poultry manure deposited onto pasture range and paddock), and the fraction of nitrogen leached or runoff in wet climates (IPCC, 2019).

Activity Data and Coverage of Management Practices: DNDC requires daily weather data including temperature, humidity, wind speed and precipitation, as well as soil data (pH, bulk density, and soil texture), and crop management data (crop areas and rotations, planting and harvest dates). Management practices that are parameterized in DNDC include tillage, fertilization, manure application, flooding, irrigation, and cultivation of cover crops. These practices in the model influence biophysical and biogeochemical reactions and their products (*DNDC Scientific Basis and Processes Version 9.5*, 2017). For management practices, the following activity data is required:

- N fertilization: rate, amount, method, and type of fertilizer,
- Manure application: amount and manure composition
- Irrigation: method (surface, drip, sprinkler, subsurface drip)
- Tillage: Operational Tillage Information System (OpTIS)

OpTIS remote sensing data is freely available for Vermont from 2015 – 2021, mapping tillage, residue cover, cover crops and soil health practices (*Conservation Technology Information Centre*, 2023).

Modelling: The processes modelled include decomposition, nitrification, denitrification, ammonia volatilization, fermentation and methanogenesis (*DNDC Scientific Basis and Processes Version 9.5*, 2017). DNDC simulates microbial activity, the nitrification/denitrification process using Michaelis-Menten kinetics, all of which drive and moderate oxidation-reduction reactions and GHG (CO_2, N_2O and CH_4) generation from the dominant microbial population(s) at a given point in time.

DNDC Summary Remarks

For Vermont to determine whether it would be a worthwhile investment to calibrate, validate, and run DNDC, or contract another organization to model direct N_2O emissions, emissions from mineral soils (grassland and cropland), and emissions from livestock systems using DNDC, Vermont should consider the following:

- Which DNDC models would be necessary and the cost to calibrate + validate them for Vermont,
- The State's available and representative data on fertilization, tillage and cover crop practices and whether there are any indications that Vermont's state specific data varies significantly from data presented in national datasets,
- Available human resources to compile and interpret state specific data, and input data into a State specific calibration of the DNDC Model, and
- Technical expertise available to compile interpret and input data, calibrate DNDC and interpret results (or the cost of outsourcing this).

3.1.5 EX-Act

Description: EX-Act is a free, Excel-based tool that is a land-based accounting system, measuring GHG impacts per unit of land (Grewer, Bockel, Schiettecatte, & Bernoux, 2017). Published by the FAO, it is an emission factor-based tool that was last updated in 2021 and undergoes ongoing maintenance. EX-Act estimates emissions and removals attributable to crop and livestock GHG emission sources, as well as soil carbon fluxes. EX-Act compares the GHG emissions and carbon stock changes from project activities, relative to a pre-project start date baseline (FAO, 2022).

Alignment with IPCC and Reporting Tier: EX-Act was developed using IPCC Tier 1 default activity data, emission factors and methods and outputs would be considered Tier 1 estimates. It is aligned with the emission source categories and methods presented in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, the 2019 IPCC Refinement, and the 2013 IPCC Wetlands Supplement. The methodology of the tool was developed primarily from Volume 4 of the 2019 Refinement to the 2006 IPCC Guidelines and the 2013 Wetlands supplement, though the tool in some cases employs emission factors and methods from current literature (FAO, 2022). The tool uses Global warming potential (GWP) values from the IPCC 5th Assessment Report (AR5) and generates Tier 1 default estimates, unless Tier 2 (in Vermont's case, state specific) values are specified by the user (FAO, 2022).

Cost: EX-Act is free.

Complexity: EX-Act requires beginner knowledge of the tool and is expected to require a medium level of effort.

Scale: EX-Act is primarily used at the project scale, but it could be used at the regional or national scale (Grewer, Bockel, Schiettecatte, & Bernoux, 2017).

Use: EX-Act was used to develop the Vermont Carbon Budget (Bonasia, Ruhl, Dube, White, & Darby, 2022). At the project scale, EX-Act was used in Tanzania for the FAO Accelerated Food Security Project (Grewer, Bockel, Schiettecatte, & Bernoux, 2017).

Activity Data and Coverage of Management Practices: To use the EX-Act tool a variety of descriptive inputs are required, including data on the location, climate, moisture, soil type, and duration of intervention (FAO, 2022). It requires a small amount of activity data input to perform basic calculations and gives the user the option to enter custom factors and additional, more specific data to aid in refining calculations (Tier 2 data).

To account for emissions from cropland management, the Tool requires the user to input areas, in hectares, for each crop/system as well as management practices for each crop/system (FAO, 2022). These management practices, derived from Table 5.5 of the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, include (FAO, 2022):

- Tillage management (full, reduced, or no-till);
- Input of organic material; and
- Residue management (burned, retained, and exported);

The user is also able to enter the yield, in tons/hectare/year, for each crop. The EX-Act Tool is able to calculate emissions related to changes in management practices for both annual and perennial systems in cropland remaining cropland, as well as in cropland land-use changes that include implemented management practices.

For annual cropping systems, the user may input specific soil carbon sequestration rates, stock change factors related to management practices (i.e. land-use, tillage, and organic amendment input factors), and available residues and biomass (FAO, 2022). For perennial cropping systems, users may add project-specific (or regionally specific in the case of Vermont) Tier 2 data for soil carbon stock estimates and stock change factors. The user may also alter above/below-ground biomass growth rates, burned residue quantities, and fire periodicity top reflect the regional conditions (FAO, 2022).

In EX-Act, emissions from fertilizer application are accounted for in the Input module, which is separate from the Cropland and Grassland/Livestock modules. This covers lime and urea application and synthetic (inorganic) and organic N-based fertilizers (excluding manure deposited directly onto on pasture by grazing livestock, which is accounted for in the Livestock module) (FAO, 2022). The amount of fertilizer applied per year is the only required activity data for this module. Project-specific (Tier 2) emissions factors can be entered for all fertilizers considered.

Required activity data for emissions from livestock and manure management includes livestock species, category (dairy, non-dairy etc. and age class), productivity level, quantity of product produced, and population. Users may choose to enter project/region specific (Tier 2) emission factors for CH_4 from enteric fermentation, CH_4 from manure management in pasture/range/paddock (PRP), and N_2O from manure management in PRP (FAO, 2022). Additionally, users may input the percentage of animals grazing on PRP. For the remaining animals (i.e., those not grazing on PRP), users can specify the manure management system used (e.g., liquid/slurry, solid storage) or can select a default EF that represents the regional average of all systems. For these non-PRP manure management systems, users can enter Tier 2 emission factors.

Other Considerations: EX-Act was designed for land management project level GHG accounting, and only one dominant soil and climate type can be considered at a time (Grewer, Bockel, Schiettecatte, & Bernoux, 2017). Vermont has multiple soil types and requires more precise climate data for more accurate manure management emission estimates. The highest level of specificity that the Tool can be calibrated to encompasses the Northeastern United States. Thus, the tool will not output results specific to Vermont (Bonasia, Ruhl, Dube, White, & Darby, 2022). However, it was indicated that further calibrating the tool to the state level would require a large research effort with potentially minimal changes in model estimates, and that the Tool is well calibrated to the Northeastern United States (Bonasia, Ruhl, Dube, White, & Darby, 2022). To up-scale to regional and national scales (i.e., of different soil and climate types, if required), the Tool's guidance recommends potential sensitivity analyses of soil and climate conditions or separate EX-Act analyses conducted by region to ensure precision (Grewer, Bockel, Schiettecatte, & Bernoux, 2017).

One noted benefit of EX-Act is its ability to calculate N mineralization based on lost SOC via change in land use or management (FAO, 2022), which was not accounted for in the 2020 Vermont Inventory.

The Tool does not estimate indirect emissions related to nitrogen application on managed soils (FAO, 2022).

EX-Act summary remarks: EX-Act was primarily developed as a tool to assist in evaluating the GHG emissions and carbon stock changes for land management projects, relative to a pre-project start date baseline and the tool can only consider one dominant soil and climate type at a time. Therefore, ICF recommend that the tool is limited in its ability to be used for inventory purposes, and for GHG impact analyses of changes in management practices for policy scenarios.

3.1.6 FEAT

Description: The Farm Energy Analysis Tool, or FEAT, is a database model in excel that was developed by individuals from the Department of Crop and Soil Sciences at The Pennsylvania State University (Camargo, Ryan, & Richard, 2011). The tool is free-to-download and performs farm-level, emission factor-based estimations of GHG emissions from crop production and cropland management, in addition to estimating the crop system's energy balance. FEAT does not estimate GHG emissions of any livestock emission sources, as it was designed for crop whole-farm system GHG accounting.

IPCC Alignment and Reporting Tier: For direct and indirect N_2O emissions from agricultural soils Tier 1 (IPCC, 2006) methods and default emission factors are used. Other FEAT GHG estimates such as for pesticides, energy used on farm, liming and other non-carbon containing fertilizers, go beyond IPCC emission source boundaries, due to FEAT's intended use, for whole-farm GHG accounting (e.g. upstream and downstream emissions are included). Provided emission factors include IPCC 2006 Tier 1 emission factors and some emission factors from literature. Additionally, the tool uses a mix of methodologies from IPCC 2006 and literature, and the tool uses GWPs from the 5th Assessment Report (AR5).

Cost: FEAT is free.

Complexity: FEAT requires previous experience of the model and is expected to require a medium level of effort.

Scale: FEAT estimates GHG emissions at the farm level.

Use: FEAT has been used to compare cropping systems for energy and GHG emissions at the farm level. Researchers at the Pennsylvania State University evaluated cropping system strategies for an average-sized Pennsylvania dairy farm to produce all of its forage, feed, and tractor fuel needs, and utilized FEAT to evaluate the systems for fuel self-sufficiency, energy, and GHG emissions (The Pennsylvania State Univesity, n.d.) (The Pennsylvania State University, n.d.). Penn State researchers also used FEAT in collaboration with researchers from USDA-ARS Beltsville Agricultural Center and the Rodale Institute to evaluate energy and GHG emissions from their long-term farming systems trials (The Pennsylvania State University, n.d.).

Activity Data and Coverage of Management Practices: FEAT requires minimal input to perform crop production and cropland management emissions calculations, requiring the user to enter only the crop field area, types of crops, and yield for each crop. This is because the model provides default values for all other activity data and factors used in the calculation of emissions; these default values are the result of an extensive literature review and include peer-reviewed literature, online documents, and simulations (Camargo, Ryan, & Richard, 2013). Default values include those for farm inputs, as well as values used in the energy analysis and calculation of GHG emissions (e.g., emission factors). FEAT allows the user to modify all default (activity data and emission factor) values, meaning the user can enter custom values to refine calculations for their specific use or location. Therefore, along with entering custom emission factors, users can refine the default values in the farm inputs section, which includes activity data such as:

- Residue removal percentage after harvest;
- Crop moisture percentage at harvest and storage;
- Fertilizer application rates (N, P_2O_5, K_2O, and Lime);
- Other input application rates (Seed/cuttings, herbicides, and insecticides);
- Crop and Residue production (in Mg WM or DM/year); and
- Other farm input activity data, such as diesel fuel used, and energy required for drying and transportation of inputs.

FEAT considers some management practices in its cropland emissions calculations but is not comprehensive. For example, farming inputs are accounted for, such as fertilizers, pesticides, and cuttings, as well as residue management (i.e., percent removal after harvest) and crop rotations (Camargo, Ryan, & Richard, 2013). However, though earlier versions of the tool required user inputs for tillage management and fuel consumption for various tillage practices is provided in the data tabs, tillage management does not appear to be an available input as of FEAT Version 1.2.7. FEAT also does not consider land-use changes and soil carbon emissions and sequestration (Camargo, Ryan, & Richard, 2013).

However, FEAT does not calculate the GHG emissions related to livestock or manure management practices, aside from N_2O emissions from manure application which is a crop GHG emission source.

Other Considerations: Additional benefits of FEAT are that it is a prediction-based model and is calibrated for the United States. However, as discussed above, the tool models emissions at the farm level, which would present challenges when scaling for a state-level inventory.

For agricultural emissions, FEAT is limited to 13 crops in the Crop module: barley harvested for grain; corn harvested for grain and silage; rye harvested for silage; wheat harvested for grain and silage; alfalfa; red clover; canola; soybean; sugar beet; miscanthus; switchgrass; hybrid poplar; and willow and limited to 2 emission sources; N2O from agricultural soils (direct and indirect) and CO2 from liming (not including emissions from urea or other non-carbon containing fertilizers).

FEAT summary remarks: FEAT's design for whole-farm emission based GHG accounting, and limited scope for GHG emission sources limits its effectiveness for use to compile state-level GHG estimates and inventory. Specifically, the tool's omission of emissions from land use, land use change and forestry (LULUCF), all livestock emission sources (enteric fermentation, and CH_4 and N_2O from managed manure), biomass burning, and urea and other non-carbon containing fertilizers means that substantial emission sources and sinks are not considered. The tool would be generally less effective than the current tool utilized by ANR to develop the state-level inventory (i.e. SIT).

3.1.7 Holos

Description: Holos is a Canadian empirical model, estimating whole farm GHG emissions including crop and livestock GHG emission sources, soil carbon fluxes, and emissions from energy used on farm, and associated with the manufacture and transportation of farm inputs on an annual basis (Little et al., 2008). The desktop-based software is primarily designed to inform GHG mitigation on Canadian farms, but various versions have been modified for international conditions. Due to inclusion of energy and upstream emissions related to farm inputs, Holos more complete in scope *when considering whole farm system* emissions than the other tools that have been reviewed for ANR, however these additional emission sources are not directly relevant for Vermont's *Agriculture GHG Inventory*.

Alignment with IPCC and Reporting Tier: Holos uses IPCC 2006 Tier 1 and Tier 2 methods, modified appropriately for the farm scale. Additionally, Holos was designed primarily as a planning tool, to test on farm GHG emission reductions, instead of an inventory tool.

Cost: Holos is free.

Complexity: Holos requires beginner knowledge of the tool and is expected to require a medium level of effort.

Scale: Holos is most appropriate for farm scale analysis and planning.

Use: Holos is extensively used for Canadian and some international farm life cycle assessment studies (Agri-Food Canada, 2023a) but to ICF's knowledge, has not been used internationally for inventory efforts.

Activity Data and Coverage of Management Practices: For international use, Holos requires the following data:

- Location: daily weather, soil data and plant hardiness zones.
- Land management:
  - Field/Crop Rotation components including dates, yield, tillage, type of crop (e.g., green manure, silage etc.), moisture content, pesticide passes, fuel energy and herbicide energy, fertilizer and manure application, cover crop, and residue management,
  - Field-Perennial/Grassland management including area, historical management crop type, irrigation, pesticide passes, fuel energy and herbicide energy, fertilizer and manure application,
  - Shelterbelts including row length and number of trees, average circumferences, species, additional rows, and average spacing,
- Livestock systems (Beef production, Dairy cattle, Swine, Sheep, Poultry, and Other livestock):
  - Population data, management periods, weight at beginning and end of management periods, diet composition including additives, housing management, bedding types, and manure handling system.
- On anaerobic digestors, including manure type, bedding material, manure added to digestor daily, total solids and volatile solids, farm residue substrate data.

All data inputs are classified as either required, optional, recommended, operational and not editable (Agri-Food Canada, 2023b) and these are further outlined in Appendix 3. To compare livestock management practices, a user must either i) set up two different farms, ii) set up two livestock components in a single farm or iii) establish two livestock "groups" within a single farm and use the comparison function of Holos (Agri-Food Canada, 2023a). Comparing livestock diets can be achieved by copying livestock groups and adjusting the diet for each group. To modify crop management practices, a user can pre-define "field component" parameters for the area of interest and modify single field parameters through addition of "single field components".

Other Considerations: Holos is currently only available via desktop software, however, may eventually be available via an online user interface. Holos is an opensource software. It is unclear what GWP values are used in Holos to convert all estimates to net farm emissions (CO_2e). Holos users have access to extensive online resources.[2] Like COMET-Planner, Holos is able to capture the effect of one management practice on other management practices and thus the complex interactions between GHGs.

Holos summary remarks: Holos is likely not suitable for Vermont's Agriculture Inventory efforts for two reasons:

1. Holos is intended to be used as a farm management and GHG emission reduction planning tool, and was not designed for inventorying purposes,
2. Holos does not account for all AFOLU emission sources due to its primary design purpose of whole-farm accounting for livestock emissions. Due to this design, crops are evaluated as they relate to animal feed production in the tool's modeling of cropland practices.

3.1.8 IFSM

Description: The Integrated Farm System Model (IFSM) is a free-to-download, software-based life cycle emissions model published by the USDA. Starting originally as a simulation model of dairy forage systems, the model has been continually added to and refined over the last several decades, culminating in a model that simulates all major farm components on a process level (Rotz, et al., 2022). IFSM estimates emissions from crop and livestock GHG emission sources, as well as soil carbon fluxes. However, where justified by a lack of available data or the relative insignificance of the emission source, IFSM sporadically uses emission factors instead of process-based modeling for certain emission sources (Rotz, et al., 2022). At the time of publication of the model, recent field data and the most current and regionally specific activity data, methods and models were used and underly estimates from enteric fermentation and manure emission sources. The IFSM model is regularly maintained, and therefore data underpinning GHG estimates can be considered to be current and generate a mix of Tier 2 and Tier 3 methods depending on the emission source.

In addition to greenhouse gas emissions and environmental impacts, IFSM models farm performance and economics (Rotz, IFSM and DairyGEM tool training presentation, 2012).

Alignment with IPCC and Reporting Tier: For soil carbon pools and N_2O from agricultural soils, IFSM uses underlying modelling from CENTURY and DAYCENT and therefore emission estimates using this modelling can be considered Tier 3. IFSM utilizes an aggregation of different methodologies from models (primarily DAYCENT), literature, and IPCC 2006.

Cost: IFSM is free.

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[2] Resources include sector specific (i.e. dairy cattle) training guides, FAQ, a summary of input requirements, various .csv files of input parameters, scripts, etc.

Complexity: IFSM requires specialist knowledge and is expected to require a high level of effort.

Scale: IFSM models emissions at the farm-level and has been designed for use mainly in the temperate regions of the northern United States and southern Canada. Most of the model verification has been done in the Midwest, Northeast, and Pacific Northwest of the United States, and most applications of the model are from these regions, as well as Quebec and Ontario, Canada (Rotz, et al., 2022).

Use: IFSM was primarily developed as a research tool to compare and evaluate different dairy-production systems, and it has been used to compare a plethora of strategies and technologies related to dairy farms (Rotz, et al., 2022). It has been used to simulate how different management changes can help dairy farms adapt to future climate change and to perform a partial life cycle assessment to estimate GHG and ammonia emissions from beef production systems in California (U.S. Department of Agriculture, 2023).

Activity Data and Coverage of Management Practices: The model runs based on parameters from three separate input files that contain farm, machinery, and weather data (Rotz, et al., 2022). The tool comes with several default farm data files that represent different farm sizes, cropping systems, and other related scenarios (Rotz, IFSM and DairyGEM tool training presentation, 2012). Data from the farm and machinery files can be modified while setting up the model to refine the simulation to the user's scenario. IFSM includes at least one default weather data file for each state and allows the user to edit these default files or create new ones, if needed (Rotz, et al., 2022). At a high level, activity data required to run IFSM includes parameters related to:

- Animals and herd structure;
- Animal feed and diet;
- Manure storage and management;
- Grazing practices and manure deposition onto pasture;
- Crop planting and characteristics;
- Tillage and harvest information;
- Fertilizer application to agricultural soils;
- Machinery and equipment used (not IPCC AFOLU source, instead related emissions are accounted for under Energy and IPPU); and
- Soil and farm characteristics.

IFSM's detailed and extensive activity data input requirements can reflect the adoption rates and GHG impacts of various management practices. These management practices include the use of cover crops, grazing practices, practices related to feed storage, feed and dietary management, manure collection and storage (including the use of anaerobic digestors), practices related to crop harvesting, tillage and planting practices, and fertilizer and manure application to fields. Agroforestry management practices are not covered. Additionally, IFSM does not allow for modelling of long-term sequestration or depletion of soil carbon, which can be affected by management practices such as tillage (Rotz, et al., 2022).

Other Considerations: IFSM models GHG emissions and removals for all agricultural GHGs (NO_2, CH_4, and CO_2). The tool models emissions from crops, soil, and livestock and manure (Rotz, et al., 2022). IFSM does not account for CH4 and N2O fluxes related to land use, land use change and forestry (LULUCF). Additionally, the tool requires a high level of technical expertise to operate, including understanding the processes that underpin emissions sources, and to calibrate, if necessary. The tool also requires a high level of effort to learn and operate.

IFSM summary remarks: IFSM was primarily developed as a farm level GHG accounting, research and teaching tool, and it does not model long-term sequestration and depletion of soil carbon, and therefore may not be suitable for state level GHG inventorying purposes. Additionally, given technical and human resource limitations ANR face, due to the high level of effort and technical expertise required to run the model, the model may not be feasible for generating state level GHG estimates.

3.1.9 SIT

Description: The EPA SIT Tool is an excel-based inventory tool that covers the same sectors and uses the same methods as the U.S. GHG Inventory (EPA, 2024) including estimates of emissions and removals from crop and livestock GHG emission sources, and soil carbon fluxes. It is closely aligned with the U.S. GHG Inventory, and much of the provided default activity data and emission factors are pulled from the U.S. GHG Inventory. Its design is simple and easy-to-use, and it requires minimal technical expertise and input to develop a basic inventory. The Tool comes in a protected Excel file and there is little opportunity for customization. The Tool is agnostic to management practice adoption and changes.

IPCC Alignment and Reporting Tier: SIT is aligned with the 2006 IPCC Guidelines and the 2019 Refinement and SIT default data and methods are based on the U.S. GHG inventory agriculture sector emission estimates and methods. For soil organic carbon and N2O from agricultural soils, SIT therefore can be considered to generate Tier 3 estimates, as the U.S. GHG inventory uses DayCENT for these estimates (at the state level). Enteric fermentation and manure emission sources can be considered to be Tier 2, as the U.S. GHG inventory incorporates state specific data and sophisticated estimation methods. CH4 and N2O fluxes from land use, and land use change (LULUC) can be considered to be Tier 2 as they are based on national state-level disaggregated data and higher tier modelling.

Cost: SIT is free.

Complexity: SIT requires no prior knowledge of the tool and is expected to require a very low level of effort.

Scale: The SIT Tool was developed specifically as a state-level inventory tool.

Use: The SIT Tool is widely used by state governments.

Activity Data and Coverage of Management Practices: The SIT Tool includes built-in, default activity data and emission factors but gives the user the option of entering their own data and emission factors in the Control tab. The default data and emission factors are pulled from a variety of sources, but the primary source of information is the U.S. GHG Inventory; data sources are provided to the user for all emissions factors and data sets within the SIT Tool via Excel comments. When using default SIT data and emission factors, the only required input is selecting the state. However, certain state-specific activity data are not provided in the default dataset and require user input, such as default data on histosols.

As previously mentioned, users can enter their own activity data and emission factors in the SIT Tool. Activity data that can be user-entered in the agriculture SIT module includes animal type and population for livestock emissions and crop type, crop production, and fertilizer use for cropland emissions. In the LULUCF module, users can enter various activity data, the most relevant being carbon flux data for both agricultural soils and forests.

The SIT suite and its GHG estimates are agnostic to management practice changes. The tool does not generate GHG estimates of a baseline situation or scenario without management practice changes, and a subsequent set of estimates that reflect if new GHG mitigation management practices were to be implemented. This means that the tool cannot estimate and track GHG impacts of conservation practice adoption.

It is able to model emissions from various manure management systems using emissions factors from the U.S. GHG Inventory that are specific to each system. These emissions are reported by animal type, adding an additional level of granularity. However, the tool does not provide a complete breakdown of all potential manure management systems and is notably missing certain systems popular in Vermont, such as anaerobic digesters and manure injection.

As discussed in the DAYCENT summary, the U.S. GHG Inventory utilizes DAYCENT to model N_2O emissions and soil organic carbon, the data from which is fed into the LULUCF module of the EPA SIT Tool. ICF recommend that ANR discuss with EPA whether the adoption of various conservation practices was reflected in DAYCENT modeling that was utilized in the U.S. GHG Inventory, because if so, SIT Tool estimates would provide emission estimates that already reflect mitigation uptake of these practices.

Other Considerations: Benefits of the SIT tool include its simple user interface, low level of required technical expertise, meaning the user can generate a state-level inventory relatively easily and quickly. The Tool is free to download, undergoes regular maintenance, and was last updated in 2024.

The agricultural module does not model soil carbon fluxes; therefore, the LULUCF module must be used in conjunction with the agricultural model to account for soil carbon fluxes related to agricultural lands. Soil carbon fluxes related to agricultural lands can still be reported alongside all other agricultural GHG emissions in a state level inventory. Direct N_2O emissions from N mineralization, Direct N2O emissions from drainage of histosols, and related indirect N_2O emissions from managed agricultural soils are not currently estimated in the SIT Agriculture module (using default data entry and no user-specific modifications).

The SIT Tool is designed to protect the user against manual data entry errors, and has limited customizability, as the majority of calculations occur in protected cells. Customization is limited to changing emission factors, constants, and activity data, where allowed.

SIT summary remarks: SIT is designed specifically as a state inventorying tool, is freely available, accounts for emission sources on at least IPCC Tier 2 level methods and requires minimal human and technical resources to carry out a complete annual GHG inventory. **Given ANR's resource availability, ICF recommend that SIT is the best-suited currently available tool for Vermont to develop a state level inventory.**

The SIT Agriculture module is not complete in its coverage of emission sources and sinks, notably not estimating two sources of N_2O emissions from agricultural soils; Direct N_2O from nitrogen mineralization in soil organic matter following drainage or management of organic soils or cultivation or land use change on mineral soils (e.g. grassland converted to cropland), and Direct N_2O from drainage of organic soils (histosols) if the user is using default SIT data. These emission sources are worth accounting for but depending on state land management *may not comprise* significant emission sources (considered to contribute >2% of all agricultural emission sources). To account for these emission sources, ANR may wish to commission development of, or develop a simple spreadsheet to generate estimates of these additional unaccounted-for sources and add the estimates to the inventory totals as generated by SIT, or use an existing tool.

Soil carbon fluxes from cropland soils and managed agricultural pasture (Vermont indicated this is all grassland in Vermont) are estimated in the SIT LULUCF module, which ANR may choose to report alongside emissions estimated by the SIT Agriculture module for agricultural production activities, which would support policies and related decision making for agricultural emission mitigation, by considering emissions and removals of agricultural land in their entirety.

SIT is agnostic to management practice changes and therefore has no way of generating outputs for mitigation GHG impacts from management practice adoption and changes. ANR would need to employ other tools, or apply empirical modifications to results output by SIT, to account for the GHG impacts of management practice changes. **ICF recommend COMET-Planner as a potential tool useful to ANR to account for the GHG impacts of management practice changes.**

3.1.10 U.S. EPA Disaggregated State Level GHG Inventory Data

Description: U.S. EPA disaggregated state level data includes state GHG data that is consistent with and complementary to the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (EPA, 2023). As such, state level GHG estimates presented in the disaggregated data are based on the same methodologies as the national inventory, and cover the same time series, greenhouse gases, and anthropogenic sources and sinks as the national inventory (EPA, 2023). Additionally, because the state level data is consistent with the national inventory, it aligns with emission source categories in international standards and guidelines including IPCC (EPA, 2023). Importantly, the U.S. GHG Inventory is not a modeling tool; however, it can be utilized as a source of activity data for state inventory development. This state level data is freely available through requests to EPA.

IPCC Alignment and Reporting Tier: The data represents GHG estimates. The tier used to develop the GHG estimates is accurately described in SIT; briefly, soil organic carbon and N_2O from agricultural soils reflect Tier 3 estimates, enteric fermentation and manure emission sources reflect Tier 2 estimates, and CH_4 and N_2O fluxes from land use, and land use change (LULUC) reflect Tier 2 estimates. There are no methods or emission factors in the data as it represents compiled estimates only.

Cost: EPA Disaggregated State Level Data is free but may require some time investment to get the data into a useable format for GHG inventorying purposes.

Complexity: The U.S. EPA Disaggregated data is not an estimation tool, so these criteria were not assessed.

Scale: The disaggregated data from the U.S. GHG Inventory is available at the state level.

Use: The *Inventory of U.S. Greenhouse Gas Emissions and Sinks* is the official inventory developed by the U.S. Government, and state-level data from this national inventory is utilized by several states in their state-level inventories.

Activity Data and Coverage of Management Practices: The U.S. GHG Inventory and its disaggregated data is not a modeling tool. As an example, the inventory uses DayCENT to model CO_2 flux from cropland and grassland, which does require data inputs that in many cases reflect management practices, and thus provide a GHG emissions estimate reflecting that management scenario, for a single point in time. Therefore, by comparing GHG estimates from two points in time, with an understanding of the management practice relevant input data that underpins the two GHG estimates, further analysis could determine what the net GHG effect of specific changes in management.

Other Considerations: The data is freely available.

U.S. EPA Disaggregated State Level Data summary remarks: ICF recommend the data is highly useful to validate estimates generated either by SIT or another emission estimation tool that ANR should choose to use to generate state level GHG estimates.

4. Activity Data

4.1 U.S. EPA State Inventory Tool Default Data

As discussed in the Model and Tool Review, when using SIT, the only required input is the state of interest, as default data is available for all other activity data. **Figure 1**, adapted from the User's Guide For Estimating Carbon Dioxide, Methane, and Nitrous Oxide Emissions from Agriculture using the State Inventory Tool, shows all activity data utilized in the SIT Agriculture module. While a variety of sources are referenced, the primary source of default activity data is the U.S. Greenhouse Gas Inventory of Emissions and Sinks.

Limitations of the SIT Agriculture module include that it lacks default histosols data. Emissions of N_2O drainage of organic histosols can be estimated in the tool, but data must be known and entered by the user. Soil organic carbon from histosols is also modeled by SIT but is estimated in the LULUCF module. Additionally, as discussed in the Model and Tool Review, SIT does not include certain manure management systems in the default manure management system breakdown percentages (e.g., anaerobic digestors).

To report a complete Agricultural GHG inventory, ICF recommend that ANR report soil carbon emissions and removals from agricultural lands as estimated by the SIT LULUCF module alongside GHG estimates from the SIT Agriculture module. The SIT LULUCF and Agricultural modules do not overlap; therefore, estimates of soil carbon fluxes in the LULUCF module can be directly added to or subtracted from GHG emissions in the Agricultural module. This can be done manually or through the SIT Synthesis Tool. If using the SIT Synthesis Tool, ANR can fully complete the agriculture module and only complete the Agricultural soil carbon fluxes section of the LULUCF module, so only these emissions and sequestration are considered when synthesizing the two modules.

Module Worksheet	Data Required	Gas(es)
Enteric Fermentation	Emission Factors by Animal Type Animal Population Numbers	CH_4
Manure Management-CH_4 Manure Management-N_2O	Typical Animal Mass (TAM) Volatile Solids (VS) Production Maximum Potential CH_4 Emissions (B_o) Kjeldahl (K) Nitrogen Excreted* Animal Population Numbers	CH_4, N_2O
Ag Soils-Plant-Residues & Legumes Ag Soils-Plant-Fertilizers Ag Soils- Animals	Residue Dry Matter Fraction Fraction Residue Applied Nitrogen Content of Residue Kjeldahl (K) Nitrogen Excreted Crop Production Fertilizer Utilization TAM*	N_2O
Rice Cultivation	Seasonal Emission Factor Area Harvested	CH_4
Liming of Soils	Emission factors for CO_2 emitted from use of crushed limestone and dolomite (ton C/ton limestone) Total limestone and dolomite applied to soils (metric tons)	CO_2
Urea Fertilization	Emission factors for CO_2 emitted from the use of urea as a fertilizer (tons C/ton urea) Total urea applied to soils (metric tons)	CO_2
Ag. Residue Burning-CH_4 Ag. Residue Burning-N_2O	Residue/Crop Ratio Fraction of Residue Burned Dry Matter Fraction* Burning Efficiency Combustion Efficiency Carbon Content Nitrogen Content*	CH_4, N_2O

* For consistency in calculations, data that overlaps between sectors are pulled through from the original input into subsequent uses.

Figure 1: Required Activity Data to run the EPA State Inventory Tool (SIT).

Soil carbon fluxes are estimated in the SIT LULUCF module. In the SIT LULUCF Version 2024.1, soil carbon fluxes on agricultural lands (cropland and grassland) use default data obtained from the U.S. GHG Inventory state-level breakdown, and consider all C pools (above ground, below ground, deadwood, litter, soil organic, and soil mineral) under *Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland,* and *Land Converted to Grassland*. This reflects a recent change in the SIT LULUCF module as, prior to 2023, the module did not consider carbon flux from aboveground biomass, belowground biomass, deadwood, and litter in cropland and grassland ecosystems (EPA, 2024). Therefore, the default data in the most current SIT LULUCF module now more accurately reflects the data reported in the U.S. Greenhouse Gas Inventory of Emissions and Sinks and is better able to represent actual emissions and removals for Vermont's AFOLU GHG Inventory.

4.2 Vermont State Specific Data

ANR provided ICF with a sample of agricultural activity data that is collected on a recurring basis. Table 1 provides a summary of key findings of the documents that ICF reviewed.

Table 1: Key findings of ICF activity data review for agriculture inventory relevant data provided by Vermont.

Name	File Type	Included Data	Notes
PDB Practice Export Examples for ICF	Excel	Crop type, acres applied, practice applied, and location applied.	The file contains useful information on practices applied to farms, such as no-till or cover cropping. If the dataset includes statewide land area, a full review of the database could inform emission scaling related to conservation practice adoption in Vermont.
VT_P_Index_6.3 (1)	Excel	Vermont specific information on growing season runoff, runoff adjustment factors, % cover, average precipitation, manure incorporation information, and hydrologic soil groups	The P Index could be useful for some parameters (such as growing season runoff, runoff adjustment factors, and average % cover) but is a tool designed for the user to input information and does not have data on P runoff. Per the tool, *the Phosphorus (P) Index is a tool developed to assess the potential for phosphorus runoff from individual fields based on soil and field characteristics and on management practices.* The P-Index also requires input on manure application, including rate; application time of year; application method; time to incorporation; and manure type (e.g., dairy). This information could potentially be used to inform inventory development, especially given Vermont's large livestock population and the standardized format of the P-Index. It could also provide information on manure application method adoption. However, the P-Index reports manure rates in terms of lbs. P_2O_5/acre, which is not particularly useful for inventorying given the lack of reporting on nitrogen and carbon.
CowPower_forICF_20230609	Excel	Farms with anaerobic digesters (count and number of head covered) and estimated biogas production	This data (combined with EPA's AgSTAR Livestock Anaerobic Digester Database) could be used to inform emission scaling for the adoption of anaerobic digesters and emissions from manure management.
2022_Ag Module	Excel	Default data on fertilizer application, crop acreage, animal population, and limestone and urea application	EPA's State Inventory Tool agriculture module, in which ANR used the default settings. Default data within the module could be improved upon with additional targeted research (e.g. confirmation of important parameters such as livestock population, typical animal mass (liveweight), and volatile solids/nitrogen excreted).
Example Ag Data for ICF	PDF	General information on farm animal population number, waste, and land area data	Animal population data is not classified by age and does not provide month of birth / slaughter / losses due to illness. Data on month of birth or slaughter could support higher tier population modelling that underpins livestock GHG emission estimates. Also not included is animal weight data and breed data (i.e., herd structure) which could support analysis of whether the averages used from U.S. GHG Inventory (SIT) are representative of Vermont's agricultural production circumstances. Animal waste data does not have excreta composition, and collection of this data could support analysis of and possible development of Vermont specific data to

			be used in estimates of N2O and CH4 from manure management, and could be used to justify any variance from the regional (Northeast) animal waste data that is used is SIT as representative of Vermont.

Two additional sources of Vermont-specific activity data were also identified and investigated in detail, namely the nutrient management plans (NMPs) provided by the Vermont Agency of Agriculture, Food and Markets (AAFM) and publicly available data inputs utilized in the development of the Vermont Carbon Budget.

A total of 37 Large Farm Operation (LFO) nutrient management plans were provided by AAFM. The plans were reviewed primarily to identify activity data, especially activity data to compare to default data in SIT, and potential adoption rates of both cropland and manure management practices. The majority of these plans were prepared by two different consultancies, Bordeau Brothers of Middlebury, Inc. (16 NMPs) and Agricultural Consulting Services (ACS) (13 NMPs), with the remainder (8 NMPs) being drafted independently or by other planners/consultants. Due to the large number of plans provided by AAFM, a sample of plans from each group were reviewed by primarily focusing on plans prepared by the two major consultancies as these made up nearly 80% of the provided plans. Each consultancy has a different format for their NMPs and reports different data, making direct comparison of NMPs prepared by different entities difficult. This reflects a general challenge that was encountered when reviewing NMPs for potential activity data and practice adoption rates. The inconsistency in reporting, in terms of both data provided and format, will limit quick data extraction and analysis for improving activity data input into SIT, or developing other inventory information to improve GHG estimates.

The plans do provide relevant information that may be used in studies related to specific inventory improvements, or to inform decisions related to improving and standardizing data collection and reporting. For example, the nutrient management plans report animal population, mass, and, in the case of dairy cows, milk production. The plans present manure analyses that include nitrogen content of manure. As outlined in the Vermont Carbon Budget, information on fertilizer rates, types, and application; manure management; and land use/crop management practice adoption, such as cover crops, residues, tillage, and nutrient additions, are also included (Galford, 2022).

ANR might consider standardizing future data collection and focus on redesign of questions/data collection for certain high priority areas of data for the GHG inventory, for example manure management data, such as types of waste management systems, quantities and types of waste being managed in each manure management system, and capture of the full manure management chain practices including, deposition, treatment, transport, storage and application. **ICF recommend this as a priority for Vermont's inventory team because at present, activity data from the nutrient management plans are not able to be easily extracted and utilized for the inventory**. This will facilitate Vermont to better represent Vermont specific manure management circumstances and will enable reporting of more accurate CH_4 and N_2O manure management inventory estimates.

Generally for inventorying, questions are carefully designed with agricultural inventory data requirements in mind, and so that respondents cannot misinterpret and potentially misreport agricultural activities occurring on land they manage. As an example, at the national level, agricultural inventory data is collected through an annual survey and validated every few years via an agricultural census. Two examples of these national level data collection mechanisms are:

1. The United States 2022 Census of Agriculture: https://www.nass.usda.gov/AgCensus/Report_Form_and_Instructions/2022_Report_Form/2022_CoA_Questionnaire_Final.pdf, and
2. The New Zealand Agricultural Production Statistics Survey: https://datainfoplus.stats.govt.nz/Item/nz.govt.stats/6362a469-f374-412e-ac25-d76fd0962003

Table 2 includes a more detailed description of sections of an example nutrient management plan that was analyzed.

Table 2: Available activity data and notes from example nutrient management plan[a]

Name	File	Data Type	Notes
[ ] Annual Report Review	PDF	General information on farm animal population numbers, waste, and land area data	Contains survey information, such as reporting whether the user has filled out the P Index and Nitrogen Leaching Index, whether manure and soil samples were submitted, and more.
[ ] Appendix D 2023	PDF	Animal waste in solid tons/ft^3) alongside gallons (as reported in Annual Report)	N/A
[ ] Farm Info 2023	PDF	General farm data	This file includes: • General farm information, including owned and leased land and which acreage is tillable. • A qualitative discussion of tillage practices and data on tillage operation and equipment, which is useful for energy-based emission estimates. • Information on typical crop rotation; however, this information is qualitative and is thus not particularly applicable to inventorying efforts. • Cattle information, provided in table format. In this table, there is a column for type/breed, but the breed is not reported. Instead, only whether dairy or beef, age, and whether lactating is reported, and the age class only considers 1-12 months or other. In this particular example, all cattle are female. This section also includes weight and milk production per day. However, milk fat and protein percent are not included, which is needed for Tier 2 inventory estimates. • Qualitative information on manure, as well as an indication of the type of manure managed (i.e., solid and/or liquid). Also included is spreader equipment information, which is useful for energy emission estimates. The temperature of

			the manure management system is not included, although local weather data could be applied.
[ ] Field Inventory 2023	PDF	Extensive data on field crop/pasture rotations, acres (owned/leased), soil type, and results from soil tests (P, K, pH).	An analysis of a representative selection of farms would be required to derive valuable inventory data from this reporting.
[ ] Manure Sources 2023	PDF	Manure type, storage type, and total N content/other nutrient content	Included is some farm-level data on the manure type and the storage type, as well as the nutrient content of manure. This could be useful for assessing manure management in Vermont.
[ ] P Index 2023	PDF	Manure application rates, application method, erosion rate, soil type, crop type, and surface cover %	This could be useful for determining fertilizer application methods and for looking at manure application rates.
Manure Tests	PDF	Tested compounds include nitrogen, ammonium nitrogen, organic nitrogen, phosphorus, phosphate equivalent, potassium, potash equivalent, total solids, and density	Various results of manure tests are included, which report nitrogen, ammonium nitrogen, and organic nitrogen; these compounds are valuable for inventory efforts. However, the data may be incomplete as it is not reported alongside animal behavior (i.e., defecation profile throughout the day), manure deposition timing, manure storage timing, weather data, and more.
S22-03855_UVM Extension NW Crops & Soils and S22-03865_UVM Extension NW Crops & Soils	PDF	Soil tests showing soil nutrient composition (e.g., K-P-Mg)	These test reports do have recommended application rates for certain crop types for Vermont, which could be useful for estimating typical N fertilizer application rates.
[ ] Shape Files	Various	GIS data	Folder includes: .cpg, .dbf (database file), .prj, .sbn, .sbx, . shp, .xml, and .shx files. File types will need to be opened in GIS software or converted to be opened in Google Earth Pro.

[a]Farm names were removed and replaced with brackets for confidentiality.

As recommended in the Vermont Carbon Budget report, ANR should aim to extract the relevant activity data from these nutrient management plans into a centralized database, which can be utilized for inventorying purposes (Galford, 2022). Once established, this database should be maintained and regularly updated to assist in the tracking of activity data and practice adoption, which will aid in future inventory development. Standardizing reporting, ideally through an online system where data is automatically populated into a spreadsheet, will assist in the extraction of data across the nutrient management plans. Depending on the specific data collected and variability in measuring methods, standardizing collection methods will also potentially increase the accuracy of the data.

The Vermont Carbon Budget (VCB) report and the accompanying publicly available datasets were also identified as having potentially relevant recommendations and activity data respectively. Particularly, the datasets included information on land use practice adoption and manure management system utilization over a time series. To determine common land use practices, such as tillage, the authors of the VCB report utilized the nutrient management plans and calculated the rate of practice use for each agricultural land use class. The adoption of other land use practices was derived from expert consultation in addition to existing data initiatives such as the VAAFM's tracking of farms' participation in water quality projects, such as cover crops. The percentages of manure managed in different systems (e.g., daily spread, liquid/slurry), disaggregated by livestock type, were provided from similar sources, including through consultation with experts familiar with the nutrient management plans (Galford, 2022).

It was observed that the percentages of manure managed in different systems that were provided in the VCB datasets were significantly different than those provided in the default SIT dataset, which pulls from the Methane Inventory Database of the U.S. Greenhouse Gas Inventory of Emissions and Sinks and represents the typical manure management system breakdown for the Northeast region of the U.S. A breakdown of the percent differences for between these two data sources, using manure from dairy cattle as an example, is provided in Table 3.

Table 3. Distribution of dairy cow manure managed in different manure management systems for the year 2020.

	EPA SIT AWMS%	Vermont Carbon Budget AWMS%	Percent Difference
Anaerobic Lagoon	23%	*Not Included*	23%
Liquid/Slurry	5%	47%	42%
Daily Spread	3%	4%	1%
Solid Storage	16%	7%	8%
Pasture	14%	29%	15%
Deep Pit	26%	*Not Included*	26%
Anaerobic Digester	*Not included*	4%	4%
Deep bedding	*Not Included*	8%	8%
Composting	*Not Included*	1%	1%

Livestock manure management systems are a source of both CH_4 and N_2O emissions. CH_4 emissions from manure management depend on the proportion of manure managed in each system, per livestock species, with the most emissions coming from confined animal management operations that handle manure in liquid-based systems. Similarly, estimates of N_2O emissions from manure management are dependent on the manure management system used. Additionally, other forms of N loss from manure management systems result in indirect N_2O emissions. Understanding N loss from manure management systems is also important for determining the amount of nitrogen excreted (Nex) that will be available in manure that is later applied to managed soils or used for feed, fuel, or construction (IPCC, 2019). Because the magnitude of CH_4 and N_2O

emissions differ based on the type of manure management system used, improving the accuracy of the percentage of manure managed in each system in an inventory could significantly increase the accuracy of manure management emission estimates.

State agricultural experts were consulted in the development of the VCB report who are familiar with the state's livestock and nutrient management plans. ICF consider these experts to have a better understanding of implemented manure management systems in Vermont and therefore recommend that ANR conduct a study to document proportions of waste managed in each manure management system that can be used to inform future GHG inventory estimates.

The USDA Agricultural Resource Management Survey (ARMS) was also considered as potentially having relevant activity data. However, due to Vermont not being a survey state under ARMS and it's small share of crop acreage, ARMS was not pursued as a potential activity data source.

5. Vermont AFOLU Inventory Improvements

5.1 Livestock GHG Emissions

Livestock GHG emission sources and their percent contribution in Vermont from the 1990 – 2020 GHG inventory, for the year 2020, included:

i. CH_4 from Enteric Fermentation, 49%
ii. CH_4 from Manure Management, 27%
iii. N_2O from Manure Management, direct and indirect, 23% and
iv. N_2O from Agricultural Soils, direct and indirect, from Manure deposited directly onto pasture, <1%.

There are several potential livestock related inventory improvements ICF noticed whilst reviewing Vermont's latest GHG Inventory, provided to ICF and published in 2020.

5.1.1 Livestock Population

Livestock population data is a core aspect of all GHG emission estimates. It is used directly for estimates of enteric fermentation emissions, and used to estimate volatile solids excreted, a precursor for CH_4 emissions from manure, and nitrogen excreted which is a precursor to estimate direct and indirect N_2O from manure, and for direct and indirect N_2O from manure deposited directly onto pasture by grazing livestock.

The IPCC (2019, 2006) recommend that livestock classification system and population by age class should be consistent for all emission sources. SIT default livestock populations were used by Vermont for enteric fermentation, CH_4 and N_2O from manure management in the SIT tool were modified by ANR and now differ for Dairy cattle and Beef cattle across livestock emission sources. The dairy cattle population used for enteric fermentation differs from the populations used for CH_4 and N_2O from manure management. ICF understands default values were updated (reduction of 25.22 thousand dairy cattle, shown in table 4) to reflect a proportion of the overall dairy cattle population that have manure managed in anaerobic digestors. Anaerobic digestors optimize production of CH_4 as biogas (Chadwick et al., 2011) however the effect of digested manure on N_2O emissions is inconsistent across scientific research studies and is further complicated by storage, handling and application conditions. SIT uses the same population entered for CH_4 and N_2O from manure management, therefore N_2O emissions from manure from the proportion of dairy cattle with manure managed in anaerobic digestors are not currently accounted for in Vermont's AFOLU GHG Inventory.

Table 4: Livestock population (thousand head) used to generate estimates for each emission source.

2020	ENTERIC FERMENTATION	CH_4, MANURE MANAGEMENT	N_2O, MANURE MANAGEMENT
TOTAL CATTLE	208.47	224.25	152.25
Dairy Cattle	177.17	151.95	151.95
Dairy Cows	122.17	96.95	96.95
Dairy Replacement Heifers	55.00	55.00	55.00
Beef Cattle	31.30	72.30	0.30
Beef Cows	13.00	13.00	
Beef Replacement Heifers	4.50	4.50	
Replacements 0-12 mos.	0.00	41.00	
Heifer Stockers	6.50	6.50	
Steer Stockers	4.00	4.00	
Feedlot Heifers	0.10	0.10	0.10
Feedlot Steer	0.20	0.20	0.20
Bulls	3.00	3.00	

ICF recommend Vermont use a single set of population data and therefore consistent cattle population numbers for generating state level livestock GHG emission estimates in SIT.

Based on Vermont's previous GHG Inventory developed in SIT, manure of 25 thousand dairy cattle was managed in anaerobic digestor systems. SIT simplifies waste management systems (WMS) into dry versus liquid and therefore is unable to account for lower emissions than would otherwise occur when manure is handled in anaerobic digestor systems.

5.1.2 Estimation of Manure Managed in Anaerobic Digestors

To account for emissions managed in anaerobic digestors, ICF recommend that Vermont determine and apply an appropriate scaling factor to the total reported CH4 emissions from Manure Management to reflect the lower emissions occurring from the 25.22 thousand dairy cattle with manure managed in anaerobic digestion systems. This is not a simple task, however default IPCC, national or where available state-specific data could be used while Vermont collects or gathers additional state-specific data to estimate CH4 emissions from dairy cattle manure managed in anaerobic digestors. A simplified example method is described in Appendix 5, and includes:

1. estimation of volatile solids (VS) excreted by for example dairy cattle,
2. estimation of the proportion of VS managed in anaerobic digestors,
3. estimation of the CH4 emitted from that proportion of dairy cattle VS managed in anaerobic digestors,

4. comparison against the current CH4 estimate from manure management for dairy cattle, as output by SIT, and finally
5. making any relevant adjustment to SIT inventory estimates.

The method outlined in Appendix 5 would be more sophisticated than the calculations that SIT currently conducts but would require effort on Vermont's part to collect relevant data and document the method and necessary assumptions. ICF understand Vermont are already aware of the inventory improvement process. However, discussion of this process is an important reminder that inventory improvement is a continual and ongoing process. Methods can be built upon over a series of years. Vermont may begin with a method based on predominantly default (IPCC) data, however in 5 years Vermont could have a method tailored entirely to Vermont's livestock production circumstances, which provides highly accurate GHG emission estimates.

Additionally, a literature review may support development of state-specific data (see Appendix 5 for more specific data needs) if any is available. Further, documentation of why a certain emission reduction was assumed for manure that is managed in anaerobic digestors is critical for GHG inventory transparency and to ensure estimates can be repeated in the same way for future inventory years.

5.1.3 Estimation of energy requirements

Estimation of the energy requirements for livestock are critical to estimate feed intake, which in turn is used to estimate enteric fermentation emissions, volatile solids (VS) excreted, and nitrogen excreted (Nex) which underpin CH_4 and N_2O from manure management respectively.

Digestible energy (DE) is expressed as a percent of gross energy (GE) intake digested by the animal (megajoules per day). DE values vary by diet, livestock herd characteristics and livestock type. In the U.S. GHG Inventory, which underpins SIT default data, DE is weighted regionally and weighted values for the Northeast[3] region are used to estimate energy requirements for beef and dairy cattle in results produced for Vermont in SIT. The data and method is publicly available and can be found in Annex 3-Part B. As an example, **Table 5** presents the weighted DE for grazing beef cattle in the Northeast.

Table 5: DE Values and Representative Regional Diets for the Supplemental Diet of Grazing Beef Cattle in the Northeast (see tables A-140 and A-141 of the most recent National GHG Inventory (1990 – 2021) https://www.epa.gov/system/files/documents/2023-04/US-GHG-Inventory-2023-Annex-3-Additional-Source-or-Sink-Categories-Part-B.pdf.

Region	Northeast	
Year	**1990-2006**	**2007-2020**
Alfalfa Hay	12%	12%
Corn	13%	13%
Corn Silage	20%	20%
Protein Supplement		10%
Timothy Hay	50%	45%
Seed	5%	
Weighted Supplement DE in % of GE (MJ/Day)	*68.6*	*68.9*

[3] Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont and West Virginia.

Percent of diet that is supplement	*15%*	*5%*

Due to the significance of enteric fermentation emissions within Vermont's agriculture GHG emissions, and given dietary energy requirements impact on estimates of enteric fermentation emissions, ICF recommend that ANR assess whether Vermont's cattle (beef and dairy) diets are accurately represented by Northeast dietary energy data used to estimate GHG emissions for the National GHG Inventory, which underpin SIT's estimates of emissions from enteric fermentation.

5.2 N_2O from Agricultural Soils

Sources of N_2O emissions from agricultural soils include:

i. Direct N_2O from synthetic fertilizer application
ii. Direct N_2O from organic fertilizer applied to agricultural soils
iii. Direct N_2O from crop residues left on agricultural soils
iv. Direct N_2O from N mineralization due to changes in land management
v. Direct N_2O from drainage/management of organic soils
vi. Indirect N_2O from volatilization (all the above sources, estimated as a fraction of remianing nitrogen (N) in soil following denitrification and nitrification processes resulting in direct N_2O emissions),
vii. Indirect N_2O from leaching or runoff

The SIT agriculture module used for the 2020 GHG Inventory did not include indirect emissions from crop residues nor indirect emissions from leaching of N applied via synthetic and organic fertilizers to agricultural soils. The 2019 IPCC Refinement to the 2006 IPCC Guidelines included guidance for estimating emissions from N mineralization associated with loss of soil organic matter resulting from change of land use or management of mineral soils. The *most recent version of the* SIT LULUCF module estimates soil carbon flux from land use change between and to cropland and grassland, see note from SIT in Figure 2.

Default data for carbon emissions/storage (flux) from agricultural soils were obtained from the state-level breakdown included in U.S. EPA's *Inventory of Greenhouse Gas Emissions and Sinks: 1990-2020.* Agricultural soil flux was updated in 2023 to include C flux from all the carbon pools (aboveground, belowground, deadwood, litter, soil organic, and soil mineral) included under *Cropland Remaining Cropland, Land Converted to Cropland, Grassland Remaining Grassland,* and *Land Converted to Grassland.* Default data for Alaska and the District of Columbia are not available. Please refer to the *Inventory of Greenhouse Gas Emissions and Sinks: 1990-2020, Chapter 6: Land Use, Land-Use Change, and Forestry* for a summary of the methodology used to calculate carbon flux from agricultural soils and Chapter 5: Land Use, Land-Use Change, and Forestry fo the *Methodology Report: Inventory of U.S. Greenhouse Gas Emissions and Sinks by State: 1990-2020* for additional detail on how carbon flux was estimated for each state (available here: https://www.epa.gov/ghgemissions/methodology-report-inventory-us-greenhouse-gas-emissions-and-sinks-state-1990-2020)

Users may also enter their own data. This may be done by selecting the appropriate option in Step 7 on the Control worksheet. For more information, please consult the Land Use, Land-Use Change, and Forestry chapter of the User's Guide.

Figure 2: LULUCF SIT module soil carbon flux description.

There is also a source of N2O associated with this loss of soil organic matter from land use change, or management of mineral soils, which is not currently estimated in SIT. Vermont might explore including this emission source in future inventories, although less of a priority than previously mentioned livestock inventory improvements, which will likely have the largest net affect on GHG estimates for Vermont.

5.3 Soil Organic Carbon in Agricultural Soils

The SIT agriculture module utilizes the U.S. GHG Inventory data, which is based on 2015 US EPA DAYCENT model runs to estimate soil organic carbon for cropland and grassland. These model runs are still considered accurate for use in the national GHG inventory however it may be worth exploring whether updated modelling or data would be more representative of Vermont specific soil conditions, and thus be collected to eventually provide more accurate GHG estimates for Vermont.

From the activity data provided by Vermont that ICF reviewed, there are various components important for measuring soil health and soil carbon stocks across multiple different datasets that are already collected for non-inventory programs. However, a soil carbon monitoring system requires long term soil carbon measurement data, collected via systematic sampling and with measurements repeated on a regular basis, for example every three years for 12 years (four separate soil organic carbon measurements). To develop a science-based carbon credit system (or other GHG mitigation incentive framework), and incentivize permanent GHG emissions removals over time for farmers in Vermont, ANR would require a scientifically robust soil organic carbon monitoring system. ICF recommend ANR look at the design of small international projects in conjunction with currently identified policy goals related to soil carbon sequestration, to inform whether development of such a research program is necessary. Relevant projects include:

- https://soils.landcareresearch.co.nz/topics/soils-at-mwlr/our-projects/browse-all-projects/national-soil-carbon-monitoring/
- https://www.fontagro.org/new/proyectos/secuestrocarbono/en
- https://www.fsa.usda.gov/news-room/news-releases/2021/usda-launches-first-phase-of-soil-carbon-monitoring-efforts-through-conservation-reserve-program-initiative
- https://www.thuenen.de/en/institutes/climate-smart-agriculture/projects/agricultural-soil-inventory-bze-lw (see methodology and other sub-links, including questionnaire given to German Farmers – useful to inform design of activity data collection, suggest using google translate to convert)

5.4 Field Burning of Agricultural Residues

ICF recommend that ANR document Field Burning of Agricultural Residues as either not occurring (NO) or not estimated (NE). This is a formal inventory notation key[4] used at national and subnational levels. From what ANR have told ICF, NE is likely more accurate as there is minimal burning of agricultural residues on farms in Vermont. ANR might also consider assuming the same average burned proportion used for the U.S. which is 3% (Chapter 5, U.S. Environmental Protection Agency, 2023).

5.5 Rice Cultivation

ICF recommend that ANR document CH_4 from Rice Cultivation as either not occurring (NO) or not estimated (NE). This is a formal inventory notation key[4] used at national and subnational levels. From what ANR have told ICF NE is likely more accurate as there are one or two rice farms in Vermont.

6. Conclusions

ICF commend Vermont as one of the leading U.S. states in ICF's knowledge to be exploring means of customizing their AFOLU GHG inventory to support AFOLU emissions and removals policy decisions. In ICF's

[4] https://unfccc.int/resource/tet/bg/bg2-02_Overview_Notation_Keys.pdf

knowledge, California and Hawaii have developed and maintain state specific AFOLU GHG inventories. Vermont, along with California and Hawaii, are well positioned to make informed policy decisions around implementing land management mechanisms to ultimately reduce GHG emissions, or enhance carbon sequestration, from the AFOLU sector.

The key Tool Review and Inventory Improvement recommendations to support Vermont moving forwards from ICF's AFOLU Inventory analysis are described below.

6.1 Tool Review Findings

The following key recommendations are provided from ICF for future development of the State of Vermont AFOLU GHG Inventory and subsequent analyses of GHG impacts from management practice implementation for GHG mitigation:

1. **APEX** is not recommended, especially in isolation, for use by ANR to develop the state inventory because its emission categories are not aligned with IPCC emission source categories and the tool does not model key agricultural CH_4 emission sources, which combined present the majority of agricultural GHG emissions in Vermont's GHG inventory.
2. **COMET-Planner** is recommended for use to account for implementation of management practices, in combination with the SIT Agriculture and LULUCF modules.
3. Process based biogeochemical models still are subject to data gaps for some regions in the U.S. and for specific crops, which limits current scientific understanding of process-based model sensitivity to management practices. Process based modelling requires collection of field conditions that are site specific, and in the case of Vermont's state GHG inventory, an appropriate sampling approach would need to be designed to ensure that soil and flux measurement data captures the significant variation in soil N_2O emissions spatially and temporally.
4. ICF recommend the **DAYCENT** model should be considered if ANR find through a comparative assessment of CEAP, ARMS, USDA-NASS, CTIC and OpTIS data against the State's available and representative data on fertilization, tillage and cover crop practices that there is evidence that Vermont's state specific data varies significantly from data presented in the national datasets, and if there are suitable human and technical resources available to ANR to generate new emission estimates using DAYCENT.
5. To determine whether generating new **DNDC** GHG emissions estimates is worthwhile for Vermont, ICF recommend that ANR assess whether there is evidence that Vermont's state specific data varies significantly from data presented in national datasets, and if there are suitable human and technical, or alternatively financial, resources available to ANR to generate new emission estimates using DNDC.
6. **EX-Act** was primarily developed as a tool to assist in evaluating the GHG emissions and carbon stock changes for land management projects, relative to a pre-project start date baseline and the tool can only consider one dominant soil and climate type at a time. Vermont has multiple soil types and requires more precise climate data for more accurate manure management emission estimates. Therefore, ICF recommend that the tool is limited in its ability to be used for state level GHG inventory purposes, and for state level GHG impact analyses of changes in management practices for policy scenarios.

7. **FEAT's** design for whole-farm emission based GHG accounting, and limited scope for GHG emission sources limits its effectiveness for use to compile state-level GHG estimates and inventory. Specifically, the tool's omission of emissions from land use, land use change and forestry (LULUCF), all livestock emission sources (enteric fermentation, and CH4 and N2O from managed manure), biomass burning, and urea and other non-carbon containing fertilizers means that substantial emission sources and sinks are not considered. ICF recommends FEAT would be generally less effective than the current tool currently utilized by ANR to develop the state-level inventory.
8. **Holos** is primarily intended to be used as a farm management and emission reduction planning tool and includes emissions from farm emission sources such as energy used on farm and pesticides etc., that are accounted for in Energy and IPPU under the IPCC Sectors. ICF recommend that due to its intended scale of GHG accounting, purpose and the way in which emission estimates are cut, Holos is not better than SIT for conducting a state level GHG inventory for Vermont.
9. **IFSM** was primarily developed as a farm level GHG accounting, research and teaching tool, and it does not model long-term sequestration and depletion of soil carbon, and therefore may not be suitable for state level GHG inventorying purposes. Additionally, given technical and human resource limitations ANR have face, due to the high level of effort and technical expertise required to run the model, ICF suggest the model may not be feasible for generating state level GHG estimates.
10. **SIT** is designed specifically as a state inventorying tool, is freely available, accounts for emission sources for the most part on at least IPCC Tier 2 level methods and requires minimal human and technical resources to carry out a complete annual GHG inventory. Given ANR's resource availability, ICF recommend that SIT is likely the best available tool for Vermont to develop a state level inventory, although SIT is agnostic to management practice changes and therefore currently cannot generate outputs for mitigation GHG impacts from management practice adoption and changes. ANR would need to employ other tools, or apply empirical modifications to results output by SIT, to account for the GHG impacts of management practice changes. ICF recommend COMET-Planner as a potential tool useful to ANR to account for the GHG impacts of management practice changes. For example, the use of VT-specific ERCs from COMET-Planner could be integrated into the inventory to account for mitigation estimates from cropland management practices. ICF recommends that ANR report LULUCF SIT module emissions and removals from Vermont's cropland remaining cropland, other land use types converted to cropland, grassland remaining grassland, and other land uses converted to grassland, alongside emissions estimated in the SIT agriculture model.
11. ICF recommend that the **U.S. Disaggregated Data** is highly useful to validate estimates generated either by SIT or another emission estimation tool that ANR should choose to use to generate state level GHG estimates.

6.2 Activity Data Recommendations

ICF acknowledges that Vermont is annually collecting various activity data, primarily through the nutrient management plans (NMPs). However, because of the current format of the NMPs and other data sources, activity data are difficult to extract and would require considerable analysis and reprocessing prior to use in an inventory. Regarding activity data collection, ICF recommend that Vermont either:

- Develop an inventory survey for farmers, with carefully constructed questions that ensure data is collected specifically for inventorying purposes; or
- Tweak questions in the NMPs and other activity data sources to ensure that data is best collected for inventorying purposes. Questions may need to be added to ensure that there are no missing sources of activity data; for example, the NMPs do not currently collect sufficient data to estimate daily energy requirements of livestock, which is useful for informing livestock emissions estimates.

Additionally, if Vermont wish to continue collecting activity data in PDF format, which is the current format of most NMPs, ICF recommend that data be centralized into a database and be collected online so that data automatically populates into the database, thus avoiding potential human error and the significant effort required to manually extract data.

ICF also recommends that Vermont investigate the differing proportions of manure managed in each manure management system between the SIT default data and the Vermont Carbon Budget report data. To do so, ICF recommends that Vermont conducts a study to document the percentages of manure managed in each management system to inform future GHG inventory estimates.

6.3 Inventory Improvement Recommendations

ICF understand Vermont faces public and policy decision pressure to be able to measure and track progress of AFOLU GHG emissions over time and particularly, the climate impact of various AFOLU conservation management practices. SIT is a highly useful and simple state level GHG inventory tool for estimating agriculture and land management-based emissions, however it has limitations in its ability to be tailored to reflect state specific production circumstances which limits the accuracy of Vermont's AFOLU GHG inventory. This is problematic given Vermont's objective of accurately measuring and tracking progress toward emission reduction targets. Therefore, ICF recommends that Vermont:

- Considers investment in developing a state specific GHG inventory tool that will be able to accommodate Vermont's state specific production circumstances far more readily than SIT and will be able to be used to inform policy decisions and estimate GHG emissions reductions due to implementation of various conservation practices in Vermont.
- Develop an inventory improvement prioritization process, to focus their resources on improvements that will result in significant impacts to reported emission estimates (revisions of absolute GHG emissions estimates either up or down), and/or are accessible in terms of cost or ease of implementation into the inventory, and/or affect key AFOLU inventory sources. There may be other criteria that Vermont wishes to include in their inventory improvement prioritization assessment.
- Attempt to establish an annual funding pool for inventory research or data collection that will directly support improvement of the Agriculture GHG Inventory, and used to fund research efforts as prioritized used the aforementioned recommended process (once established).

The following specific inventory improvement recommendations will support Vermont to understand either a) how to approach adjustment of a select few SIT GHG inventory estimates or b) determine a path forward for GHG estimates if it is decided that a state-specific inventory tool should be developed.

Between 1990 and 2020, **livestock GHG emissions** contributed between 69% and 77% of agricultural GHG emissions (not including emissions and removals from croplands and grasslands). Therefore, ICF recommend that Vermont:

- Identifies priority areas for improvements of livestock GHG emission reporting and justify focus on these due to high overall contribution to Vermont's AFOLU emissions profile, which may include but should not be limited to:
    - Validation of the accuracy of livestock population data used for their SIT inventory estimates, and adjust accordingly the population if deemed necessary,
    - Validation of SIT's underlying assumptions around livestock feed and dietary energy requirements as a key factor in estimation of enteric fermentation emissions (the highest AFOLU emission source for Vermont) and for estimates of volatile solids excretion and nitrogen excreted for calculating CH4 and N2O from manure management, respectively, and adjust accordingly the estimates to more accurately reflect Vermont specific livestock feed and dietary energy requirements if deemed necessary.

We understand **capturing management practices and efforts that enhance soil organic carbon storage and avoid losses of soil carbon** in the AFOLU GHG inventory is a priority for ANR. Therefore, ICF recommends that Vermont:

- Develops a data collection process and establishes a research project to collect soil carbon measurements that can be used as the basis for quantifying changes in soil organic carbon on Vermont's agricultural soils over time. These studies need to occur on longer time horizons to capture the longer-term equilibrium of soil organic carbon, and ANR should look at similar international research projects to inform sample design.

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8. Appendices

Appendix 1: DNDC Model Overview

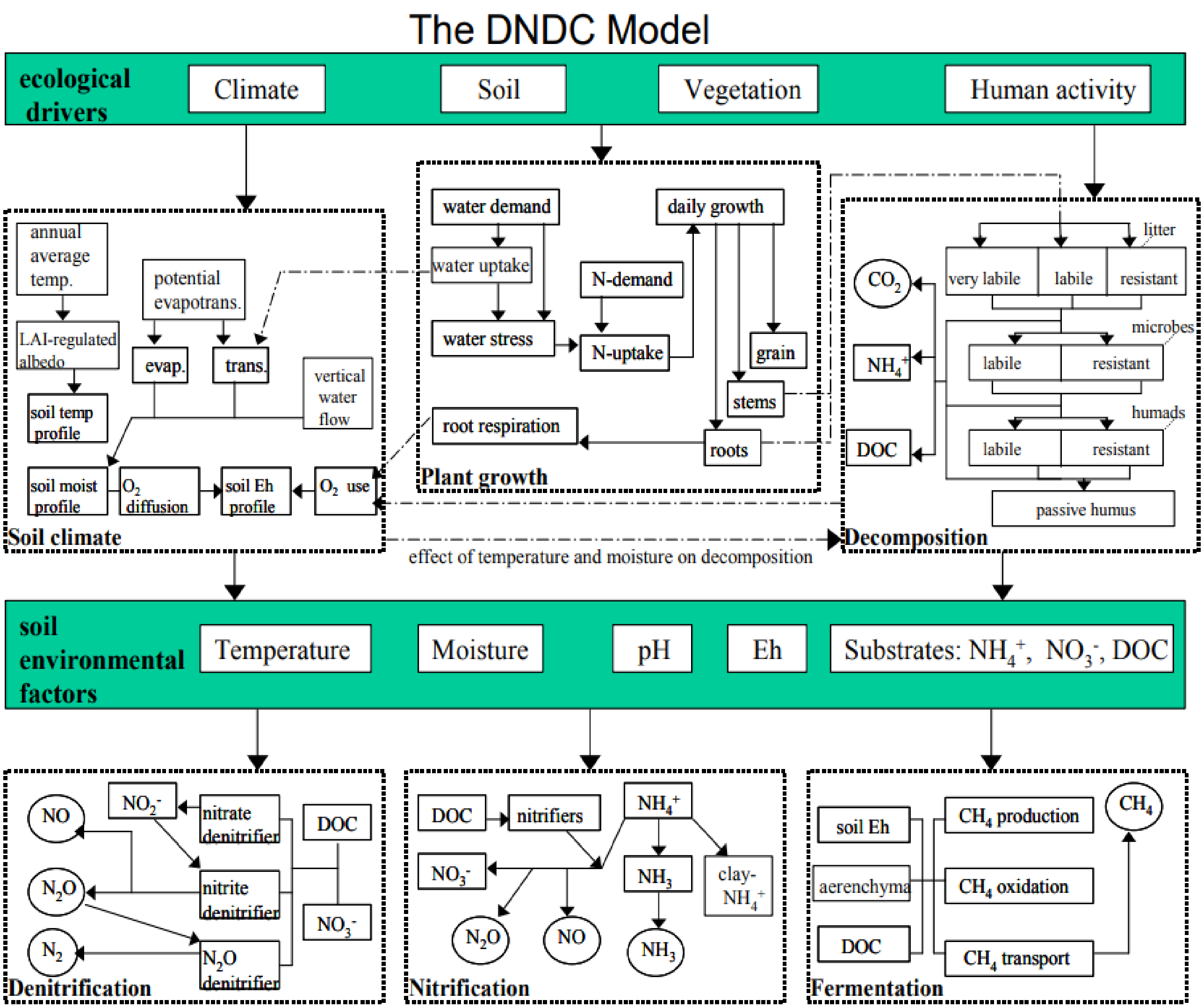


Figure 1. Structure of the DNDC model.

Appendix 2: COMET-Planner Methods and Modelling

Table 6: Summary of COMET-Planner methods for agricultural emission sources. Adapted from Table ES-1 (Eve et al., 2014)

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
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	—
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	—	—	—

Table 7: Summary of COMET-Planner estimation methods including modelling, relevant management practices and emission factors used by COMET-Planner. Table ES-2 (Eve et al., 2014).

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.

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.
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]

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.
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.
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.

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).
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.

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.
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				

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.
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				

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.

Land-use Change				
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.

Appendix 3: Holos Overview

Table 6: Holos overview (Little et al., 2008)

Farm operation	User input required	Defaults provided, user may override	Emissions calculated
Crops/grassland/ land use change	Area of annual crops & fallow Area of perennial crops (past and present) Area of grassland (past and present) Tillage system (past and present) Area of irrigation Herbicide usage	Fertilizer inputs Crop yields Soil type and texture	Soil N_2O Soil carbon storage or emission Energy CO_2
Beef cow-calf	# cows Type of grazing area Pasture and feed quality Feed additives in diet Spring or fall calving Year round grazing or winter feeding Calves sold or kept for backgrounding & # months kept Manure handling system for backgrounders	Calf crop rate # bulls	Enteric CH_4 Manure CH_4 Manure N_2O Energy CO_2
Beef feedlot	Type of feedlot (finishing or backgrounding) Feedlot capacity and/ or #months filled Barn housing usage Ration mix Feed additives in diet % steers in lot Feed:gain ratio (if known) Average daily gain (if known) Manure handling system	Initial and final weights	Enteric CH_4 Manure CH_4 Manure N_2O Energy CO_2
Beef stocker	# cattle # months grazed Pasture quality Feed additives in diet % steers in herd Average daily gain (if known)	Initial and final weights	Enteric CH_4 Manure CH_4 Manure N_2O
Dairy	# cows # months calves kept Feed additives in diet Pasture usage and length of time used Manure handling system Season of manure application	# replacement heifers # bulls # calves Length of dry period Total digestible nutrients or net energy for lactation and protein content in diets (dry and lactation)	Enteric CH_4 Manure CH_4 Manure N_2O Energy CO_2

Farm operation	User input required	Defaults provided, user may override	Emissions calculated
Swine	Type of operation (farrow to wean, farrow to finish, nursery or finishing barn) # pigs (in each category, defaults provided in some cases) Type of diet Manure handling system Season of manure application	Yearly birth rate Pre-weaning death loss	Enteric CH_4 Manure CH_4 Manure N_2O Energy CO_2
Sheep – market lamb	# ewes Weaned lambs sold or kept on farm Feed quality Pasture usage and length of time used Type of pasture Manure handling system	# rams lambing rate # lambs per birth	Enteric CH_4 Manure CH_4 Manure N_2O
Sheep feedlot	Feedlot capacity # months filled Feed quality Manure handling system		Enteric CH_4 Manure CH_4 Manure N_2O
Poultry	Type of poultry Barn capacity Wet or dry manure system		Enteric CH_4 Manure CH_4 Manure N_2O Energy CO_2
Other animals (goats, llamas & alpacas, deer & elk, horses, mules, bison)	# animals		Enteric CH_4 Manure CH_4 Manure N_2O
Lineal tree plantings/ shelterbelts	Type of tree Age of planting Length of planting		Carbon storage

Appendix 4: Management Practice Climate Impact Rankings

Climate impacts range from +4 as the largest sequestration/mitigation potential to -4 indicating that the highest (U.S. Department of Agriculture, n.d.) level of emissions occur. Climate impact ratings are based on a combination of USDA NRCS conservation practice climate impacts and literature review results and expert opinion when NRCS conservation practice climate impacts were not available.

System	Vermont Practices	NRCS Practice Number(s)	NRCS Practice Sub-Group	Climate Rating[5]
Crop	Crop to Hay (permanent seed down)	E512A, E512C	Pasture and Hay Planting	4
Livestock	Feed Management	592	Dietary strategies	4
Livestock	Manure Storage	366	Anaerobic digestors	4
Livestock	Manure Storage	367, 313, 359, 632	Manure storage (solid storage), covers and handling practices (manure separation)	4
Crop	Nutrient Management	590	Nutrient management	3
Crop	Reduced Tillage	345	Conservation tillage	3
Crop	Riparian Forest Buffer	391		3
Crop	No-Till	329	Residue and tillage management, no-till	3
Livestock	Manure Injection	590	Manure injection	3
Livestock	Manure Incorporation	590		3
Crop	Precision Agriculture	590, E590B	Precision Agriculture: N based fertilizers	3
Crop	Cover Crop	340	Cover crop	3
Crop	Silvopasture	381		2
Crop	Alley Cropping/Multi-Story Cropping	311, 585		2
Livestock	Grazing Management	528	Prescribed Grazing	2
Crop	Agroforestry	612,		2
Livestock	Grazing Management	528, 512	Grazing practices to manage livestock manure deposition	2
Livestock	Grazing Management	E528R	Rotational grazing	2

[5] A list of all 2024 practice climate impacts can be found at: https://www.nrcs.usda.gov/sites/default/files/2023-12/RMSPlanningToolNational_2024.xlsm

Livestock	Application of nitrification or urease inhibitors	590	Application of nitrification or urease inhibitors to stored manure or to urine patches	2
Livestock	Rumen manipulation	592	Rumen manipulation	2
Crop	Sustainable Crop Rotation	328	Sustainable Crop rotation	2
Crop	Filter Strip (grass buffer)	390, 412, 393		1
Crop	Precision Agriculture		Precision Agriculture: Liming, and other C containing fertilizers	1

Appendix 5: Simplified Method for Vermont specific estimates of CH4 from Manure Management of Anaerobic Digestors

This simplified method is relevant for estimates of all manure management systems, ICF recommend Vermont see the linked IPCC Guidance for extended recommended methods.

Method:

Step 1: Determine annual volatile solid excretion per livestock type to estimate CH_4 from Manure Management

EQUATION 10.22A (NEW)
ANNUAL VS EXCRETION RATES (TIER 1)

$$VS_{(T,P)} = \left(VS_{rate(T,P)} \bullet \frac{TAM_{T,P}}{1000} \right) \bullet 365$$

Where:

$VS_{(T,P)}$ = annual VS excretion for livestock category T, for productivity system P (when applicable), kg VS animal^{-1} yr^{-1}

$VS_{rate(T,P)}$ = default VS excretion rate, for productivity system P (when applicable), kg VS (1000 kg animal mass)$^{-1}$ day^{-1} (see Table 10.13a)

$TAM_{(T,P)}$ = typical animal mass for livestock category T, for productivity system P (when applicable), kg animal^{-1}

NOTE: *ignore P for production as North America has only one level of production in these default activity data tables.*

1.1 Determine daily default volatile solid (VS) excretion rates per 1000 kg animal mass per livestock type for North America (IPCC 2019, Table 10.13a). Vermont could collect state-specific VS excretion data, perhaps through survey of expert opinion. At least two experts opinions should be used and up to 10 experts would be ideal. ICF could support draft of expert opinion surveys in future efforts as needed.
1.2 Multiply by default live weights (typical animal mass, TAM) per livestock type (IPCC 2019, Table 10A.5). Ideally, Vermont would include state-specific live weight data here as this will ensure accuracy of the estimates.
1.3 Divide by 1000 kg animal mass to get the VS per kg of animal mass.
1.4 Multiply by 365 days in the year to determine annual VS excretion per head of livestock type.

IPCC Data / Information for Step 1

https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf

IPCC default values for volatile solids (VS) excreted (IPCC, 2019)

TABLE 10.13A (NEW)
DEFAULT VALUES FOR VOLATILE SOLID EXCRETION RATE (KG VS (1000 KG ANIMAL MASS)$^{-1}$ DAY^{-1})

Category of animal	Region																		
	North America	Western Europe	Eastern Europe	Oceania[7]	Latin America			Africa[6]			Middle East[6]			Asia			India subcontinent		
					Mean	High PS[1]	Low PS[1]	Mean	High PS	Low PS	Mean	High PS	Low PS	Mean	High PS	Low PS	Mean	High PS	Low PS
Dairy cattle[4]	9.2	8.4	6.7	6.0	7.9	9.0	7.1	18.2	21.7	15.2	10.7	8.4	11.8	9.0	8.1	9.2	14.1	9.1	16.1
Other cattle[4]	7.6	5.7	7.6	8.7	8.5	8.1	8.6	12.1	10.2	12.7	12.3	9.3	14.5	9.8	6.8	10.8	12.2	13.5	12.0
Buffalo[4]	NA	7.7	6.2	NA	11.2	NE		12.9	NE		9.8	NE		13.5	NE		15.2	NE	
Swine[3]	3.3	4.5	4.0	4.0	5.0	3.3	8.3	7.2	4.3	8.7	4.3	3.9	7.2	5.8	4.3	7.1	7.7	5.5	8.7
Finishing	3.9	5.3	4.9	5.6	6.4	4.3	10.0	8.2	5.3	9.4	4.9	4.4	7.8	6.8	5.1	8.1	8.6	6.5	9.5
Breeding	1.8	2.4	2.0	2.1	2.7	1.7	4.8	4.4	2.4	6.0	2.5	2.3	4.6	3.4	2.3	4.3	4.6	3.0	5.5
Chicken[3]	14.5	12.3	12.6	15.4	13.5	13.3	15.7	12.6	12.3	13.0	14.2	14.1	16.5	11.2	10.6	14.3	14.9	14.3	15.7
Hens ±1 yr	9.4	8.6	9.4	8.6	10.1	9.3	14.7	10.2	8.0	11.6	9.0	8.4	15.8	9.3	8.5	12.8	13.2	11.6	14.6
Pullets	5.9	5.3	5.9	6.2	7.6	5.7	18.5	12.0	5.8	16.5	6.8	5.6	18.5	7.5	5.4	17.7	13.2	6.8	18.9
Broilers	16.8	16.1	16.0	18.3	15.6	15.5	17.8	15.9	16.0	15.4	17.7	17.7	17.9	15.7	15.6	17.1	17.7	17.6	18.2
Turkeys[8]	10.3																		
Ducks[8]	7.4																		
Sheep[3]	8.2				8.3														
Goats[5]	9				10.4														
Horses[8]	5.65				7.2														
Mules/ Asses[8]	7.2																		
Camels[8]	11.5																		

IPCC default values for animal liveweight (typical animal mass, TAM) (IPCC, 2019)

TABLE 10A.5 (NEW)
DEFAULT VALUES FOR LIVE WEIGHTS FOR ANIMAL CATEGORIES (KG)

Category of animal	Region																		
	North America	Western Europe	Eastern Europe	Oceania	Latin America			Africa			Middle East			Asia			India subcontinent		
					Mean	High PS[1]	Low PS[1]	Mean	High PS	Low PS	Mean	High PS	Low PS	Mean	High PS	Low PS	Mean	High PS	Low PS
Dairy cattle[2]	650	600	550	488	508	520	500	260	250	270	349	510	270	386	485	355	285	350	265
Other cattle[2]	407	405	389	359	303	329	295	236	302	208	275	362	232	299	310	296	226	167	236
Buffalo[2]	NA	509	467	NA	315			339			381			336			321		
Swine[3]	77	76	77	61	65	81	59	49	72	37	59	70	53	58	69	52	59	68	53
Finishing	61	61	59	41	51	59	47	41	54	33	52	60	48	49	56	44	51	55	48
Breeding	184	190	204	163	143	205	121	100	200	61	118	157	99	122	160	102	121	162	99
Chicken[3]	1.4	1.4	1.3	1.3	1.1	1.3	0.9	0.9	1	0.8	0.9	1.2	0.7	1.2	1.4	1	1.0	1.2	0.8
Hens >/= 1 yr	1.5	1.9	1.9	2	1.4	1.6	1.3	1.4	1.9	1.1	1.2	1.7	1	1.5	1.9	1.3	1.3	1.5	1.1
Pullets	1.2	1.5	1.3	1.4	0.7	1.3	0.5	0.7	1.4	0.5	0.6	1.2	0.4	0.8	1.5	0.6	0.6	1.3	0.4
Broilers	1.4	1.2	1.1	1.2	0.9	1.2	0.7	0.8	0.8	0.7	0.7	1	0.5	0.8	1	0.7	0.8	1	0.6
Turkeys[4]	6.8																		
Ducks[4]	2.7																		
Sheep[3]	40				31														
Goats[5]	41	40	36	33	24														
Horses[4]	377				238														
Mules and asses[4]	130																		
Camels[4]	217																		
Ostrich[5]	120																		

Step 2: Estimate absolute CH4 emissions from manure management and use to estimate per head emission factor

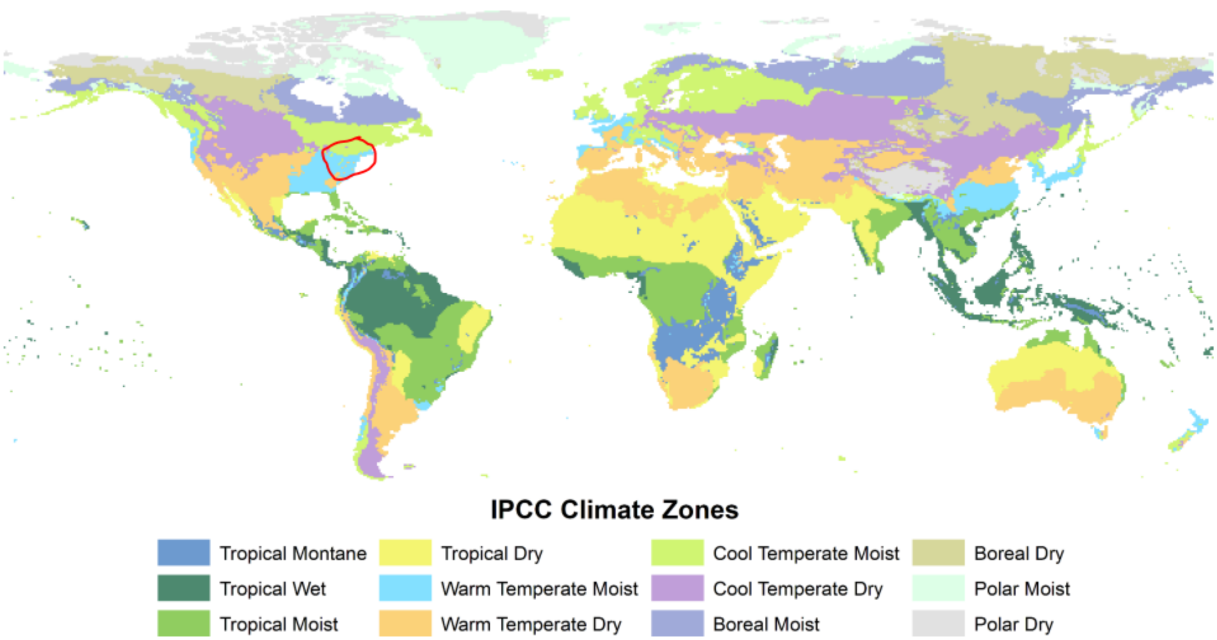
NOTE: Vermont's default climate zone straddles cool/warm temperate moist.

2.1 Multiply annual VS excretion rate (previous step) by the IPCC default CH_4 emission factor specific to livestock type, productivity level, and climate zone (IPCC 2019, Table 10.14). For example, for anaerobic digestors, the default values for beef cattle for cool/warm temperate moist respectively for these climate zones are 2.4 and 2.7 g CH4 per kg VS.
2.2 Multiply this value by the proportion (%) of manure managed (IPCC 2019, Table 10A.6) in each of nine manure management systems including anaerobic digestors (IPCC 2019, Table 10.18). Vermont would need to collect this data as there is no IPCC default data available.
2.3 Sum of emissions from all manure management systems provides an annual average CH_4 emission factor by livestock type, weighted by and reflecting the default proportions of manure managed in each manure management system.
   - Individual emissions factors per head of livestock disaggregated by manure management system can also be derived using this method.
2.4 The output is a Tier 1 emission factor for each of the relevant IPCC livestock types in kg CH_4 $head^{-1}$ $year^{-1}$.
   - The output could only be considered Tier 2 when state-specific data on the proportions of manure from each livestock type is known, and/or any other system specific information on the other variables is known and incorporated. IPCC guidance explains what and how to incorporate this information.

ICF would be happy to advise on prioritizing information collection to support state specific estimates.

IPCC Data / Information for Step 1
https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch03_Land%20Representation.pdf

Figure 3A.5.1 (Updated) **Delineation of major climate zones, updated from the 2006 IPCC Guidelines.**



https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf

TABLE 10.14 (UPDATED) (CONTINUED)
METHANE EMISSION FACTORS BY ANIMAL CATEGORY, MANURE MANAGEMENT SYSTEM AND CLIMATE ZONE (G CH_4 KG VS^{-1}) [7]

Livestock species	Productivity Class	Manure Storage System[4]	Cool				Temperate		Warm			
			Cool Temp. Moist	**Cool Temp. Dry**	**Boreal Moist**	**Boreal Dry**	**Warm Temp. Moist**	**Warm Temp. Dry**	**Tropical Montane**	**Tropical Wet**	**Tropical Moist**	**Tropical Dry**
Non Dairy Cattle	High Productivity	Uncovered anaerobic lagoon	72.4	80.8	60.3	59.1	88.0	91.7	91.7	96.5	96.5	96.5
		Liquid/Slurry, Pit storage > 1 month[5]	25.3	31.4	16.9	16.9	44.6	49.4	71.2	91.7	88.0	89.2
		Solid storage	2.4				4.8		6.0			
		Dry lot	1.2				1.8		2.4			
		Daily spread	0.1				0.6		1.2			
		Anaerobic Digestion -Biogas[8]	2.4				2.7		2.8			
		Burned for fuel	12.1									
	Low Productivity[1,6]	Uncovered anaerobic lagoon	52.3	58.4	43.6	42.7	63.6	66.2	66.2	69.7	69.7	69.7
		Liquid/Slurry, Pit storage > 1 month[5]	18.3	22.6	12.2	12.2	32.2	35.7	51.4	66.2	63.6	64.5
		Solid storage	1.7				3.5		4.4			
		Dry lot	0.9				1.3		1.7			
		Daily spread	0.1				0.4		0.9			
		Anaerobic Digestion -Biogas[8]	9.2				9.5		9.5			
		Burned for fuel	8.7									

NOTE: see full table 10.14 for other livestock types. See figure 3A.5.1 for default climate zones (but Vermont can check climate zone classification and adjust as necessary).

TABLE 10A.6 (NEW)
ANIMAL WASTE MANAGEMENT SYSTEM (AWMS) REGIONAL AVERAGES FOR CATTLE AND BUFFALO

Animal Category	Region[1]	AWMS (%)								
		Lagoon	**Liquid /Slurry**	**Solid storage**	**Drylot**	**Pasture/ Range/ Paddock**	**Daily spread**	**Digester**	**Burned for fuel**	**Other**
Dairy Cattle	North America	26	24	24	no data	15	11	no data	no data	no data
	Western Europe	no data	43	29	no data	26	2	no data	no data	no data
	Eastern Europe	no data	5	74	no data	20	1	no data	no data	no data
	Oceania	5	no data	no data	no data	94	1	no data	no data	no data
	East Asia and South-East Asia (Asia)	no data	1	21	29	38	no data	no data	11	no data
	South Asia (Indian subcontinent)	no data	no data	1	49	30	no data	no data	20	no data
	Latin America and the Caribbean	no data	no data	5	38	57	no data	no data	no data	no data
	Near East (Middle East) and North Africa	no data	no data	14	35	46	no data	no data	5	no data
	Sub-Saharan Africat	no data	no data	20	29	45	no data	no data	6	no data
non-Dairy Cattle	North America	no data	1	43	14	42	no data	no data	no data	no data
	Western Europe	no data	22	26	no data	48	4	no data	no data	no data
	Eastern Europe	no data	64	5	no data	31	no data	no data	no data	no data
	Oceania	no data	no data	no data	no data	100	no data	no data	no data	no data
	East Asia and South-East Asia (Asia)	no data	no data	29	28	36	no data	no data	7	no data
	South Asia (Indian subcontinent)	no data	no data	1	49	30	no data	no data	20	no data
	Latin America and the Caribbean	no data	no data	3	5	92	no data	no data	no data	no data
	Near East (Middle East) and North Africa	no data	no data	5	46	42	no data	no data	7	no data
	Sub-Saharan Africa	no data	no data	15	30	50	no data	no data	5	no data

TABLE 10.18 (UPDATED)
DEFINITIONS OF MANURE MANAGEMENT SYSTEMS[3]

<table>
<tr><th colspan="2">System</th><th>Definition</th></tr>
<tr><td colspan="2">Pasture/Range/Paddock (PRP)</td><td>The manure from pasture and range grazing animals is allowed to lie as deposited, and is not managed.</td></tr>
<tr><td colspan="2">Daily spread</td><td>Manure is routinely removed from a confinement facility and is applied to cropland or pasture within 24 hours of excretion.</td></tr>
<tr><td colspan="2">Solid storage</td><td>The storage of manure, typically for a period of several months, in unconfined piles or stacks. Manure is able to be stacked due to the presence of a sufficient amount of bedding material or loss of moisture by evaporation.
Solid stores can be covered or compacted. In some cases, bulking agent or additives are added.</td></tr>
<tr><td colspan="2">Solid storage-Covered/compacted</td><td>Similar to solid storage, but the manure pile is a) covered with a plastic sheet to reduce the surface of manure exposed to air and/or b) compacted to increase the density and reduce the free air space within the material.</td></tr>
<tr><td colspan="2">Solid storage - Bulking agent addition</td><td>Specific materials (bulking agents) are mixed with the manure to provide structural support. This allows the natural aeration of the pile, thus enhancing decomposition (e.g. sawdust, straw, coffee husks, maize stover).</td></tr>
<tr><td colspan="2">Solid storage - Additives</td><td>The addition of specific substances to the pile in order to reduce gaseous emissions. Addition of certain compounds such as attapulgite, dicyandiamide or mature compost have shown to reduce N_2O emissions; while phosphogypsum reduces CH_4 emissions.</td></tr>
<tr><td colspan="2">Dry lot</td><td>A paved or unpaved open confinement area without any significant vegetative cover. Dry lots do not require the addition of bedding to control moisture. Manure may be removed periodically and spread on fields.</td></tr>
<tr><td colspan="2">Liquid/Slurry [1]</td><td>Manure is stored as excreted or with some minimal addition of water or bedding material in tanks or ponds outside the animal housing. Manure is removed and spread on fields once or more in a calendar year. Manure is agitated before removal from the tank/ponds to ensure that most of the VS are removed from the tank.</td></tr>
<tr><td colspan="2">Uncovered anaerobic lagoon</td><td>A type of liquid storage system designed and operated to combine waste stabilization and storage. Lagoons have a lower depth and a much larger surface compared to liquid slurry stores. Anaerobic lagoons are designed with varying lengths of storage (up to a year or greater), depending on the climate region, the volatile solids loading rate, and other operational factors. The supernatant water from the lagoon may be recycled as flush water or used to irrigate and fertilise fields.</td></tr>
<tr><td colspan="2">Pit storage below animal confinements</td><td>Collection and storage of manure usually with little or no added water typically below a slatted floor in an enclosed animal confinement facility, usually for periods less than one year. Manure may be pumped out of the storage to a secondary storage tank multiple times in one year, or stored and applied directly to fields. It is assumed that VS removal rates on tank emptying are >90%.</td></tr>
<tr><td rowspan="2">Anaerobic digester</td><td>Digesters of high quality and low leakage</td><td>Animal manure with and without straw is collected and anaerobically digested in a containment vessel. Co-digestion with other waste or energy crops may occur.
Digesters are designed, constructed and operated according to industrial technology standard for waste stabilization by the microbial reduction of complex organic compounds to CO_2 and CH_4.
Biogas is captured and used as a fuel.
Digestate is stored either in open storage, in covered storage with no leakage control, or in gas tight storage with gas recovery or flaring.</td></tr>
<tr><td>Digesters with high leakage</td><td>Animal manure with and without straw is collected and anaerobically digested in covered lagoon.
Digesters are used for waste stabilization by the microbial reduction of complex organic compounds to CO_2 and CH_4.
Biogas is captured and flared or used as a fuel.
After anaerobic digestion, digestate is stored either openly, covered, or gas tightly.</td></tr>
<tr><td colspan="2">Burned for fuel</td><td>The dung and urine are excreted on fields. The sun dried dung cakes are burned for fuel.</td></tr>
</table>

Table 10.18 (Updated) (Continued)
Definitions of manure management systems

System		Definition
Deep bedding		As manure accumulates, bedding is continually added to absorb moisture over a production cycle and possibly for as long as 6 to 12 months. This manure management system also is known as a bedded pack manure management system and may be combined with a dry lot or pasture. Manure may undergo periods where animals are present and are actively mixing the manure, or periods in which the pack is undisturbed.
Composting	In-vessel[2]	Composting, typically in an enclosed channel, with forced aeration and continuous mixing.
	Static pile	Composting in piles with forced aeration but no mixing, with runoff/leaching containment.
		Composting in piles with forced aeration but no mixing, without runoff/leaching containment.
	Intensive windrow[2]	Composting in windrows with regular (at least daily) turning for mixing and aeration, runoff/leaching containment.
		Composting in windrows with regular (at least daily) turning for mixing and aeration, no runoff/leaching containment.
	Composting - Passive windrow[2]	Composting in windrows with infrequent turning for mixing and aeration, with runoff/leaching.
		Composting in windrows with infrequent turning for mixing and aeration, no runoff/leaching.
Poultry manure with litter		Similar to cattle and swine deep bedding except usually not combined with a dry lot or pasture. Typically used for all poultry breeder flocks, for alternative systems for layers and for the production of meat type chickens (broilers) and other fowl. Litter and manure are left in place with added bedding during the poultry production cycle and cleaned between poultry cycles, typically 5 to 9 weeks in productive systems and greater in lower productivity systems.
Poultry manure without litter		May be similar to open pits in enclosed animal confinement facilities or may be designed and operated to dry the manure as it accumulates. The latter is known as a high-rise manure management system and is a form of passive windrow composting when designed and operated properly. Some intensive poultry farms installed the manure belt under the cage, where the manure is dried inside housing.
Aerobic treatment		The biological oxidation of manure collected as a liquid with either forced or natural aeration. Natural aeration is limited to aerobic and facultative ponds and wetland systems and is due primarily to photosynthesis. Hence, these systems typically become anoxic during periods without sunlight.

[1] Covers on manure management systems can impact emissions of direct N_2O, CH_4 and NH_3. With N_2O and CH_4 emission, the effect of the cover depends upon character of the cover material.

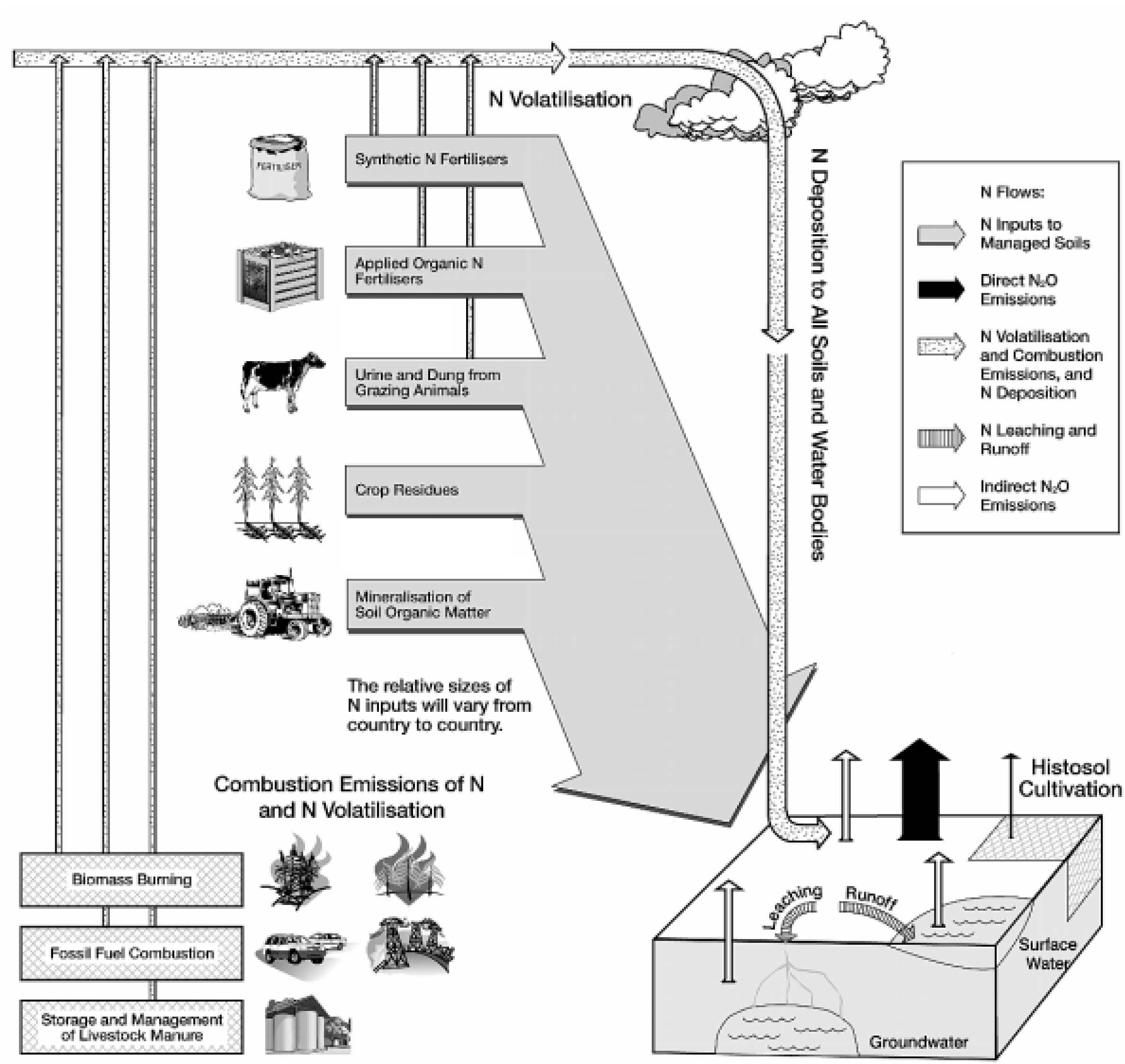
[2] Composting is the biological oxidation of a solid waste including manure usually with bedding or another organic carbon source typically at thermophilic temperatures produced by microbial heat production.

[3] Comparative definitions with the EMEP/EEA Air Pollutant Emission Inventory 2016 Guidebook can be found in Annex 10A.2, Table 10A.10.

Appendix 6: Chemical Oxidation of NH3 to N2O

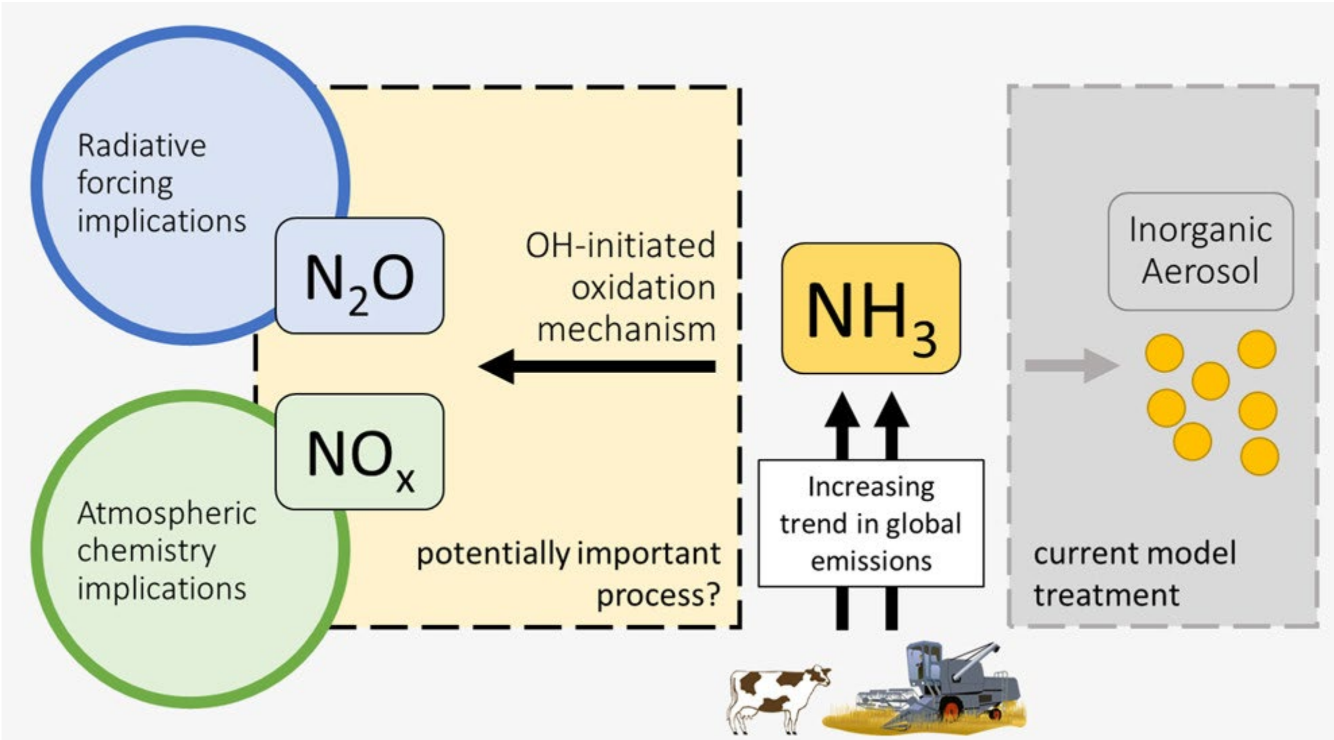
Please refer to the IPCC 2019 Refinement, Volume 4, Chapter 11, Section 11.2.2 and Figure 11.1, for a description of volatilization in agricultural soils and accounting: https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch11_Soils_N2O_CO2.pdf

Figure 11.1 Schematic diagram illustrating the sources and pathways of N that result in direct and indirect N_2O emissions from soils and waters



Note: Sources of N applied to, or deposited on, soils are represented with arrows on the left-hand side of the graphic. Emission pathways are also shown with arrows including the various pathways of volatilisation of NH_3 and NO_x from agricultural and non-agricultural sources, deposition of these gases and their products NH_4^+ and NO_3^-, and consequent indirect emissions of N_2O are also illustrated. "Applied Organic N Fertilisers" include animal manure, all compost, sewage sludge, tankage, etc. "Crop Residues" include above- and below-ground residues for all crops (non-N and N fixing) and from perennial forage crops and pastures following renewal. On the lower right-hand side is a cut-away view of a representative sections of managed land; Histosol cultivation is represented here.

In terms of atmospheric oxidation of NH_3 into N_2O, please refer to Pai et al., 2021, including the following graphic:



Appendix 7: Conservation practices implemented in Vermont from largest to smallest GHG mitigation potential.

Climate Impact Rating[6]	Practice Definition	Climate Change Impact
Manure Management: Manure Storage, Covers, Handling and Application (digestors, liquid / slurry system covers, manure separation, solid storage)		
4	• **Anaerobic digestors** are a waste management practice that anaerobically breaks down animal manure and other organics via biological treatment in a digestor/reactor.	• Anaerobic digestion produces methane (CH_4) as a byproduct of decomposition, thus digesters can reduce CH_4 emissions though biogas collection. Efficient biogas systems reduce up to 60 – 80% of CH_4 emissions that would otherwise occur o Biogas/methane can be used as an energy source resulting in indirect reduction of GHG emissions through replacement of fossil fuels. o Emissions reductions may also occur from reductions of nitrous oxide (N_2O) emissions from soils amended with digested manure due to its reduced organic matter content. o Leakage is a consideration for all biogas systems.
2	• **Manure covers** include natural or induced crusts or manmade structures placed over manure storage facilities to reduce or prevent emissions.	• Permeable (natural crusts where solid content is high, straw, wood chips, expanded clay, oil, wood etc.), semi-permeable and sealed plastic covers can reduce CH_4 and ammonia (NH_3) emissions but the effect on N_2O emissions is highly variable and not well understood scientifically[7].

[6] Climate impacts range from +4 as the largest sequestration/mitigation potential to -4 indicating that the highest (U.S. Department of Agriculture, n.d.) level of emissions occur. Climate impact ratings are based on a combination of USDA NRCS conservation practice climate impacts (see https://www.nrcs.usda.gov/sites/default/files/2023-12/RMSPlanningToolNational_2024.xlsm for a list of the NRCS 2024 GHG rankings of all practices), literature review results and expert opinion when NRCS conservation practice climate impacts were not available. See Appendix 4 for the table of management practice climate impact rankings.

[7] Note that while ammonia is not itself a greenhouse gas, it can be converted into N_2O either by nitrogen transforming microorganisms in the soil, or through chemical transformation in the air. For more information on ammonia conversion to N2O please see Appendix 5

		• Net impact on emissions of different GHGs are affected by the current and proposed manure cover characteristics.
1	• **Manure separation** involves separation of solids from the liquid waste stream	• Manure separation can reduce emissions if the solid portion of manure is prevented from undergoing anaerobic storage, and generally N_2O emissions decrease with slurry separation.
2	• **Manure application** involves management of the type and timing of incorporation to agricultural soils	• Using the appropriate timing, form and quantity of manure application can mitigate direct and indirect N_2O emissions from agricultural soils (not accounted for under manure management emission sources).
2	• **Manure storage** involves management of the overall manure storage duration, and manipulation of manure storage temperatures which in turn alter manure pH levels.	• Reduced manure storage times can reduce CH_4 emissions, but can also potentially increase N_2O emissions if manure is more frequently applied to agricultural soils (affect is variable depending on time and season of manure application).[8][9] • Reducing the temperature of manure during storage can reduce CH_4 emissions, while lowering the pH reduce NH_3 volatilization, the largest pathway of manure nitrogen loss.[10]
1	• **Manure composting** involves storing manure and allowing it to decay to a slow-release end product that can be used as a crop fertilizer.	• Manure composting can emit N_2O, carbon dioxide (CO_2), CH_4 and NH_3 if not properly managed or if gasses are not captured[11], however may enhance soil carbon storage through stabilization of organic matter[Error! Bookmark not defined.]
Feed Management Strategies		
4	Animal and feed management may include feed processing, genetic selection, TMR feeding	• Genetic selection decreases herd emissions by selection of low emission animals. • Feed processing and total mixed ration (TMR) feeding raises the overall nutritional profile of feed by

[8] (U.S. Department of Agriculture, n.d.; Gerber, et al., 2013)
[9] Gerber, et al., 2013
[10] (Meinen et al., 2013) https://doi.org/10.2527/jas.2013-6584
[11] (Ba, Qu, Zhang, & Groot, 2020)

		incorporation of additional ingredients, which may reduce CH_4 per unit of product through increasing productivity.
2	Diet Formulation including mechanisms such as by-products, minerals and salts, oils and fats, oilseeds, tanniferous forages and urea	• Diet manipulation can decrease through multiple mechanisms including increased nonfermentable energy and related decreased feed intake and fiber digestibility, and inhibition of methanogenesis (introduction of fatty acids). • Due to decreased fiber digestibility CH_4 emissions could be increased. • Inclusion of oils and fats, and oilseeds may have undesirable increase to upstream emissions when compared to other concentrate feeds and so their inclusion should be carefully assessed.[Error! Bookmark not defined.]
4	Rumen Manipulation includes additives, defaunation (removal of rumen protozoa which impacts CH4 production from enteric fermentation) and electron sinks	• Market ready feed additives include 3NOP, and more recently *Asparagopsis taxiformis*, which have been shown to reduce CH_4 emissions from enteric fermentation by 32% and up to 80% respectively[12]. • Additives in some cases must be fed continuously so are not suitable for grazing livestock systems, and more and longer-term research is needed to determine net effect on productivity (3NOP has been shown not to affect productivity). • Electron sinks reduce hydrogen available to methanogens, methane generating bacteria, which would otherwise be available.
Crop to Hay (permanent seed down)		
4	Establishing adapted and compatible species, varieties, or cultivars of perennial herbaceous plants suitable for pasture or hay production. Can be applied to improve	Converting land with annual crops to perennial crops can result in increased soil carbon sequestration and reduced N_2O

12 (Arndt et al., 2022)

	livestock nutrition and health, increase forage, reduce soil erosion, improve water quality, improve air quality and improve soil health.	emissions depending on fertilizer practices used.
Agroforestry (silvopasture, alley cropping , multi-story cropping and riparian forest buffers)		
4	• **Agroforestry** the intentional integration of trees and shrubs into crop and animal production systems to enhance productivity, profitability, and environmental stewardship of agricultural operations	Can increase C sequestration in plant biomass and soil as well as reduce N2O emissions by reducing fertilizer application rates and nutrient loss by increasing utilization and cycling of nutrients. May result in decreased fossil fuel consumption from reduced equipment use and reduced farmstead heating and cooling. Improved forage quality can also result in reduced methane emissions [13]
3	• **Silvopasture** trees combined with pasture and livestock production	Can increase C storage in plant biomass and soil and reduce indirect N2O emissions by reducing nutrient loss. Improved forage quality can also result in reduced methane emissions. [14]
3	• **Alley Cropping** trees or shrubs planted in sets of single or multiple rows with agronomic crops, horticultural crops, or forages produced in the alleys between the trees that can also produce additional products	Can increase C storage in plant biomass and soil and reduce indirect N2O emissions by increasing utilization and cycling of nutrients.[15]
3	• **Multistory cropping** existing or planted stands of trees or shrubs that are managed as an overstory with an understory of plants that are grown for a variety of products	Can increase C storage in plant biomass and soil and reduce indirect N2O emissions by improving nutrient cycling. [16]
3	• **Riparian Forest Buffers** an area of trees, shrubs, and herbaceous vegetation established and managed adjacent to streams, lakes, ponds, and wetlands	Can increase C storage in plant biomass and soil reduce indirect N2O emissions from agricultural runoff and leaching. [17]
No-Till		
3	The no till practice addresses the amount, orientation, and distribution of crop and	Due to minimal disturbance of the soil, no-till farming can preserve more soil carbon

[13] (Schoeneberger et al, 2017)
[14] (Schoeneberger et al, 2017)
[15] (Schoeneberger et al, 2017)
[16] (Schoeneberger et al, 2017)
[17] (Schoeneberger et al, 2017)

	other plant residue on the soil surface year-round. Crops are planted and grown in narrow slots or tilled strips established in the untilled seedbed of the previous crop.	beneath the surface of the soil compared to conventional till. However, the increase in soil carbon varies (or may not occur) depending on soil type, climate, equipment used and duration of the practice. In general, soil carbon increases are greater in warmer and wetter climates than drier and cooler climates.[18]
Cover Crop		
3	Grasses, legumes, and forbs planted for seasonal vegetative cover that are not harvested. Can be planted to reduce erosion, maintain soil health, reduce water quality degradation, suppress weeds and pests, improve soil moisture, and minimize soil compaction.	Meta analyses indicate that cover crops can significantly reduce nitrogen (N) leaching and significantly increase soil organic carbon (SOC) sequestration. There was no significant impact found on direct N_2O emissions.[19] However, other studies have found mixed results on increases in SOC depending on cover crop biomass accumulation rates,[20] soil moisture levels, and type of cover crop planted.[21]
Reduced Tillage		
3	The reduced tillage practice manages the amount, orientation, and distribution of crop and other plant residue on the soil surface year-round while limiting the soil-disturbing activities used to grow and harvest crops in systems where the field surface is tilled prior to planting. Includes seasonal no-till, ridge tillage, strip tillage and mulch tillage.	By disturbing the soil less than conventional till, reduced tillage can result in increased soil carbon sequestration compared to conventional till. However, similar to no-till, results vary depending on soil type, climate, equipment used and duration of the practice[22]
Manure Injection		
3	Manure is applied below the soil surface to reduce emissions and the potential for nutrient runoff to surface waters.[23]	Manure injection can reduce ammonia emissions up to 100% (typically 50 >90%) compared to surface applied manure which reduces indirect N_2O emissions.[24] Manure injection was also found to conserve more available nitrogen in the soil while resulting in low levels of N_2O emissions compared to surface application. Manure application

[18] (Ogle, et al., 2019)
[19] (Abdalla, et al., 2019)
[20] (Blanco-Canqui, 2022)
[21] (Garba, Bell, & Williams, 2022)
[22] (Haddaway, et al., 2017)
[23] (Leytem, Leinmann, Pote, & Dell, n.d.)
[24] (Leytem, Leinmann, Pote, & Dell, n.d.)

		effects on CH_4 and CO_2 fluxes are less consistent and appear to be more tied to weather, especially soil moisture and temperature.[25]
Manure Incorporation		
3	The mixing of dry, semi-dry, or liquid organic nutrient sources (including manures, biosolids, and compost) into the soil profile within a specified time period from application.[8]	Manure application effects on CH_4 and CO_2 fluxes are inconsistent and appear to be more tied to weather, especially soil moisture and temperature.[26] Studies indicate that manure incorporation increases N_2O fluxes compared to broadcast/surface application due to greater NH_3/ ammonium (NH_{4+}) conservation.[27] Other studies found that immediate manure incorporation reduced NH_3, CH_4 and CO_2 emissions but increased N_2O fluxes.[28]
Nutrient Management		
3	Managing the rate, source, placement, and timing of plant nutrients and soil amendments while reducing environmental impacts.	Can reduce N application rates and N_2O emissions and can increase soil carbon sequestration.[29]
Precision Agriculture		
3	Precision agriculture is a general term to describe farming tools based on observing, measuring, and responding to within-field variability via crop management. It is made possible through the use of Global Positioning System or Global Navigation Satellite System (GNSS), which enable farm managers to respond to field irregularities. This approach allows farmers to make important resource management decisions both on-site and in real-time.[30]	By increasing accuracy and only applying needed levels of nutrients variable rate nutrient application can reduce fertilizer application rates thus reducing N2O emissions and can also increase crop yields.[31]
Conservation Crop Rotation		

[25] (Sherman, Young, Jokela, & Kieke, Manure Application Timing and Incorporation Effects on Ammonia and Greenhouse Gas Emissions in Corn, 2022)
[26] (Sherman, Young, Jokela, & Kieke, Manure Application Timing and Incorporation Effects on Ammonia and Greenhouse Gas Emissions in Corn, 2022)
[27] (Sherman, Young, Jokela, & Kieke, Manure Application Timing and Incorporation Effects on Ammonia and Greenhouse Gas Emissions in Corn, 2022)
[28] (Livestock and Poultry Environmental Learning Community, 2019; Sherman, Young, Jokela, & Cavadini, Impacts of Low Disturbance Liquid Dairy Manure Incorporation on Alfalfa Yield and Fluxes of Ammonia, Nitrous Oxide, and Methane, 2021)
[29] (Pape, et al., 2016)
[30] (Ashworth & Owens, 2023)
[31] (Balafoutis, et al., 2017)

2	Growing a planned sequence of various crops on the same piece of land for a variety of conservation purposes. Can be applied to reduce erosion, maintain soil health, reduce water quality degradation, improve soil moisture, reduce pest pressure, provide feed for livestock and provide food and cover habitat for wildlife.	Conservation crop rotations can increase soil carbon sequestration depending on the specific crops grown and practices used (e.g. cover crops, compost addition, reduced tillage).[32]
Grazing Management Practices including Rotational Grazing		
2	Managing the harvest of vegetation with grazing and/or browsing animals with the intent to achieve specific ecological, economic, and management objectives. Rotational grazing is the practice of moving animals through pasture to improve soil, plant, and animal health.[33]	Management of grazing lands and pasture can increase soil carbon sequestration depending on soil, climate and ecosystem conditions.[34] Grazing management practices can reduce emissions by avoiding consequences of degrading grass systems and encouraging deeper root systems and greater carbon sequestration.[35]
Filter Strip (grass buffer)		
2	An area of vegetation established for removing sediment, organic material, and other pollutants from runoff and wastewater.	Reduces emissions by absorbing nitrogen prior to runoff, thus reducing subsequent N_2O emissions, in addition to the carbon sequestration occurring from the new vegetation.[36]

[32] (Vittoria Guidoboni, et al., 2023)
[33] (Rodale Institute, n.d.)
[34] (Wang, et al., 2021)
[35] (Favor, Lewis, Rinehart, & Haschke, n.d.)
[36] (U.S. Department of Agriculture, n.d.)

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