7-2022

# Whole Farm Net Zero: approaches to quantification of climate regulation ecosystem services at the whole farm scale. Vermont Payment for Ecosystem Services Technical Report #7

Christopher Bonasia

Lindsey Ruhl
*University of Vermont*

Benjamin Timothy Dube
*University of Vermont*

Alissa C. White
*The University of Vermont*, awhite32@uvm.edu

Heather M. Darby
*University of Vermont*

## Recommended Citation

Bonasia, C., Ruhl, L., Dube, B., White, A., and H. Darby. (2022). Whole Farm Net Zero: approaches to quantification of climate regulation ecosystem services at the whole farm scale. Vermont Payment for Ecosystem Services Technical Report #7. The University of Vermont.

The University of Vermont

# Whole Farm Net Zero:

## Approaches to quantification of climate regulation ecosystem services at the whole farm scale

Vermont Payment for Ecosystem Services Technical Research Report #7

Version 2

Prepared for the Vermont Soil Health and Payment for Ecosystem Services Working Group

July 2022

Contributors: Christopher Bonasia, Lindsey Ruhl, Benjamin Dube, Alissa White & Heather Darby

GUND INSTITUTE FOR ENVIRONMENT

THE UNIVERSITY OF VERMONT EXTENSION

## 1) Introduction

In this report, approaches to the quantification of climate mitigation ecosystem services at the whole farm scale are reviewed and summarized for easy comparison. Eight quantification tools, and three case studies demonstrating possible tool applications, are summarized to fulfill the requirements of the Technical Services Contract—Task 7. Information from a combination of literature review and expert interviews served to document the inputs, outputs, strengths, weaknesses, opportunities, and threats for each quantification tool. This research was conducted in service to the Vermont Soil Health and Payment for Ecosystem Services (PES) Working Group (VT PES working group).[1] It is our hope that this report provides productive information and insights for the implementation of whole farm scale payment for ecosystem services programs, Vermont's Climate Action Plan, and similar efforts elsewhere.

Emissions reductions on farms are of interest to farmers in Vermont and will be required by the implementation of the Global Warming Solutions Act (GWSA).[2] Management changes that reduce emissions at the farm scale could possibly be supported and encouraged through a PES program. Given the work and goals of the PES Working Group and the requirements to implement the GWSA it is critical to understand the degree of accuracy and scope of currently available greenhouse gas assessment tools that could possibly be implemented to measure and monitor outcomes from VT agriculture.

Section 2 of this report describes the methods used to collect information reviewing eight tools for quantifying agricultural greenhouse gas emissions and sequestration rates, including the CarbOn Management & Emissions Tool (COMET)-Farm, COMET-Planner, COOL-Farm, DayCent, DNDC (DeNitrification-DeComposition), Environmental Policy Integrated Climate (EPIC) & APEX Agricultural Policy / Environmental eXtender (APEX), Holos, and the Integrated Farm Systems Model (IFSM). These eight tools were each reviewed using a systematic literature review, interviews with experts who are well-versed in using the specific tools, and a Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis.

Section 3 presents some larger-context considerations for choosing an appropriate tool. Section 4 gives a high-level overview of the SWOT analysis performed for each tool reviewed for this task. Section 5 describes three example applications of emissions modelling tools. Section 6 contains concluding remarks. The report's Appendix section includes the SWOT analyses for each tool to allow for more in-depth review, as well as a series of tables to present a high-level comparison of the tools.

---

[1] State of Vermont Agency of Agriculture, Food & Markets, "Payment for Ecosystem Services and Soil Health Working Group," (2022), https://agriculture.vermont.gov/pes#:~:text=The%20purpose%20of%20this%20Working,reduce%20agricultural%20runoff%20to%20waters.

[2] Vermont Act 153 (2020), "Vermont Global Warming Solutions Act", https://legislature.vermont.gov/Documents/2020/Docs/ACTS/ACT153/ACT153%20As%20Enacted.pdf

### a) Framing for Vermont Soil Health & Payment for Ecosystem Services Working Group

Soils are the largest terrestrial sink of carbon and critical to global climate regulation. Protecting and managing soil carbon is a critical climate change mitigation strategy that will help meet state and national global greenhouse gas mitigation goals by supporting farmers to influence their overall impact on atmospheric greenhouse gas (GHG) concentrations through changes in soil management. However, soil and cropping management decisions are embedded within a complex decision-making context of the whole farm, and in many cases, management changes beyond soil and cropping practices have greater effects on overall net GHG balance.

Farms are managed as whole systems, where changes in one aspect of the farm have implications for other pieces of the system. Vermont farms manage more than just crop fields--they may also have substantial forested acreage, sugarbush, riparian areas, perennial plantings, and a diversity of animals.[3] In this way, farm management can provide many ecosystem services beyond producing food and fiber, and manure and feed management practices can have some of the biggest impacts on a farm's overall greenhouse gas emission levels.

While the PES Working Group explores options for expanding the scope of PES in Vermont from soil health within crop fields, to edge-of-field and whole farm perspectives, the complexity of quantifying performance for all ecosystem services of interest at the whole farm scale becomes overwhelming in complexity and scope. However, broken up into parts, this task becomes much more approachable. Climate regulation ecosystem services is a natural place to start as there are existing quantification tools and similar current interest across the globe. Should the PES working group maintain their focus on crop field soil health it will remain important to understand how that fits into whole farm net-zero assessments.

Approaches to incentivizing enhanced climate regulation in the agriculture sector advanced by the VT PES working group should align with those advanced to meet the 2020 GWSA as the state of Vermont begins to implement its Climate Action Plan. This necessitates a careful consideration of how the quantification tools available for farms comport, or don't, with international and state assessment standards. Notably, there is already acknowledgment that the Vermont emissions inventory protocol that is informing ongoing GWSA efforts at the state scale differs from international IPCC scientific standards and may not adequately assess the suite of interventions in agroecosystems that farms can use to influence greenhouse gas emissions and overall climate regulation ecosystem services. Additionally, alignment with other emerging whole farm carbon accounting efforts by industry and the federal government should align as much as possible.

---

[3] Ryan Patch, "Agriculture Soil Health Co-benefits," presented to VT PES & Soil Health Working Group on 11/16/21, https://agriculture.vermont.gov/sites/agriculture/files/documents/Water_Quality/PES/AAFM-PES-Cobenefits-11162021.pdf. [*hereinafter* Soil Health Co-benefits].

### b) Framing for Vermont's Global Warming Solutions Act

The GWSA sets targets to reduce Vermont state emissions by not less than 26% from 2005 levels by 2025, not less than 40% from 1990 levels by 2030, and not less than 80% from 1990 levels by 2050.[4] Pursuant to these requirements, the GWSA created the Vermont Climate Council (VCC) to identify, analyze, and evaluate strategies and programs to reduce emissions pursuant to these targets,[5] and to identify means to accurately measure the state's emissions and progress towards meeting the targets.[6]

Agriculture and forestry play significant roles in Vermont's state economy and will therefore play an important role in the state's Vermont Climate Action Plan.[7] To understand the current initiatives in the agriculture and forestry sectors and to develop policies in line with the state's climate targets, the GWSA also directed the VCC to establish an Agriculture and Ecosystem's Subcommittee (hereafter referred to as the Subcommittee) to "focus on the role Vermont's natural and working lands play in carbon sequestration and storage, climate adaptation, and ecosystem and community resilience."[8] The outcome of this report can be used to support the Subcommittee's inquiry.

Two separate reports published in 2021 support the state in assessing how it will meet the goals of the GWSA; *A Carbon Budget for Vermont: Task 2 in Support of the Development of Vermont's Climate Action Plan* (Carbon Budget),[9] and the *Vermont Greenhouse Gas Emissions Inventory and Forecast: 1990 – 2017* (Emissions Inventory).[10] The EX-Ante Carbon-balance tool (EX-Act) designed by the Food and Agriculture Organization[11] was used to calculate emissions for the Carbon Budget with a focus on Agriculture, Forestry and Other Land Uses (AFOLU) and the Emissions Inventory used the State Inventory and Projection Tool (SIT) designed by the US Environmental Protection Agency (EPA) that looks at all sectors but has historically been limited in the scope of analysis for AFOLU.[12]

---

[4] 10 V.S.A. § 578 (a)(1-3).

[5] 10 V.S.A. § 591 (b)(1).

[6] 10 V.S.A. § 591 (b)(3).

[7] *See* Soil Health Co-benefits.

[8] 10 V.S.A. § 591 (c)(4).

[9] Dr. Gillian Galford, Dr. Heather Darby, Frederick Hall, & Dr. Alexandra Kosiba, "A Carbon Budget for Vermont: Task 2 in Support of the Development of Vermont's Climate Action Plan," (2021), https://outside.vermont.gov/agency/anr/climatecouncil/Shared%20Documents/Carbon%20Budget%20for%20Vermont%20Sept%202021.pdf. [*hereinafter* Carbon Budget].

[10] Air Quality and Climate Division, "Vermont Greenhouse Gas Emissions Inventory and Forecast: 1990 – 2017," (2021), https://dec.vermont.gov/sites/dec/files/aqc/climate-change/documents/_Vermont_Greenhouse_Gas_Emissions_Inventory_Update_1990-2017_Final.pdf. [*hereinafter* Emissions Inventory].

[11] Food and Agriculture Organization of the United Nations, "Economic and Policy Analysis of Climate Change: EX-ACT TOOL," (2022), https://www.fao.org/in-action/epic/ex-act-tool/overview/en/. [*hereinafter* EX-ACT].

[12] United States Environmental Protection Agency, "State Inventory and Projection Tool," (last updated 12/6/21), https://www.epa.gov/statelocalenergy/state-inventory-and-projection-tool. [*hereinafter* SIT].

The Emissions Inventory to meet the GWSA targets will quantify emissions reductions across all sectors. The Carbon Budget was developed specifically to account for all emissions and sinks, estimating the extent to which carbon sequestration in natural and working lands balances GHG emissions from all fossil fuels. Thus, the Emissions Inventory essentially estimates gross emissions, while the Carbon Budget estimates net emissions for the Agriculture, Forestry, and Other Land Use (AFOLU) sector. The Carbon Budget report focuses on the AFOLU sector as instructed by the VCC, because the sector "provides opportunities to reduce emissions and boost carbon sequestration."[13]Although the Carbon Budget is not yet used to account for emissions reductions towards the GWSA, it was conducted in a manner that it could be used for the AFOLU sector should the Climate Council decide to use it.

The measurements provided by the SIT tool does not accurately portray emissions levels of Vermont's agriculture sector, and the Subcommittee found that SIT "cannot quantify specific land use practices and farmer management in quantifying emissions reduction and sequestration," and that SIT "decouples the analysis of agricultural emissions from agricultural and forestry sinks and prevents a net accounting of agriculture and forestry emissions per the 2019 IPCC Update."[14]

In contrast, the Carbon Budget used the EX-Act tool because it "better accounts for emissions related to land use practices common to Vermont, including cover cropping, reduced tillage, and no-tillage,"[15] but the authors acknowledge the estimates, in their current form, can not be disaggregated by field or by season [16] (*see footnote*[17]). EX-ACT can be calibrated with Tier III data (IPCC definition), which would be field level data from the region for future efforts.[18]

Dr. Gillian Galford, a lead author of the Carbon Budget, explained that EX-Act could be a promising option for a Vermont whole-farm inventory and calibrating the EX-Act tool to regional or subregional data is possible. As Ex-ACT has already been used for the Carbon Budget, it could easily be leveraged for farm scale estimates if relevant Tier III data is available.

Importantly, the level of rigor of all bookkeeping approaches are essentially the same-- the differences come from which land uses are included, and if Tier 1, 2 or 3 data is used. Dr.

---

[13] *See* Carbon Budget at 8.

[14] Vermont Agriculture and Ecosystems Subcommittee, "Resolution recommending amendments to the State of Vermont GreenHouse Gas Inventory protocol," bullets 12 & 13 (9/10/2021). [*hereinafter* Ag & Eco Subcommittee].

[15] *See* Carbon Budget at 8.

[16] *See* Carbon Budget at 10.

[17] "EX-ACT is well-suited to assessing project activities at a range of scales. While the tool works best at project level, given that only one dominant soil and climate type can be considered at a time, it can nonetheless be easily up-scaled to regional and national scales. In such cases, sensitivity analyses of soil and climate conditions or separate EX-ACT analyses conducted by region may be undertaken to supplement the usual appraisal process and ensure precise results." *See* Uwe Grewer, Louis Bockel, Laure-Sophie Schiettecatte & Martial Bernoux, "Ex-Ante Carbon-balance Tool (EX_ACT): Quick Guidance," *Food and Agriculture Organization of the United Nations*, 8 (2017), https://www.fao.org/fileadmin/templates/ex_act/pdf/EX-ACT_quick_guidance.pdf.

[18] Gillian Galford, personal correspondence, (7/18/22).

Galford added that DNDC is very already well calibrated to the Northeast, originating from New Hampshire, and could be used. Further parameterization to use a tool which is specifically calibrated for Vermont would be a large research effort without much change in the model estimates, and therefore may not be worth the investment of resources.[19]

With these shortcomings in mind, the Subcommittee issued a set of recommendations to VCC to pursue technical research on "the shortcomings of each of the tools currently used by the State of Vermont to quantify greenhouse gas emissions (SIT, Ex-act, and LEAP) for evaluating changes in the agriculture sector," and "recommend options for creating a more accurate and nuanced quantification approach to enable agriculture in Vermont to meet the goals of the GWSA, including consideration of process-based models developed for North America, such as DNDC."[20] This report informs this need from the Subcommittee, in part, and could be used to inform the work of VT PES working group.

## 2) Methods

### a) Systematic Literature Review

Tools were chosen for review based on direction from Vermont Agency of Agriculture Food and Markets personnel and from the recommendations of the PES Working Group and the Subcommittee. Researchers compiled sources relevant for each tool, including user manuals, peer-reviewed studies, and websites.

### b) Interviews

To gain a deeper understanding of each tool's effectiveness the researchers conducted personal interviews with experts familiar with the tools. Interviews were conducted by either phone call, zoom meeting, or email exchange. Dr. Gillian Galford, Research Associate Professor with UVM, provided information for background on EX-Act and the Carbon Budget by email. Judson Peck, Agricultural Water Quality Program Coordinator with VAAFM, provided general project background also by email. Online interviews were conducted with the following experts: Roland Kröbel for Holos; Clarence Rotz for Integrated Farm System Management (IFSM); Horacio Aguirre for the Farm Level Environmental Assessment of Organic Dairy Systems in the U.S.; Ward Smith for DNDC; Michaela Aschbacher for COOL Farm Tool; Jaehak Jeong and Phillip Gassman for EPIC/APEX; Stephen Del Grosso for DAYCENT, and Adam Chambers for COMET. Interviewees were asked the following questions (or variations):

> 1. To start, please tell me about how you got into this work. What is your background and why do you do what you do?

---

[19] *Id.*

[20] Ag & Eco Subcommittee at bullet (a).

2. Which Whole Farm Ecosystem Services Assessment are you familiar with?

3. We are doing a SWOT analysis to summarize key aspects of each model in our report. a) In your opinion, what are the strengths of this model? b) What are the weaknesses? c) What is not accounted for or included in it? d) What do you see as opportunities for impact and use in the world, currently or in the future? e) Are there any external threats or challenges that will limit its use, impact, or effectiveness in the world?

4. What would need to change for this tool to be used for policy, regulations, or incentive programs, like a PES system?

5. What is the future for the models? Will there be new additions/expansion of capabilities? When was the last time it was updated? Who updates them and how often?

6. How would the model be calibrated in the face of climate change?

7. What needs to be adjusted or calibrated to use the tool in Vermont?

8. Can the model accommodate diversified farms?

### c) Information Presentation: SWOT Analysis, Table

Following the research process, information from the various sources for each tool were compiled and analyzed using a SWOT analysis to identify specific Strengths, Weaknesses, Opportunities, and Threats. This information is summarized for each individual tool and is also presented in tables attached to this report for comparison. Relevant information regarding GHG accounting tools that was not appropriate for the SWOT analysis or tables is included in Section 3 of this report.

## 3) Overview of both general and larger context items and functionality to evaluate for each tool

There are many factors to consider when comparing different GHG accounting tools, though not all were appropriate to include in the SWOT analysis or Tables. This section includes several important factors to consider, both pertaining to selecting tools themselves and for the wider context in which they will be used in Vermont.

### a) Steps for Selecting a Tool

Tool comparisons are complex and, in some ways, not fully possible because different tools frame emissions according to different criteria (i.e., some use product type as a distinguishing factor while others use land uses).[21] Previous studies have compared greenhouse gas accounting tools, though there is not yet a comparison that focuses on this specific selection of tools or on the Vermont context.

Still, some studies offer useful frameworks for comparing and selecting tools, such as one process defined by the World Bank and the Food and Agriculture Organization of the United Nations (FAO). This process recommends progressing from predefined criteria (aim, geographical zone/application, available data, time, and skills) before then identifying 1) land use activity being measured, 2) land use changes to be accounted for, and 3) greenhouse gases, carbon pools, and leakage.[22]

To use these steps to choose a model for the objectives outlined in this report, the predefined criteria include an aim of accurately assessing whole-farm emissions for a PES system and to inform policies intended to meet Vermont's required emissions reductions within the timeframe laid out in GWSA. To fulfill the remaining predefined criteria, policy makers will need to determine 1) what data is available and what resources can be allocated to collecting more data, 2) what skills are currently available for using the tools, and 3) and what resources can be allocated to hiring and training personnel. Following that, policy makers can determine specifics of agriculture and forestry land uses to measure, what land use changes need to be considered, and which specific outputs are being sought.

### b) Tool Characteristics

#### *i) Life Cycle Analysis*

Life cycle analysis (LCA) is used to evaluate the full impact of a product on the environment (in this case, the impact of agriculture on GHG emissions).[23] This methodology therefore includes emissions measurements for all on-farm activities, as well as those linked to products sourced off-farm (fertilizer, feed, etc.).[24]

Typically, LCAs consist of five steps:

1) Goal and scope definition, which includes defining the system boundary and functional unit of analysis

---

[21] Vincent Colomb et al., "Review of GHG Calculators in Agriculture and Forestry Sectors," UN Food and Agriculture Organization, 8 (June 2012), https://www.fao.org/fileadmin/templates/ex_act/pdf/Review_existingGHGtool_GB.pdf.

[22] Anass Toudert et al., "Carbon Accounting Tools for Sustainable Land Management," World Bank Group, 122 (2018), https://openknowledge.worldbank.org/handle/10986/31062.

[23] Sustainable Agriculture Research & Education Program, "Life Cycle Assessment (LCA)," (n.d.; accessed 1/24/22), https://sarep.ucdavis.edu/are/energy/lca.

[24] *Id.*

2) Life cycle inventory (LCI), which includes identification and quantification of all inputs at each stage of the life cycle included within the system boundary

3) Impact analysis

4) Interpretation of impact analysis.[25]

Because LCAs provide a holistic method for inventorying emissions produced by different farm management systems, emission inventory tools that incorporate a LCA will more accurately inform farm decisions for reducing greenhouse gases. However, calculations for upstream emissions are vulnerable to large uncertainties.[26] Section 5 includes further discussion of integrating emissions modelling tools, such as those reviewed in this report, into a LCA.

### *ii) Inclusion of Forests, Wetlands, Land-Use Change*

Forests and wetlands are integrated with farmland in Vermont's working landscape.[27] Many farms include wooded areas, both as part of the property but also as part of the business and management of the farm.[28] Many farm GHG inventories conducted in Vermont will be incomplete if these areas are left out of the estimate calculations.

As the Subcommittee identified as a key shortcoming for SIT,[29] many greenhouse gas quantification tools include these land areas but have decoupled them from farmland in their calculations. Additionally, the Carbon Budget noted that this complicates net-balance calculations on farms that establish or remove tree cover on their farms—for example, areas that have been reforested along riparian areas could then be included in the inventory for forest land resulting in the carbon sequestered in that area not being credit/attributed to the farm's carbon inventory.[30]

### *iii) Follows Intergovernmental Panel on Climate Change (IPCC) guidelines*

As part of the research process for this report, tools were evaluated to ensure that they comply with methodology described by the IPCC, which delineates tool scope into three tiers. Tier 1 covers very large-scale approaches and uses average emission factors for "large eco-regions of the world," while Tier 2 uses data specific to a state or region, and Tier 3 uses a very

---

[25] *Id.*

[26] A. Del Prado, P. Crosson, J.E. Oleson, & C.A. Rotz, "Whole-farm models to quantify greenhouse gas emissions and their potential use for linking climate change mitigation and adaptation in temperate grassland ruminant-based farming systems," *Animal*, (2013), https://www.researchgate.net/publication/259433671_Whole-farm_models_to_quantify_greenhouse_gas_emissions_and_their_potential_use_for_linking_climate_change_mitigation_and_adaptation_in_temperate_grassland_ruminant-based_farming_systems. [*hereinafter* Del Prado et al.].

[27] *See* Soil Health Co-Benefits

[28] *Id.*

[29] Ag & Eco Subcommittee bullets (12) &(13).

[30] *See* Carbon Budget at 58.

detailed approach at the farm or field scale that usually includes biophysical modelling.[31] Calculators should be chosen to accurately reflect their intended use.

#### *iv) Model Type*

This report includes both process-based models and bookkeeping approaches to estimating greenhouse gas emissions, but prioritizes the latter option. Bookkeeping models are based on emissions factors[32], and use research based standard emissions values for different management and ecosystem characteristics alongside information of a farm's production and management records to estimate emissions.[33] On the other hand, process-based biogeochemical models use mechanistic equations based on historical research to simulate growth, nutrient, water, soil, and GHG dynamics.[34] Process based models can "offer significant advantages in predicting the effects of global change as compared to purely statistical or rule-based models based on previously collected data."[35]

##### (1) Time-Step

Both model types can calculate information according to different time-steps, or the temporal intervals between output values.[36] The relevant time-steps for this report are yearly and daily, where a yearly time-step will quantify factors based on a single value representing an entire year, but a daily time-step can capture greater variations by quantifying values for a factor for each day.[37] It should be noted that time steps can be any length of time and monthly time-steps are used in other common modelling tools, like CENTURY.[38]

All else being equal, a short time step will give more accurate results because of the model's great capability "to represent interactions between the farmer, climate and management," though modelling on a shorter time step can also require more extensive data collection.[39]

---

[31] Vincent Colomb et al., "Selection of appropriate calculators for landscape scale greenhouse gas assessment for agriculture and forestry," *Environmental Research Letters*, 3 (2013), https://iopscience.iop.org/article/10.1088/1748-9326/8/1/015029.

[32] *Defined as* "a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant*."* US EPA, "Basic Information of Air Emissions Factors and Quantification," *Air Emissions Factors and Quantification*, (updated 1/4/22; accessed 3/2/22), https://www.epa.gov/air-emissions-factors-and-quantification/basic-information-air-emissions-factors-and-quantification.

[33] *See* Del Prado et al.

[34] *Id.*

[35] K. Cuddington et al., "Process-based models are required to manage ecological systems in a changing world," (2013), https://esajournals.onlinelibrary.wiley.com/doi/10.1890/ES12-00178.1.

[36] SORTIE-ND, "Timesteps and run length," (accessed 3/11/22), http://www.sortie-nd.org/help/manuals/help/using/timesteps.html#:~:text=The%20basic%20time%20unit%20in,listed%20in%20the%20parameter%20file.

[37] *Id.*

[38] Natural Resource Ecology Laboratory, "The CENTURY Model," *Colorado State University*, (accessed 3/11/22), https://www.cgd.ucar.edu/vemap/abstracts/CENTURY.html#:~:text=The%20CENTURY%20model%20is%20a,agricultural%20lands%2C%20forests%20and%20savannas.

[39] *See* Del Prado et al.

### c) Larger Context Considerations

#### *i) Available Data*

The Carbon Budget noted that poor data is a key limitation on Vermont greenhouse accounting, especially for calculations related to AFOLU.[40] Additionally, much of the literature and information gathered from interviews indicate that the degree of model uncertainty—especially for the most sophisticated tools like DNDC—depends on the comprehensiveness and accuracy of data available for inputs (*see footnote*[41]) making data availability a principal determinant of tool effectiveness.

However, collecting comprehensive data for Vermont's agriculture sector would be a large research effort.[42] Policy makers will need to consider whether the state has sufficient resources for such an undertaking, and the models for some tools that are already calibrated for regional conditions–like Holos and IFSM–may not be significantly improved to warrant the expense of data collection.[43]

A more feasible option may be to use sources of existing data to fill information gaps. As put forward by the authors of the Carbon Budget, "a database could be created from existing nutrient management plans required for farms; such a database would centralize information on fertilizer rates and types and provide precise information about manure management at different rates and could be regularly updated. Additionally, tracking changes in land use requires knowing both the prior and the current land use for the same location."[44] Other useful pre-existing data sources include the United States Department of Agriculture (USDA) National Land Cover Database, the US Forest Service Forest Inventory and Analysis, databases from the USDA National Agricultural Statistics Service (NASS), the IPCC, and, to the extent necessary, fossil fuel emissions from the VT GHG Inventory.[45]

Additionally, consideration should be given to data that does not need to be collected or that should not be included because of potential redundancy in a statewide inventory. For example, farm emissions from fossil fuels are already documented as transportation emissions and energy consumption in the VT GHG Inventory,[46] so a cross-sectoral inventory that includes fossil fuel emission in whole-farm measurements could be double-counted if those same emissions are also included in the transportation and energy inventory.

---

[40] *See* Carbon Budget at 6.
[41] *For specific instances of this assertion, look to analyses for DNDC and Holos.*
[42] Gillian Galford, notes from personal correspondence by email, (2/8/22).
[43] *Id.*
[44] *See* Carbon Budget at 6.
[45] *Id.* At 11.
[46] *Id.*

### *ii) Consider cross-over between GWSA, PES and other uses*

The policy objectives and the research for this project align strongly with both those of the Vermont Payment for Ecosystem Services and Soil Health Working Group (PES working group) and of the Subcommittee. Among the options that the PES working group has considered is a possible PES system funded through trading carbon credits on a market.[47] A tool chosen to inventory GHGs on Vermont farms could allow the time and resource investment by both the VCC and PES working group if it were applicable to both groups' objectives. Therefore, the VCC could benefit from selecting a tool that was considered credible for market participation or applicable to quantification of other ecosystem services in a PES system.

Furthermore, many of the tools are already used by other organizations whose scope could overlap with Vermont's stakeholder goals. For example, the (USDA) used APEX for its Conservation Effects Assessment Project (CEAP) and Soil and Water Assessment Tool (SWAT), the USDA Natural Resources Conservation Services (NRCS), uses COMET-Planner for conservation practice planning, and Ben & Jerry's—a major customer for Vermont Dairy Farmers—selected COMET-farm to measure emissions to monitor progress towards their carbon goals.[48] Any tool that is used by an organization whose objectives align with the Subcommittee or PES Working Group should be especially considered because of the potential to share resources and have measurements that are directly aligned between organizations. Consistent quantification approaches across these groups would also ensure consistent messaging and information to farmers

### *iii) Socio-economic factors*

Using the results of a whole-farm emissions inventory to drive change in the agriculture sector will need to take an inter-connected response to design policies that reduce emissions without causing other harms to state residents.[49] Though emissions are a primary factor driving climate change, it is important to avoid "carbon tunnel vision" and to consider emission reduction strategies within the context of their social and economic implications.[50] Several of the tools included in this report—IFSM, Holos, and APEX—include economic analyses for projected management scenarios, which can be a helpful aid when designing policy to meet state emission reduction requirements. As well, many of the tools include assessment of ecosystem services other than climate mitigation.

---

[47] VT Agency of Agriculture, Food, and Markets, "Soil Conservation Practice and Payment for Ecosystem Services Working Group Report," 6, (January 15, 2020), https://legislature.vermont.gov/assets/Legislative-Reports/Soil-Conservation-Practice-and-PES-Working-Group-Report-01152020.pdf

[48] USDA NRCS, "Commonly Used NRCS Tools - COMET Farm," (n.d.), https://comet-farm.com/. "*COMET is the official greenhouse gas quantification tool of USDA.*"; USDA, "Climate Smart Conservation Partnership Serves Two Scoops of On-Farm Solutions," (2017),https://www.usda.gov/media/blog/2016/12/21/climate-smart-conservation-partnership-serves-two-scoops-farm-solutions. ; *For other examples see report tables in appendix.*

[49] Tina Nybo Jensen, "Expert Opinion: Avoiding Carbon Tunnel Vision," *Environmental Analyst | Global*, (2021), https://environment-analyst.com/global/107463/expert-opinion-avoiding-carbon-tunnel-vision. [*hereinafter* Jensen].

[50] *Id.*

## 4) Modelling Tools[51]

To support Vermont policy makers' goals, this report evaluates eight tools that could be applied for modelling greenhouse gas emissions at the whole-farm level; COMET-Farm, COMET-Planner, COOL-Farm, DayCent, DNDC, EPIC & APEX, Holos, and IFSM. EPIC and APEX are both considered as one tool within this report because of their close similarities and applications (and because APEX is based on EPIC). Although COMET-Farm and COMET-Planner use the same GHG estimation methodology and COMET-Planner is based on COMET-Farm, these two have different applications and will be considered separately. It should be noted that DayCent is a component of COMET-Farm but is not the only methodology Comet-Farm incorporates into its estimations. This section offers a brief high-level summary of these eight tools, with more detailed information framed as a SWOT analysis pertaining to each tool represented in the appendix.

### *a) Emissions modelled*

All of the tools model carbon dioxide ($CO_2$) and nitrous oxide ($N_2O$), simulate carbon sequestration, and include measurements for manure management (note that DNDC has a supplementary Manure-DNDC tool that produces more comprehensive manure management simulations than the primary DNDC tool). Holos, DayCent, IFSM, COOL-Farm, COMET-Farm, and COMET-Planner also model methane ($CH_4$). All tools measure enteric emissions (*see footnote*[52] *for definition*) except DayCent, Comet-Planner, and EPIC/APEX, though DNDC only measures enteric emissions through the Manure-DNDC model. EPIC/APEX can simulate emissions for forested areas and wetlands, while DNDC can do so if used alongside supplementary Forest-DNDC and Wetland-DNDC tools. IFSM can model forest emissions as land use change. DayCent and IFSM do not estimate GHG emissions for forested areas.

Holos, IFSM, and EPIC/APEX include upstream (*see footnote*[53] *for definition*) emissions calculations for pesticides, while COOL-Farm only partially models pesticide impacts. All models except DNDC measure on-farm and/or off-farm emissions associated with fuel and energy use.

---

[51] *All references and citations for information to this section can be found in corresponding appendices.*

[52] *For a definition of Enteric Methane, see* US EPA, "AP-42, CH 14.4: Enteric Fermentation - Greenhouse Gases," 14.4-1, https://www3.epa.gov/ttnchie1/ap42/ch14/final/c14s04.pdf.; "Enteric fermentation is fermentation that takes place in the digestive systems of animals. In particular, ruminant animals (cattle, buffalo, sheep, goats, and camels) have a large "fore-stomach," or rumen, within which microbial fermentation breaks down food into soluble products that can be utilized by the animal."

[53] *For an example of Upstream Emissions, see* World Resources Institute & World Business Council for Sustainable Development, "Greenhouse Gas Protocol," 10 (n.d.), https://ghgprotocol.org/sites/default/files/standards/GHG%20Protocol%20Agricultural%20Guidance%20%28April%2026%29_0.pdf.; "Upstream companies include manufacturers of farm inputs, such as seeds, fertilizers, herbicides, and pesticides."

### *b) Accuracy*

Three of the tools evaluated—Holos, COMET-Planner, and COOL-Farm--rely on emission factors to calculate expected emissions for various farm-management practices and systems. These tools are often user friendly but produce outputs that are less accurate and site-specific than the process-based models that are represented by the other four included in this report (DayCent, IFSM, DNDC, and EPIC/APEX). COMET-Farm's methodology is a combination of emissions factors and process based modelling, and thus COMET-Farm uses both process-based measurements and emissions factors.

Other accuracy considerations include the models' time-step, where both Holos and COOL-farm model emissions use a yearly-time step that produces less accurate outputs than the daily time-step employed by the other six tools, as well as the IPCC tier methodology—COMET-Farm and COMET-Planner use tier 1, 2, and 3 methodology; Cool-Farm uses tiers 1 and 2; IFSM uses tier 2; Holos uses tiers 2 and 3; and DayCent, DNDC, and EPIC/APEX use tier 3.

### *c) Opportunities*

Many of the opportunities described for each tool regard ongoing research and development. Some tools also have other features that can be used for other policy initiatives outside of modelling emissions. For example, all tools reviewed, except COOL-Farm and older Holos versions (*see footnote*[54]), offer some outputs regarding water quality (Holos' newest version will also include these calculations for water). COOL-Farm is the only tool reviewed that models water footprint and biodiversity. Holos, IFSM, and EPIC/APEX also include economic analyses for management changes modeled by the tool.

Many of the tools are used in other programs or by other organizations that may work synergistically with Vermont policy, such as the USDA's use of EPIC/APEX for CEAP and SWAT.

All tools except DNDC and DayCent are free and easy to download from the internet. For DNDC, free access may be contingent on contacting the University of New Hampshire and signing a waiver to use the tool for strictly research purposes. DayCent is free and available upon request from the University of Colorado. Agriculture and Agri-Food Canada have supported Holos for the past two decades. DayCent, EPIC/APEX, Comet-Farm, Comet-Planner, Holos and IFSM receive robust support from their host organizations.

### *d) Threats*

---

[54] *Distinction of Holos versions specified because of the recency of the newest versions release; at the time of writing, ongoing applications of Holos measurements that have not yet transitioned to the new version—and all but the most recent existing research—will be based on older Holos versions.*

The most common threats for tools are based on a tool's difficulty, where the more sophisticated models–DNDC, DayCent, EPIC/APEX, IFSM–require users to have advanced training. This threatens the tool's applicability for modelling Vermont farm emissions because there may be a shortage of qualified technicians to use the models.

Additionally, the outputs of any model are only as good as the inputs and will need regular updates to reflect current management. In this way, models are threatened by the burden of data entry, poor data quality, inaccessible data, or limited resources for compiling sufficient data.

## 5) Example Applications

This section will give an overview of three examples of greenhouse gas modelling tools being used to measure emissions, and then describe each in detail.

The Farm Level Environmental Assessment of Organic Dairy Systems in the U.S (FLEAODS) was developed by Dr. Horacio Aguirre-Villegas at the University of Wisconsin and is currently utilized by Organic Valley. FLEAODS carefully coordinates IFSM outputs alongside several other information sources (for example, other available software and emissions factors and USDA databases for weather and crop yields calibrated to different areas of the U.S.) through Excel to create a comprehensive LCA for organic dairy farms. Though this LCA does not currently include the range of land uses needed to be applicable in Vermont (notably, it does not incorporate forest land), ongoing developments aim to expand the range of land uses. This LCA is a good example for developing a framework to measure whole farm emissions that addresses the limitations of using a single modelling tool, but which requires robust technical assistance to use effectively.

The Logiag Carbon Project aims to help farmers determine management changes to reduce emissions. Logiag couples strong reliance on Holos based calculations with supplementary information sources, like government geospatial data. An important characteristic of Logiag's approach is its reliance on historical farm data to create a baseline against which farmers can make comparative emissions reductions. While this approach is not highly accurate and does not yield results that can be comparable between different farms, it shows a strategy for modelling emissions that can be done by farmers with minimal or no technical assistance and may identify practices or fields where the biggest impact on GHG emissions may take place.

The He Waka Eke Noa Primary Sector Climate Action Partnership does not include any of the tools reviewed in this report. However, it does demonstrate a strategy designed by farmer initiative. It relies on farmers' self-reporting in a regulatory context to generate estimates of on-farm emissions. Currently, He Waka Eke Noa is pursuing a strategy that uses a central calculator (still to be designed) that all eligible farmers can record data into and that would, ideally, allow other emissions tracking tools to seamlessly import their data.

### A) FLEAODS[55]

This LCA aims to calculate whole-farm emissions for organic dairy farms in the U.S. Although the current model only considers emissions for dairy production—as well as crops linked to those production systems— the research team of Dr. Aguirre-Villegas also evaluated beef systems and ongoing research aims to expand the farm boundaries to include emissions from other landscape features like forested areas and wetlands.

The LCA combines various tools and models into a framework within Excel to relate different farm practices and characteristics to emissions related to farm activities. Emissions from manure collection, manure storage, and related activities are calculated from IFSM. Simapro LCA software[56] is used for emissions produced from on-farm energy and other materials (e.g., fertilizers, feed supplements, etc.) and IPCC emission factors are used for $N_2O$ emissions from manure deposition on grassland.

All data are regionally calibrated by leveraging data sources like crop yields from USDA records, meteorological data for rainfall and other weather factors, and regional energy supply information for electrical and energy use. To accommodate the various tools, the LCA includes methods linked to IPCC Tiers 1, 2, and 3 (for example, $CH_4$ emissions from manure storage are for Tier 3, but manure $N_2O$ emissions are for Tier 1).

Developing and calibrating the LCA required extensive data collection from real farms within each region, which Dr. Aguirre-Villegas says is a great strength of this LCA over others. As with other LCAs, FLEAODS is vulnerable to inaccuracies due to the various assumptions and data sets used to generate emissions calculations. Furthermore, because FLEAODS is an amalgamation of multiple models that each use their own data sets and assumptions, the different models may include different calculations for emissions depending on the methodology that model applies.

While this LCA is already parameterized for different regions—including the northeast United States—using the model for the purpose of calculating emissions for a Vermont PES program or to inform policy for the GWSA would require modifying the data for state-specific variations like differences in forages, climatic conditions, and soil types. Fortuitously for developing Vermont policy, this LCA already includes outputs—such as nutrient runoff—that are relevant to ecosystem services other than carbon storage, and ongoing research aims to expand those calculations to include other environmental factors. Furthermore, the LCA places a greater emphasis on carbon sequestration than other models.

The Organic Valley LCA is more approachable than some of the more complex process-based tools and could be more readily employed across Vermont's agriculture sector. Still, the

---

[55] All following information is from Horacio Aguirre-Villegas, Personal Interview, March 7, 2022, except where otherwise noted. *Also see* UVM Extension Northwest Crops and Soils Program, "Dairy Webinar Series: Green House Gas Emissions on Organic Dairy," (March 2, 2022), https://www.youtube.com/watch?v=3Thg-uatTg8.

[56] Simapro, "LCA Software for Informed Change-makers," (accessed 3/7/22), https://simapro.com/.

range of data input required and the cruciality of using the most accurate data available means that users should receive some level of training.

B) Logiag Carbon Project[57]

The Logiag Carbon Project is a framework for estimating whole farm emissions using the Holos tool and aims to help farms strategize methods to reduce emissions but does not consist of an environmental assessment or lifecycle analysis. The framework does not incorporate all outputs that can be generated by Holos. It also supplements Holos with some calculations that the software does not cover and adapts some parameters to be more site-specific. Logiag also leverages data—mostly related to provincial regulatory elements of production and phosphorus reduction—from its register of thousands of Quebec farms that employ Logiag as an agronomy service provider, as well as government data for information regarding bodies of water and woodlands.

The estimated values resulting from the framework include Scope 1 emissions, like those from crops and soil, fossil fuel combustion, livestock, land-use change, and tree planting of windbreaks (but not forestland); Scope 2 emissions like imported electricity; and Scope 3 emissions like those from mineral fertilizer and herbicide production.[58] Logiag recognizes that their inventory does not include all Scope 3 emissions from upstream and downstream activities like transportation of goods to and off farm. Logiag's inventory and greenhouse gas declarations follow international standards, and mathematical calculations are based on the 2006 IPCC guidance.[59]

The Carbon Project estimates emissions by first setting a boundary to differentiate between emissions within the farm and those outside of the farm. Farm and field boundaries relevant to the analysis correspond to areas declared in each farm's Agro-Environmental Fertilizer Plan (AEFP), indicating that Logiag's inventory does not account for non-crop land.[60] Logiag then creates a baseline with three years of historical farm data. It estimates emissions for $CO_2$, $N_2O$, and $CH_4$, which are calculated into units of $CO_2$ equivalents ($CO_2e$) to facilitate comparisons. By

---

[57] All following information is from Logiag, "Farm Greenhouse Gas Emissions Inventory: For Jacques Nault's Farm," (Juse 2021), https://docs.google.com/document/d/1bn13Da21yK7br2nwVMjFpIsU7Escmd3THFf-pn4Xoao/edit, [*hereinafter* Logiag], except where otherwise noted.

[58] For a definition of emissions scopes, *See:* Carbon Trust, "Briefing: What are Scope 3 emissions?," (2022), https://www.carbontrust.com/resources/briefing-what-are-scope-3-emissions. "Scope *Greenhouse gas emissions are categorised into three groups or 'Scopes' by the most widely-used international accounting tool, the Greenhouse Gas (GHG) Protocol. Scope 1 covers direct emissions from owned or controlled sources. Scope 2 covers indirect emissions from the generation of purchased electricity, steam, heating and cooling consumed by the reporting company. Scope 3 includes all other indirect emissions that occur in a company's value chain.*

[59] *See* Logiag; "*To produce the inventory, Logiag referred to the Greenhouse Gas Protocol (GHG Protocol Agricultural Guidance) and ISO 14064-1 for guiding principles on the quantification and disclosure of GHG sources and sinks. Both guides present a normative framework for measuring, managing, and reporting a farm's GHG emissions."*

[60] *Id.*; *also see* "[chapter Q-2, r. 26 Environment Quality Act: Agricultural Operations Regulation Division IV (3)] *and* [chapter Q-2, r. 26 Environment Quality Act: Agricultural Operations Regulation Division IV (22)] *for a definition of Quebec 'Agro-*environmental *fertilization plan.'*

combining farm management information and data from the sources listed above into Holos, Logiag can correlate estimated emission levels with changes in farm management by comparing against the baseline calculated from historical data.

Logiag's analysis is currently only applicable to Canadian farms because of its reliance on Holos; however, the summary for Holos included in this report indicates that the tool could be calibrated to Vermont conditions.[61] Alternatively, a similar tool could be substituted in and used within the same framework.

C) He Waka Eke Noa Primary Sector Climate Action Partnership

The circumstances surrounding the He Waka Eke Noa Primary Sector Climate Action Partnership share many similarities with those of the Vermont farming community and the PES Working Group. The partnership is a collaboration between Maori, New Zealand government, and industry leaders to reduce agricultural greenhouse gas emissions,[62] and is currently undertaking its second year of a five-year initiative developed in response to the government's proposal to meet legislative emissions reduction requirements by pricing agricultural greenhouse gas emissions through the New Zealand Emissions Trading Scheme (ETS).[63]

The collaborators issued a proposal to the government in October 2019 for the groups to work together to design an alternative to the government proposed solution that is "practical and cost-effective system for reducing emissions at the farm level by 2025."[64] Some primary aims of the partners are to include carbon-sequestration within the pricing system—which is currently excluded from the ETS—and to measure $CH_4$ separately.[65]

Some key milestones that the collaboration plans to accomplish include a) by the end of 2021, having 25% of farms know their annual emissions and 25% developing plans to measure and manage emissions, b) presenting a carbon pricing system to ministers in April 2022, c) having 100% of farms completed emissions calculations by the end of 2022, d) completing a pilot project to test a system for farm level accounting and reporting by the end of 2023, and e) having all farms maintain a written plan to measure and manage greenhouse gas emissions, and f) launch a market ready on-farm pricing system.[66]

---

[61] Roland Kröbel personal interview, January 27, 2022. [*hereinafter* Kröbel Interview].

[62] He Waka Eke Noa Primary Sector Climate Action Partnership, "About," (accessed 3/7/22), https://hewakaekenoa.nz/about/. [*hereinafter* About He Waka Eke Noa].

[63] Dairy NZ, "He Waka Eke Noa," (accessed 3/7/22), https://www.dairynz.co.nz/environment/climate-change/he-waka-eke-noa/.

[64] *See* About He Waka Eke Noa.

[65] *Id.*

[66] He Waka Eke Noa Primary Sector Climate Action Partnership, "Our Work: The Five-year Programme," (accessed 3/7/22), https://hewakaekenoa.nz/our-work/#sec-programme.

The collaborators' proposed options so far include a farm-level tax and a processor-level hybrid tax.[67] The farm-level tax is based on net emissions, with rewards for sequestration and lower emissions costs for farmers that took early action.[68] The processor-level hybrid tax emissions are calculated for the meat, milk, and fertiliser processing stages. The cost of this tax is passed on to farmers by processors, who may offer farmers emissions management contracts to incentivize select management strategies that sequester carbon or reduce emissions.[69] While early action farmers are not rewarded here, overall administrative costs are lower than the farm-level tax.[70]

He Waka Eke Noa currently supports the farm-level tax as the best option. A critical component in this program design is a central calculator for on-farm emissions that all eligible farmers and growers can capture and record data into[71] that would, ideally, allow an easy pathway for current emissions tracking tools to import data.[72] He Waka Eke Noa has reviewed available farm-level modelling tools that farmers could use to perform their own calculations,[73] but the central calculator has not yet been developed.[74] It is important to note that as a part of program design, on-farm audits would only take place when reported emissions are outside of normal ranges.[75] He Waka Eke Noa is currently deliberating between a simple calculation option that recognizes farms for a range of farm management improvements that result in reductions calculated according to industry averages, or a detailed method that costs more but also captures emissions from adopting on-farm efficiencies.[76]

The initial design of He Waka Eke Noa does not include all possible emissions sinks and sources.[77] For instance, the proposed program design is not currently considering wetlands as carbon sinks because of their complexity, but plans to do so in the future.[78] Soil carbon sequestration is also "unlikely to be recognized within the first stages of implementation" because the collaborators recognize more research is needed first.[79] Energy use, because it is

---

[67] He Waka Eke Noa Primary Sector Climate Action Partnership, "He Waka Eke Noa Agricultural Emissions Pricing Options," *Consultation Document*, (February 2022), https://www.dairynz.co.nz/media/5795066/consultation-document_final.pdf. [*hereinafter* Pricing Options].

[68] *Id.* at 5.

[69] *Id.*

[70] *Id.* at 5-6.

[71] *Id.* at 18.

[72] *Id.*

[73] Phil Journeaux, Louis Batley, & Erica van Reenan, "Review of Models Calculating Farm Level GHG Emissions #2: Prepared for He Waka Eke Noa," *AgFirst*, (May 2021), https://hewakaekenoa.nz/wp-content/uploads/2021/05/Review-of-Models-Calculating-Farm-Level-GHG-Emissions-2-June-2021.pdf. [*hereinafter* Models Review].

[74] *See* Pricing Options at 16.

[75] *Id.* at 18.

[76] *Id.*

[77] He Waka Eke Noa Primary Sector Climate Action Partnership, "He Waka Eke Noa Frequently Asked Questions," (accessed 3/7/22), https://hewakaekenoa.nz/faqs/.

[78] *Id.*

[79] *Id.*

already accounted for in New Zealand's ETS, will also not be covered in the emission budget.[80] However, forest land will likely be included as a carbon sink but will be attributed to a different emissions inventory because of New Zealand regulations like the Zero-Carbon Act, which stipulates that $CH_4$ emissions cannot be offset directly through forest sequestration.[81]

## 6) Conclusion

The tools listed in this report present several options for measuring whole-farm emissions in Vermont. The information here can aid the Subcommittee and the PES Working Group to select a tool or suite of tools that is best suited to meeting their objectives.

Based on the framework outlined by the World Bank and FAO, and on the information presented regarding the tools, the primary factors that Vermont policymakers will need to outline before moving forward are 1) data availability and resources to allocate for data collection, 2) the level of output accuracy that is being sought (i.e. the degree of uncertainty the groups are willing to accept), or that is necessary to fulfill GWSA requirements, and 3) the amount of resources that can be allocated to hiring and training technicians, respective to the different skill levels needed to use each tool effectively. In a scenario of ample resources it would be possible to collect extensive data and deploy trained technicians to generate highly accurate simulations with tools like DNDC or EPIC/APEX. In another scenario of low resources, Vermont could use bookkeeping models with emissions factors and rely on farmers to input their own data using tools like Holos, Cool-Farm, COMET-Farm, or COMET-Planner. IFSM requires medium level of data input and technician training (*see footnote*[82]*)*.

Additionally, determinations need to be made regarding the whole range of objectives that a chosen tool will need to fulfill. If the tool is to be used solely for measuring whole-farm emissions with no other policy applications it can then be assessed strictly on its own merits for modelling emissions. As shown by the LCA used by Organic Valley, and by Logiag's Carbon Project, a tool that has some information gaps can still be used effectively alongside supplementary data sources.

But if the tool were to be used in a PES system, then other factors—like other services measured by the tool, or what tool is regarded as credible by possible 'buyers' participating in a PES program—become more important. Choosing a model that aligns with another organization or program is likely to be an important factor outside of PES applications, both for perceived

---

[80] *Id.*

[81] *See* Models Review at 24.

[82] Clarence Rotz related during his interview that, in his experience as a highly trained user of the IFSM, a whole farm data collection will take about 4 hours.

credibility but also for resource efficiency and to reduce the amount of times individual farms must gather information for, take measurements for, or enter data into different models.

Whichever tool is chosen, policy surrounding the tool's use should avoid "carbon tunnel vision" by considering emission reduction strategies within the context of their environmental, social, and economic implications,[83] and "an integrated approach is needed to avoid pollution swapping (i.e. leaching) when selecting among GHG mitigation options."[84] Similarly, a Vermont program that quantifies farm-level greenhouse gas emissions could also use the built-in economic analyses present in several of the tools to evaluate social and economic impacts, though a tool without such analyses could incorporate social and economic factors through policy design.

---

[83] *See* Jensen.

[84] *See* Del Prado et al.

# APPENDICES

---

[85] *Data for this chart was taken from user manuals describing inputs for these tools. We tried to frame inputs as the model developers framed them, but in some cases we consolidated similar groups of inputs for brevity.*

[86] *Data in these charts for the eight tools reviewed in this report can be cited to sources listed in the report. However, Ex-Act and SIT (marked with an asterisk), were covered less extensively in the report. Information in this chart can be found in the following sources.*

**Ex-Act**
1. E. Milne, et a., “Methods for the quantification of emissions at the landscape level for developing countries in smallholder contexts: CCAFS Report No. 9,” CGIAR Research Program on Climate Change Agriculture and Food Security (CCAFS), (2012). https://cgspace.cgiar.org/bitstream/handle/10568/24835/CCAFS9%20WEB%20FINAL.pdf
2. Louis Bockel, Uwe Grewer, Chlo Fernandez, & Martial Bernoux , "EX-ACT User Manual: Estimating and Targeting Greenhouse Gas Mitigation in Agriculture," FAO, IRD, & World Bank, (n.d.).
3. https://documents1.worldbank.org/curated/en/611041487662158062/pdf/112809-WP-EX-ACTUserManuaFinal-WB-FAO-IRD-PUBLIC.pdf

**SIT**
1. CF International, “Assessment of the Comparability of Greenhouse Gas and Black Carbon Emissions Inventories in North America,” Commission for Environmental Cooperation, (2012). http://www.cec.org/files/documents/publications/10938-assessment-comparability-greenhouse-gas-and-black-carbon-emissions-inventories-en.pdf
2. ICF International, “User’s Guide for Estimating Carbon Dioxide, Methane, and Nitrous Oxide Emissions from Agriculture Using the State Inventory Tool,” State Energy and Environment Program, U.S. Environmental Protection Agency, (2022)

## APPENDIX 1: Holos[87]

Summary

The Holos tool is a bookkeeping model that uses IPCC Tier 2 emissions factors to produce estimates of $CO_2$, $N_2O$, and $CH_4$ emissions based on management practices for individual farms[88] on a yearly time-step.[89] The version currently available on the government website is 4.0, released March 16, 2022, which aims to "provide a deeper look at practices that affect soil carbon levels"[90] and will include a new shelterbelt and anaerobic digestion component alongside a number of updates to existing components.[91] Agriculture and Agri-Food Canada have provided robust support for Holos for the last two decades.

Holos was designed to help project the outcomes of different management scenarios to inform management decisions and is intended as an exploratory, rather than accounting, tool.[92] However, the outputs from the tool are still accurate inventories (depending on the accuracy of inputs) and can be used for accounting emissions.[93]

To generate an emissions inventory with Holos, users select from amongst various scenarios that best describe an individual farm before adding more detailed information specific to their unique circumstances.[94] The program is intentionally designed to simplify the accounting process by using default values as much as possible to calculate results, but while also allowing the opportunity to override those default values to generate more accurate outcomes.[95] The Holos 3.0.6 model includes options for 18 major crops (now "greatly expanded" in version 4.0) with detailed estimates for beef, dairy, swine, and poultry, and less detailed estimates for other

---

https://www.epa.gov/system/files/documents/2022-03/ag-module-users-guide.pdf

3. ICF International, "User's Guide for Estimating Emissions and Sinks From Land Use, Land-Use Change, and Forestry Using the State Inventory Tool," State Energy and Environment Program, U.S. Environmental Protection Agency, (2022).

[87] Government of Canada, "Holos Software Program," (01-24-2020), https://agriculture.canada.ca/en/agricultural-science-and-innovation/agricultural-research-results/holos-software-program. [*hereinafter* Agri-Food Canada].

[88] *Id.*

[89] Karen A.Beauchemin et al., "Life cycle assessment of greenhouse gas emissions from beef production in western Canada: A case study," *Agricultural Systems,* (2010), https://www.sciencedirect.com/science/article/abs/pii/S0308521X10000387?via%3Dihub.

[90] Piper Whelan, "Researchers see producer feedback on environmental assessment software," *Canadian Cattlemen: The Beef Magazine,* (July 8, 2020), https://www.canadiancattlemen.ca/features/researchers-seek-producer-feedback-on-environmental-assessment-software/. *Also see* Kröbel et al., "The Canadian whole-farm Model Holos-development of the new Version 4," *American Geophysical Union* (2020), https://ui.adsabs.harvard.edu/abs/2020AGUFMGC0990007K/abstract. [*hereinafter*

[91] *See* Agri-Food Canada.

[92] Kathryn Slebodnik et al., "Holos as a Greenhouse Gas Estimation Tool for Animal Agriculture Northern Utah," (2020), https://projects.sare.org/wp-content/uploads/Holos-Factsheet_Version4.pdf. [*hereinafter* Slebodnik et al.].

[93] *See* Kröbel interview.

[94] Roland Kröbel et al., "Demonstrations and Testing of the Improved Shelterbelt Component in the Holos Model," *Environmental Science* (2020), https://www.frontiersin.org/articles/10.3389/fenvs.2020.00149/full. [*hereinafter* Kröbel et al.]

[95] *See* Kröbel interview.

livestock.[96] Estimates for emissions are calculated from this management information using algorithms based on IPCC methods but modified for Canadian conditions.[97] Summary calculations for net outcomes are expressed as CO2 equivalent (CO2eq),[98] though reports that distinguish between CH4, NO2, and CO2 can also be generated.[99]

Holos is based on IPCC tier 2 and 3 methodologies, with modifications for Canadian conditions.[100] Carbon storage calculations were based on the "methodology developed for the National Inventory Report, the Canadian Agriculture Monitoring Accounting and Reporting System (CanAG-MARS)," which includes calculations for changes in tillage practice, use of fallow, percentage of perennial crops, and areas of permanent cover.[101] In Version 4.0, the Holos model features both the IPCC Tier 2 carbon model (based on the widely used CENTURY model) and also the Introductory Carbon Balance model (ICBM) to permit a more detailed assessment of soil carbon change due to crop rotation and residue management practices.[102]

Strengths

The two great strengths of the Holos software are 1) its adaptability, as it was designed to accommodate user modification, and 2) its simplicity, which allows the software to be used beyond research to also inform decisions by farmers and policymakers.[103]

Although the $N_2O$ algorithms for Holos are calibrated to Canadian conditions and so do not accurately reflect those of Vermont, Holos "can be applied to regions with similar climates in the United States … by manually overriding soil and climatic parameters when used with a proper understanding of its design and limitations."[104]

The livestock calculations (enteric $CH_4$) and carbon change estimates can be readily utilized, emission factors for manure storage and application, however, might require verification, despite their temperature adjustment.

Holos aims to calculate emissions based on the farm as an integrated whole, rather than the sum of its parts, and its projections take into account the interactions of different

---

[96] *Id.*
[97] *See* Slebodnik et al.
[98] *Id.*
[99] *See* Kröbel interview.
[100] E.J. McGeough et al., "Life-cycle assessment of greenhouse gas emissions from dairy production in Easter Canada: A case study," *Journal of Diary Science*, (2012), https://www.sciencedirect.com/science/article/pii/S0022030212005322.
[101] *Id.*, at 19.
[102] *Id.*.; Also *see* Alister K. Metherell, Laura A. Harding, C. Vernon Cole, & William J. Parton, "CENTURY Soil Organic Matter Model Environment," (1993), https://www2.nrel.colostate.edu/projects/century/MANUAL/html_manual/man96.html.; *Also see* FAO, "Measuring and modelling soil carbon stocks and stock changes in livestock production systems," 17 (2019), https://www.fao.org/3/ca2933en/CA2933EN.pdf.
[103] *Id.*
[104] *See* Slebodnik et al.

components.[105] Emissions that are calculated for farm activities include manufacture and transport for farm inputs like fertilizer and herbicide.[106] Carbon storage for lineal tree plantings, farm shelterbelts, and riparian plantings is included in the estimates.[107]

Holos projects estimates for individual farms and may not be applicable for a state- or sector-wide assessment.[108]

Weaknesses

Holos is not intended to inventory emissions, and instead is better suited for strategizing management to reduce emissions.[109] Although lineal tree plantings, etc., are included in the estimates, the model "does not calculate storage or emissions from managed, long-established or natural woodlots."[110] Although the Holos algorithms can be manually overridden to better reflect Vermont, doing so requires a sophisticated understanding of the software's design and limitations.[111]

Though the program's ease-of-use is counted above as a strength, the model's corresponding simplicity also threatens the tool's accuracy if the appropriate data is not overridden for greater specificity.[112] Additionally, although the tool is simple and easy to understand, the actual process of data entry can be time consuming.[113]

Opportunities

Holos is free to download through the Agriculture and Agri-Food Canada website.[114] The tool can also be used to measure Life-Cycle Assessments and to establish baseline measurements for tracking progress of reducing farm emissions, as was done by Logiag (*see footnote*[115]).

Because the tool is widely usable it can be applied to many decision-making processes beyond the farm, including policy or education.[116]

---

[105] *See* Kröbel et al.
[106] Agriculture and Agri-Food Canada, "Holos: A tool to estimate and reduce GHGs from farms," 10 (2008), https://publications.gc.ca/collections/collection_2009/agr/A52-136-2008E.pdf. [*hereinafter* Holos Guidebook].
[107] *Id.*, at 44.
[108] Aditi Maheshwari, "Automating and Analyzing Whole-Farm Carbon Models," *Graduate Thesis: Utah State University*, 12 (2020), https://digitalcommons.usu.edu/etd/7869/.
[109] *See* Slebodnik et al.
[110] *See* Holos Guidebook at 44.
[111] *See* Slebodnik et al.
[112] *See* Kröbel interview.
[113] Vincent Colomb et al., "Review of GHG Calculators in Agriculture and Forestry Sectors," UN Food and Agriculture Organization, 8 (June 2012), https://www.fao.org/fileadmin/templates/ex_act/pdf/Review_existingGHGtool_GB.pdf.
[114] *See* Agri-Food Canada.; Training *Documents can be found at:* https://drive.google.com/file/d/13A1j-Vjrlz6HshXjIt1EQlL-D9pIEHer/view.
[115] Logiag, "Farm Greenhouse Gas Emissions Inventory: For Jacques Nault's Farm," (Juse 2021), https://docs.google.com/document/d/1bn13Da21yK7br2nwVMjFpIsU7Escmd3THFf-pn4Xoao/edit.
[116] *See* Kröbel interview.

Additionally, the adaptability of the software means that it can be applied to uses other than emissions modelling, such as for PES programs.[117] Adapting the tool in this way will require utilizing what it already outputs into something that represents an ecosystem service—for example, Holos' current design to calculate $N_2O$ emissions is based on a factor of how much nitrate is leached, which could be transferred into a water quality assessment.[118]

<u>Threats</u>

Manually overriding the program to better reflect Vermont requires a sophisticated understanding of the software that will be difficult for many individuals.[119] Holos is updated every few years to reflect new data or technological advancements, which will pose a particular problem if the program needs to be overridden again to reflect Vermont's conditions.[120]

Although older versions of the model were free to download, and although Holos version 4.0's calculation core will be released open source, the interface of Holos version 4.0 cannot be released as open source due to having proprietary software until the tool's programmers can design it as an open-source HTML interface.[121]

---

[117] *Id.*
[118] *Id.*
[119] *See* Slebodnik et al.
[120] *Id.*
[121] *See* Kröbel interview.

## APPENDIX 2: DayCent

### Summary

"DAYCENT is the daily time-step version of the CENTURY biogeochemical model."[122] Simulation time steps for soil process are simulated on a daily or finer scale, vegetation production daily, and management practices daily. DayCent uses the IPCC Tier 3 three approach for calculating greenhouse gas (GHG) emissions which "use complex simulation models or extension monitoring systems."[123] Based on weather, field management practices, vegetation, soil type, fuel use, and other parameters, it estimates GHG emissions ($N_2O$, $NO_X$, $N_2$, $CO_2$), carbon sequestration, leaching of $NO_3$, and net primary production, and other ecosystem parameters.[124,125] It is used as the underlying model for COMET-Farm.[126] See Figure 1 at the end of this document for a diagram of the model flow.

### Strengths

DayCent is a process-based model and has some life cycle analysis assessments (biofuel).[127] DayCent is a widely recognized tool and components of it are included in Comet-Farm. It is currently used by the US EPA, USDA, and Colorado State University to create a national $N_2O$ inventory for U.S. agricultural soils. These results are different from the IPCC's U.S. emissions inventory as the IPCC uses emissions factors (as opposed to process-based modeling).[128] For example, IPCC assumes nitrogen applied in one year is used that year while DayCent can account for legacy nitrogen from previous applications.[129] Following IPCC guidelines, DayCent models indirect $N_2O$ emissions. DayCent has been accessible for decades and compared to other models in peer-reviewed journal publications.

DayCent is well supported and has had recent improvements including moving from weekly vegetation production and monthly management practice time-steps to daily. It has been

---

[122] Colorado State University. (2012 DayCent. https://www2.nrel.colostate.edu/projects/daycent/
[123] Del Grosso, Stephen. S. Davis, and P. Adler. (2012). DayCent Model Simulations for Estimating Soil Carbon Dynamics and Greenhouse Gas Fluxes from Agricultural Production Systems. Managing Agricultural Greenhouse Gases. doi:10.1016/B978-0-12-386897-8.00014-0
[124] Colorado State University. (2012). DayCent. https://www2.nrel.colostate.edu/projects/daycent/
[125] Del Grosso, Stephen, A. Mosier, W. Parton, and D. Ojima. (2005). DAYCENT model analysis of past and contemporary soil N2O and net greenhouse gas flux for major crops in the USA. Soil & Tillage Research 83 (9-24). doi:10.1016/j.still.2005.02.007.
[126] Steenworth, K.L., X. Barker, M. Carlson, K. Killian, M. Easter, A. Awan, L. Thompson, S. Williams, and K. Paustian (2016) Developing COMET-Farm and the DayCent Model for California Specialty Crops. Abstract. American Geophysical Union, Fall Meeting.
[127] Del Grosso, Stephen. S. Davis, and P. Adler. (2012). DayCent Model Simulations for Estimating Soil Carbon Dynamics and Greenhouse Gas Fluxes from Agricultural Production Systems. Managing Agricultural Greenhouse Gases. doi:10.1016/B978-0-12-386897-8.00014-0
[128] Del Grosso, Stephen, A. Mosier, W. Parton, and D. Ojima. (2005). DAYCENT model analysis of past and contemporary soil N2O and net greenhouse gas flux for major crops in the USA. Soil & Tillage Research 83 (9-24). doi:10.1016/j.still.2005.02.007.
[129] *Id.*

adapted to include specialty crops for use in California.[130] Furthermore, DayCent is calibrated with field research,[131] but this field research is limited by its locations and may not be representative of all growing conditions in the U.S.

DayCent is able to simulate average crop production by state with reasonable accuracy for many common crops.[132] Inputs for DayCent are easy to acquire and DayCent can be used to estimate impacts on GHG emission of changing cropping systems at the regional scale (e.g. corn ethanol to miscanthus or switchgrass)[133] or management practices (e.g. conventional tillage to no-till).[134] "Results from DAYCENT suggest that conversion to no tillage at the national scale could mitigate 20% of USA agricultural emission or 1.5% of total USA emission of greenhouse gases."[135] DayCent can model outcomes based on climate change e.g. extreme weather scenarios and increased levels of $CO_2$ in the atmosphere.[136]

Weaknesses

In order to generate site-specific estimates, a high level of user data input is required and some amount of transparency is lost with more complex calculations.[137] Due to the robustness of DayCent, programming expertise and sophisticated software is required to keep the model relevant and current.[138] DayCent is better calibrated for growing conditions in some states than others. Although DayCent does not calculate GHG from fuel emissions on farms, or emissions from manufacture and transportation of farm inputs, model outputs can be combined with other methods to perform life cycle assessments (e.g., Adler P.R, Del Grosso, S.J and Parton, W.J. 2007. Life cycle assessment of net greenhouse gas flux for bioenergy cropping systems. Ecological Applications. 17(3):675–691).

Although DayCent, "simulates decomposition and nutrient mineralization of plant litter and soil organic matter, plant growth and senescence, and soil water and temperature fluxes," it

---

[130] Steenworth, K.L., X. Barker, M. Carlson, K. Killian, M. Easter, A. Awan, L. Thompson, S. Williams, and K. Paustian (2016) Developing COMET-Farm and the DayCent Model for California Specialty Crops. Abstract. American Geophysical Union, Fall Meeting.
[131] Del Grosso, Stephen. Personal communication. February 15, 2022.
[132] Del Grosso, Stephen, A. Mosier, W. Parton, and D. Ojima. (2005). DAYCENT model analysis of past and contemporary soil N2O and net greenhouse gas flux for major crops in the USA. Soil & Tillage Research 83 (9-24). doi:10.1016/j.still.2005.02.007.
[133] Del Grosso, Stephen. S. Davis, and P. Adler. (2012). DayCent Model Simulations for Estimating Soil Carbon Dynamics and Greenhouse Gas Fluxes from Agricultural Production Systems. Managing Agricultural Greenhouse Gases. doi:10.1016/B978-0-12-386897-8.00014-0
[134] Del Grosso, Stephen, A. Mosier, W. Parton, and D. Ojima. (2005). DAYCENT model analysis of past and contemporary soil N2O and net greenhouse gas flux for major crops in the USA. Soil & Tillage Research 83 (9-24). doi:10.1016/j.still.2005.02.007.
[135] *Id.*
[136] Del Grosso, Stephen. Personal communication. February 15, 2022.
[137] Del Grosso, Stephen. S. Davis, and P. Adler. (2012). DayCent Model Simulations for Estimating Soil Carbon Dynamics and Greenhouse Gas Fluxes from Agricultural Production Systems. Managing Agricultural Greenhouse Gases. doi:10.1016/B978-0-12-386897-8.00014-0
[138] *Id.*

is not a whole farm assessment. Although it is similar to DNDC (models use similar data sets, require similar inputs, and compute similar results (which reduced uncertainties)), DayCent does not explicitly represent soil microbial dynamics It does not quantify GHG emissions from manure storage.[139] Like most models, DayCent makes certain assumptions on data inputs (bulk density, C:N of vegetation, $NH_4$ confinement to top 15 cm, etc.).[140] Although DayCent can account for tile drainage when modeling $NO_3$ leaching, its assumptions are one dimensional meaning it does not factor topography or hydrology and therefore erosion into the analysis.[141] DayCent is designed to run simulations for major crops and grassland[142] and therefore may not be well suited for more diversified livestock operations or rice production.[143]

Opportunities

DayCent can be used to model the impact of different cropping systems or management practices on GHG emissions, reductions, or sequestration.[144] DayCent has been adapted to include elements of PH REdox EQuilibrium (PHREEQC; in C language) to form DayCent-Chem, a tool that models nutrient cycling (including $NO_3$, $NH_4$, and $SO_4$ loss into surface water) and GHGs in forests.[145] This model that utilizes DayCent for forests could be modified to be included in a Vermont whole-farm GHG and water quality assessment. Although DayCent defaults to nitrogen analysis for water quality, it does have a phosphorus sub-model. However, the phosphorus sub-model could benefit from more internal assessment to minimize uncertainties and incorporation of a hydrological model.

DayCent could be calibrated to better fit Vermont growing conditions. DayCent developers are working to increase experimental sites, compare model ensembles, add a soil microbial component, and create a global version (limited by global data sets e.g. weather and to major crops like rice, wheat, corn, cotton, rangeland, etc.). [146] DayCent development is subject to

---

[139] Del Grosso, Stephen. S. Davis, and P. Adler. (2012). DayCent Model Simulations for Estimating Soil Carbon Dynamics and Greenhouse Gas Fluxes from Agricultural Production Systems. Managing Agricultural Greenhouse Gases. doi:10.1016/B978-0-12-386897-8.00014-0

[140] *Id.*

[141] Del Grosso, Stephen. Personal communication. February 15, 2022.

[142] Del Grosso, Stephen. S. Davis, and P. Adler. (2012). DayCent Model Simulations for Estimating Soil Carbon Dynamics and Greenhouse Gas Fluxes from Agricultural Production Systems. Managing Agricultural Greenhouse Gases. doi:10.1016/B978-0-12-386897-8.00014-0

[143] Del Grosso, Stephen, A. Mosier, W. Parton, and D. Ojima. (2005). DAYCENT model analysis of past and contemporary soil N2O and net greenhouse gas flux for major crops in the USA. Soil & Tillage Research 83 (9-24). doi:10.1016/j.still.2005.02.007.

[144] Del Grosso, Stephen, D. Ojima, W. Parton, E., M. Heistemann, B. DeAngelo, S. Rose. (2009). Global scale DAYCENT model analysis of greenhouse gas emissions and mitigation strategies for cropped soils. Global and Planetary Change. Vol (67) 1–2, 44-50. doi: 10.1016/j.gloplacha.2008.12.006

[145] Hartman, Melanie, J. Baron, D. Clow. E. Creed, C. Driscoll, et. al. (2009). DayCent-Chem Simulations of Ecological and Biogeochemical Processes of Eight Mountain Ecosystems in the United States. Scientific Investigations Report 2009–5150. U.S. Department of the Interior, U.S. Geological Survey, in cooperation with Natural Resource Ecology Laboratory, Colorado State University.

[146] Del Grosso, Stephen. Personal communication. February 15, 2022.

funding and stakeholder priorities, one of which is quantifying GHG, water quality, and habitat benefits for a whole-system approach.[147]

Threats

As with all models, output is only as good as the input and algorithms. Algorithms and parameters are always subject to some internal and structural uncertainties.[148] However, rigorous uncertainty analysis of DayCent results have been performed (e.g., Gurung, R.B., Ogle, S.M., Breidt, F.J., Parton, W.J., Del Grosso, S.J., Zhang, Y., Hartman, M.D., Williams, S.A. and Venterea, R.T., 2021. Modeling nitrous oxide mitigation potential of enhanced efficiency nitrogen fertilizers from agricultural systems. Science of The Total Environment, p.149342, doi.org/10.1016/j.scitotenv.2021.149342).. A potential threat to DayCent is misuse of the tool by by changing model inputs or parameter values to achieve desired results (conflict of interest) or misunderstanding of the outputs especially if sufficient attention is not paid to uncertainties.

When DayCent output is compared to field data, $N_2O$ estimations are often within 33% of measured values and $NO_3$ leaching is within 30% (compared to 50% underestimation with IPCC emissions factors methodology and a difference of factoring leaching of N from fixation).[149] It can model mean annual $N_2O$ estimations reasonably well, but not daily fluxes.[150] DayCent, like all models could benefit from more robust field data sets that are long-term and capture different growing conditions. For example, national $N_2O$ monitoring stations would not only benefit modeling software, it would also inform our current state of emissions. DayCent has limitations on the specificity of certain field management practices. For example, although it can model impacts of nitrification inhibitors, it cannot fully account for type and placement of fertilizers.[151] DayCent, like other government or university funded projects, may be subject to high competition for experienced staff and future model development and application could be limited by resource availability.

---

[147] *Id.*

[148] Del Grosso, Stephen. S. Davis, and P. Adler. (2012). DayCent Model Simulations for Estimating Soil Carbon Dynamics and Greenhouse Gas Fluxes from Agricultural Production Systems. Managing Agricultural Greenhouse Gases. doi:10.1016/B978-0-12-386897-8.00014-0

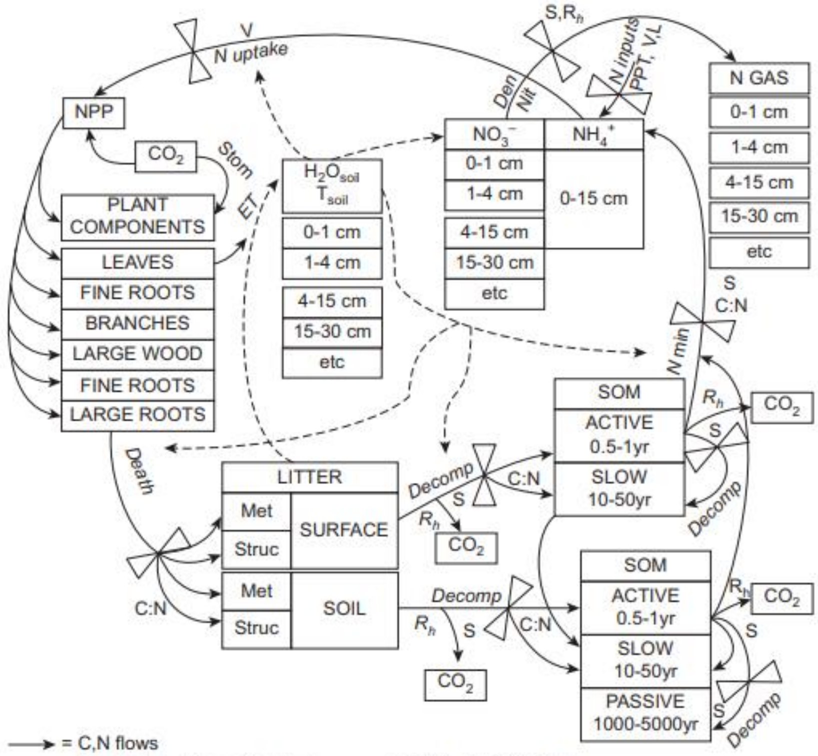
[149] Del Grosso, Stephen, A. Mosier, W. Parton, and D. Ojima. (2005). DAYCENT model analysis of past and contemporary soil N2O and net greenhouse gas flux for major crops in the USA. Soil & Tillage Research 83 (9-24). doi:10.1016/j.still.2005.02.007.

[150] *Id.*

[151] Del Grosso, Stephen. S. Davis, and P. Adler. (2012). DayCent Model Simulations for Estimating Soil Carbon Dynamics and Greenhouse Gas Fluxes from Agricultural Production Systems. Managing Agricultural Greenhouse Gases. doi:10.1016/B978-0-12-386897-8.00014-0

**SECTION 4**

Modeling to Estimate Soil Carbon Dynamics and Greenhouse Gas Flux



→ = C,N flows

- - → = Feedbacks, information flows

⋈ = Control on process

$H_2O_{soil}$ = Soil water content

$T_{soil}$ = Soil Temperature

S = Soil Texture

C:N = Carbon: Nitrogen ratio of material

V = Vegetation type

SOM = Soil Organic Matter

L = Land use

Met = Metabolic

Struc = Structural

N GAS = $N_2O$, $NO_x$, $N_2$

Processes designated by *italics*

*Stom* = Stomatal conductance

*Death* = Plant component death

*Decomp* = Decomposition

*N inputs* = N Fixation, N deposition, N fertilization

*Nit* = Nitrification

*Den* = Dentrification

*N min* = N mineralization

*ET* = Evapotranspiration

$R_h$ = Heterotrophic respiration

**FIGURE 14.1**

**DayCent model flow diagram.**

## APPENDIX 3: COMET-Farm

### Summary

COMET-Farm estimates a carbon footprint and allows users to evaluate different options to sequester carbon or reduce greenhouse gas (GHG) emissions. It was developed by the United States Department of Agriculture (USDA), Natural Resources Conservation Services (NRCS), and Colorado State University. It was developed in response to 1605 B Title of the Energy Policy Act to allow voluntary reporting of GHGs.[152] COMET-Farm uses methods from Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory.[153]

COMET-Farm has four accounting activities: Field (cropland, pasture, range, orchard/vineyard management practices), livestock (animal number, size, breed, and manure management information), agroforestry (tree type, dbh/age, and stocking rate), and forestry (tree stand type and management). [154] The platform allows users to see changes in GHG based on changes in field management practices (cover crops, reduced tillage, more precise fertilizer applications). COMET-Energy is also available, as a separate tool, to assess fuel related emission reductions.

### Strengths

COMET-Farm estimates are based on GHG inventory methods that are defined by independent expert science working groups and are vetted in a public review process by other expert scientists and government agencies which make it one of the most transparent and scientifically robust GHG inventory systems of its kind.[155] There are approximately 25 different models within COMET-Farm.[156] In other words, estimate methodology aligns with national inventory methods and is endorsed by the USDA.[157]

COMET-Farm is actively supported, maintained, and updated. Overall, COMET-Farm can estimate GHG emissions for a diversity of operations and farm management systems.[158] In 2021, new features were added to account for more specific irrigation information, the nutrient balance calculator was updated to display total amount of nitrogen applied, and other upgrades were made to improve performance.[159] In 2022, a carbon farm planning curriculum is anticipated

---

[152] Paustian, Keith and H. Nagle. Personal communication. March 25, 2022.
[153] Eve, Marlen, D. Pape, M. Flugge. R. Steele, D. Man, M. Riley-Girlbert, and S. Biggar (eds). 2014. Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory. USDA Technical Bulletin 1939.
[154] H. Nagle. Personal communication. July 16, 2022.
[155] Paustian, Keith and H. Nagle. Personal communication. March 25, 2022.
[156] Paustian, Keith. Personal communication. July 16, 2022.
[157] Chambers, Adam. Personal communication. March 23, 2022.
[158] *Id.*
[159] Comet. 2021. "Welcome to COMET-Farm™." Info. http://comet-farm.com/News

to be released.[160] COMET-Farm uses spatially explicit data which means climate and soil conditions are locally based. COMET-Farm creates baseline and projected 10-year[161] estimates based on the information the user inputs which means it is flexible to create estimates for select fields or the whole-farm.[162]

In addition to the Field Module, COMET-Farm also has a livestock module and an optional energy tool (COMET-Energy).[163] The advanced Livestock Module allows for users to input information on feed and supplement characteristics. The energy tool requires on-farm energy use information in addition to the Field Module. COMET-Farm incorporates different land management systems (annual and perennial crops, pasture, range, and agroforestry).[164] Sugaring and wood harvested for heating in fireplaces is accounted for in the biogenic cycle land use section.[165]

Each module relies on scientifically verified methods of calculation. DayCent is used to calculate soil carbon estimates in the Field Module (as of July 2022), though later in 2022, it will be updated to the 30cm DayCent Model and account for both soil carbon and N2O changes.[166] The Livestock Module's estimates are based on USDA and models and university research.[167] This tool allows for robust, historical data entry which increases its prediction accuracy. Although this may be a data entry burden, the user interface is streamlined to allow users to copy management practices to subsequent years and/or fields.

Data entered is not used, shared, or viewed by the USDA.[168]

Reports are created to show differences between the baseline practices and up to ten alternative[169] scenarios. Reports display information in tables and graphs. Results are exportable into a spreadsheet.[170]

---

[160] Chambers, Adam. Personal communication. March 23, 2022.

[161] Paustian, Keith, M. Easter, K. Brown, A. Chambers, M. Eve, A. Huber, E. Marx, M Layer, M. Stermer, B. Sutton, A Swan, C. Toureene, S. Verlayudhan, and S. Williams. 2018. Field- and farm-scale assessment of soil greenhouse gas mitigation using COMET-Farm. Precision Conservation: Geospatial Techniques for Agricultural and Natural Resources Conservation, Vol. 59 https://doi.org/10.2134/agronmonogr59.c16

[162] Comet. 2021. "Why should I use COMET-Farm." Dashboard pop-up. http://comet-farm.com/#

[163] Comet. 2021. "What information do I need?" Dashboard pop-up. http://comet-farm.com/#

[164] Paustian, Keith, M. Easter, K. Brown, A. Chambers, M. Eve, A. Huber, E. Marx, M Layer, M. Stermer, B. Sutton, A Swan, C. Toureene, S. Verlayudhan, and S. Williams. 2018. Field- and farm-scale assessment of soil greenhouse gas mitigation using COMET-Farm. Precision Conservation: Geospatial Techniques for Agricultural and Natural Resources Conservation, Vol. 59 https://doi.org/10.2134/agronmonogr59.c16

[165] Chambers, Adam. Personal communication. March 23, 2022.

[166] H. Nagle. Personal communication. July 16, 2022.

[167] Comet. 2021. "How are my results calculated?" Dashboard pop-up. http://comet-farm.com/#

[168] USDA. N.d. Privacy Policy. https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/about/?cid=nrcsdev11_000885

[169] H. Nagle. Personal communication. July 16, 2022

[170] Allen, Gemma. 2020. Multiple Perceptions of Soil Health: A Transdisciplinary Collaborative Study of two Contrasting Grain Farms in Columbia County, NY. Division of Social Studies. Bard Undergraduate Senior Projects. https://digitalcommons.bard.edu/cgi/viewcontent.cgi?article=1029&context=senproj_s2020

COMET-Farm is widely utilized tool. For example, as of 2021, COMET-Farm had 12,834[171] visitors and is listed as a tool in the National Oceanic and Atmospheric Administration's (NOAA) U.S. Climate Resilience Toolkit[172], Cornell University's Climate Smart Farming,[173] and the Land Trust Alliance.[174]

Weaknesses

COMET-Farm is limited in cover crop options i.e., it does not create estimates for complex cover crop mixes.[175] COMET-Farm does not account for GHG from machinery or vehicular use as that is included in other sections of the National GHG inventory.[176] As with other models there are uncertainties when it comes to time and weather, and uncertainties are not quantified.[177] GHG emissions under climate change are not estimated as there is too much uncertainty of attributing influence to climate change and not weather variability.[178] COMET-Farm may refer to IPCC defaults to create estimates for diversified farm scenarios (farming operations with non-dominant crops).[179] Like most other models, COMET-Farm does not quantify co-benefits and ancillary benefits.[180] Consistent with USDA GHG flux methodology, COMET-Farm supports, but does not perform life cycle analysis.[181]

Opportunities

COMET-Farm could be expanded to include modules on water quality, soil health, or biodiversity. Including an economics module may expand COMET-Farm's decision-making support tool applications to include carbon markets or payment for ecosystem services programs.[182] Furthermore, COMET-Farm could be expanded to include more comprehensive life

---

[171] Miller, Spencer 2017.COMET-Farm™: Conservation Calculation. USDA blog. https://www.usda.gov/media/blog/2013/08/21/comet-farmtm-conservation-calculation

[172] U.S. Climate Resilience Toolkit. 20s1.COMET-Farm. NOAA. https://toolkit.climate.gov/tool/comet-farm

[173] Cornell University. 2022.COMET-Farm GHG Accounting Tool. Climate Smart Farming. http://climatesmartfarming.org/tools/comet-farm/

[174] Land Trust Alliance. 2021.COMET-Farm GHG Accounting Tool. Conservation in a Changing Climate. https://climatechange.lta.org/comet-farm/

[175] Allen, Gemma. 2020. Multiple Perceptions of Soil Health: A Transdisciplinary Collaborative Study of two Contrasting Grain Farms in Columbia County, NY. Division of Social Studies. Bard Undergraduate Senior Projects. https://digitalcommons.bard.edu/cgi/viewcontent.cgi?article=1029&context=senproj_s2020

[176] Chambers, Adam. Personal communication. March 23, 2022.

[177] Chambers, Adam. Personal communication. March 23, 2022.

[178] *Id.*

[179] Paustian, Keith, M. Easter, K. Brown, A. Chambers, M. Eve, A. Huber, E. Marx, M Layer, M. Stermer, B. Sutton, A Swan, C. Toureene, S. Verlayudhan, and S. Williams. 2018. Field- and farm-scale assessment of soil greenhouse gas mitigation using COMET-Farm. Precision Conservation: Geospatial Techniques for Agricultural and Natural Resources Conservation, Vol. 59 https://doi.org/10.2134/agronmonogr59.c16

[180] Chambers, Adam. Personal communication. March 23, 2022.

[181] Eve, Marlen, D. Pape, M. Flugge. R. Steele, D. Man, M. Riley-Girlbert, and S. Biggar (eds). 2014. Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory. USDA Technical Bulletin 1939.

[182] Paustian, Keith, M. Easter, K. Brown, A. Chambers, M. Eve, A. Huber, E. Marx, M Layer, M. Stermer, B. Sutton, A Swan, C. Toureene, S. Verlayudhan, and S. Williams. 2018. Field- and farm-scale assessment of soil

cycle analysis. Currently, COMET-Farm does not provide estimates for management systems that utilize precision agriculture.[183] COMET-Planner (uses a fixed baseline) has been adapted for use in the California Healthy Soils Program.[184] More applications of COMET-Farm are upcoming with a CIG grant to estimate benefits of conservation.[185]

Threats

COMET-Farm requires history data entry (crop or pasture management information from as far back as 2000) which can be a data entry burden. As with any model, the quality of output is dependent on the accuracy of input. Also similar to other models, there is a shortage of literature to integrate into the tool.[186] COMET-Farm seems to be well-supported and maintained by the USDA, but nonetheless will need to be updated to reflect changes in management technologies, cropping systems, and climate and calibrated as new data becomes available. There are many users utilizing the tool and this level of use requires more hours of expert involvement and more cloud storage space which adds to the overall cost of supporting COMET-Farm.[187]

---

greenhouse gas mitigation using COMET-Farm. Precision Conservation: Geospatial Techniques for Agricultural and Natural Resources Conservation, Vol. 59 https://doi.org/10.2134/agronmonogr59.c16

[183] *Id.*

[184] Jabbour, Randa. S. McClelland, & M. Schipanski. 2021. Use of decision-support tools by students to link crop management practices with greenhouse gas emissions: A case study. Nat Sci Educ. doi.org/10.1002/nse2.20063.

[185] Chambers, Adam. Personal communication. March 23, 2022.

[186] Chambers, Adam. Personal communication. March 23, 2022.

[187] *Id.*

## APPENDIX 4: COMET-Planner

### Summary

COMET-Planner is a web-based conservation planning tool that uses COMET-Farm, utilizes greenhouse gas (GHG) emission and reduction quantification methods from COMET-Farm, and the USDA entity scale inventory methods to produce generalized estimates of GHG impacts based on conservation practice adoption.[188]

Like Comet-Farm, it was developed by Colorado State University and USDA-NRCS. COMET-Planner evaluates five broad categories of NRCS conservation practices: cropland management, grazing lands, cropland to herbaceous cover, woody plantings, and restoration of disturbed lands.[189] It compares these field practices or suites of practices to a fixed baseline.[190]

### Strengths

Compared to COMET-Farm, COMET-Planner is a streamlined tool that allows farmers to quickly estimate regionally-averaged GHG emissions and reductions from field-based practices and compare them to a representative baseline management scenario or business as usual. It therefore requires less data than COMET-Farm. Based on changes in field practices, COMET-Planner can quantifu impacts on carbon emissions from improved fuel-efficiency of farm equipment (CPS 372), reduced carbon and $N_2O$ emissions from soils, and soil carbon sequestration.[191] Results from the online tool are downloadable. COMET-Planner provides a quick, low-cost solution to comparing the impact of management practices.

### Weaknesses

COMET-Planner is intended for initial conservation planning purposes and generates estimates based on county scale. Therefore, it is not for site-specific analysis.[192] COMET-Farm provides more robust analysis. COMET-Planner provides assessments for field-based practices only and is not a whole-farm assessment.[193] COMET-Planner provides estimated impacts of NRCS conservation practices and therefore is subjected to the bounds of the conservation

---

[188] Colorado State University. N.d. Comet-Planner. Brochure. https://planner-prod2-dot-comet-201514.appspot.com/static/media/COMET-Planner_Brochure.a22406c5.pdf

[189] Amy Swan, Mark Easter, Adam Chambers, Kevin Brown, Stephen A. Williams, Jeff Creque, John Wick, and Keith Paustian. 2020. COMET-Planner: Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning. https://planner-prod2-dot-comet-201514.appspot.com/static/media/COMET-Planner_Report_Final.41c0b5e0.pdf

[190] Colorado State University. N.d. Comet-Planner. Brochure. https://planner-prod2-dot-comet-201514.appspot.com/static/media/COMET-Planner_Brochure.a22406c5.pdf

[191] Amy Swan, Mark Easter, Adam Chambers, Kevin Brown, Stephen A. Williams, Jeff Creque, John Wick, and Keith Paustian. 2020. COMET-Planner: Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning. https://planner-prod2-dot-comet-201514.appspot.com/static/media/COMET-Planner_Report_Final.41c0b5e0.pdf

[192] Colorado State University. N.d. Comet-Planner. Brochure. https://planner-prod2-dot-comet-201514.appspot.com/static/media/COMET-Planner_Brochure.a22406c5.pdf

[193] *Id.*

practice standard (CPS) and not all conservation practices may be listed for VT yet.[194] Thus, COMET-Planner does not provide estimates for all conservation practices farmers may implement. In addition, the streamlined nature of the tool does not allow users to modify assumptions of practices. For example, perennial forage in the strip cropping practice (CPS 585) is not fertilized with nitrogen.[195] COMET-Planner is limited in its ability to quantify the impact of CPS on GHG emissions. It aims to quantify $CO_2$, $N_2O$, and $CH_4$ for specific CPSs, but is not able to calculate $N_2O$ and $CH_4$ for all practices. COMET-Planner is not a life cycle assessment tool nor does it provide estimates for whole-farm or forestry GHG emissions and reductions,

## Opportunities

COMET-Planner could be expanded to quantify impacts from additional management practices, beyond the scope NRCS practices standards, and the impact of management practices on water quality (nitrogen and phosphorus loss). COMET-Planner has been adapted for use in the California Healthy Soils Program, expanded by American Farmland Trust as their Carbon Reduction Potential Evaluation (CaRPE) tool,[196] and will be used by the USDA Climate Smart Commodity grant program.[197] Therefore could serve as a viable tool for Vermont farm field GHG emission and reduction quantification. There is global interest in COMET-Planner and the tool could benefit from calibration to other locations outside the US and explore relationships with supporting institutions and trade partners.[198]

## Threats

COMET-Planner is well supported by Colorado State University and NRCS. However, one of its biggest limitations is its narrow scope. COMET-Planner is a general tool and is not designed to be site-specific or quantify GHG emission or reductions outside of its pre-defined conservation practices. The greatest threat to utilizing this tool may be the slow pace of incorporating new technology or cropping methods into its model.

*For more information on strengths and limitations of the Comet-Planner:* Swan, Amy, S. Williams, K. Brown, A. Chambers, J. Creque, J. Wick, and K. Paustian. (n.d). COMET-Planner Carbon and Greenhouse Gas Evaluation for NRCS Conservation Practice Planning. A companion report to the original version of the COMET-Planner tool. https://planner-prod2-dot-comet-201514.appspot.com/static/media/COMET-Planner_Report_V1Legacy.d4f77ec6.pdf

---

[194] Chambers, Adam. Personal communication. March 23, 2022.

[195] Comet-Planner. N.d. Comet-Planner homepage. http://comet-planner.com/

[196] Jabbour, Randa. S. McClelland, & M. Schipanski. 2021. Use of decision-support tools by students to link crop management practices with greenhouse gas emissions: A case study. Nat Sci Educ. doi.org/10.1002/nse2.20063.

[197] Chambers, Adam. Personal communication. March 23, 2022.

[198] *Id.*

## APPENDIX 5: IFSM (Integrated Farm System Model)

### Summary

The Integrated Farm System Model (IFSM) is a simulation program maintained by the USDA that tracks nutrients flows on dairy, beef, grazing, and crop (no livestock) farm operations.[199] Animal feed intake, crop production, fertility management practices, and field operation information is simulated over 25 years of weather data.[200] The IFSM provides a whole-farm nutrient balance for N, P, K, and C, predicts the environmental impact of farm operations on greenhouse gas (GHG) and other important air emissions, water quality, and whole-farm budget.[201]

### Strengths

IFSM is one of the most comprehensive, processed based models available. Its simulations are run on daily weather conditions. Weather files include historical or projected future climate for many locations across the U.S. For projected future climate, IFSM utilizes 18 climate files for each location developed using multiple climate models. It predicts "potential nutrient accumulation in the soil and loss to the environment" and takes burning of fossil fuels into account when calculating GHG emissions.[202] The model predictions for phosphorus flow and GHGs are well calibrated for many common crops, production types, field management operations, and manure storage methods.[203,204,205,206] IFSM includes a farm-gate life cycle assessment (LCA)[207] and provides economic analysis. The software is available for free and includes numerous parameter files for farm production systems, farm equipment, and weather.[208] "The IFSM is generic in design and can simulate a wide range of crop rotations, feeding

---

[199] Rotz, C.A. (2005). The Integrated Farm System Model: A Tool for Whole Farm Nutrient Management Analysis.
[200] *Id.*
[201] *Id.*
[202] *Id.*
[203] Ghebremichael, L.T., P.E. Cerosaletti, T.L. Veith, C.A. Rotz, J.M. Hamlett, and W.J. Gburek. (2007). Economic and Phosphorus-Related Effects of Precision Feeding and Forage Management at a Farm Scale. J. Dairy Sci. 90:3700–3715. doi:10.3168/jds.2006-836
[204] *Id.*
[205] Belflower, J.B., J. K. Bernard, D. K. Gattie, D. W. Hancock, L.M. Risee and C. A. Rotz. (2012). A case study of the potential environmental impacts of different dairy production systems in Georgia. Agricultural Systems Volume 108, April 2012, Pages 84-93. doi:10.1016/j.agsy.2012.01.005
[206] Rotz, Alan, M. Corson. D. Chianese, F. Montes, S. Hafner, H. Bonifacio, and C. Cioner. (2018) The Integrated Farm System Model Reference Manual Version 4.4
[207] Asem-Hiablie, S., Battagliese, T., Stackhouse-Lawson, K.R. *et al.* (2019). A life cycle assessment of the environmental impacts of a beef system in the USA. *Int J Life Cycle Assess* **24,** 441–455
[208] Rotz, C.A. (2005). The Integrated Farm System Model: A Tool for Whole Farm Nutrient Management Analysis.

strategies, equipment, facilities, and other management options."[209] IFSM accommodates six groups of dairy or beef animal groups.[210]

IFSM simulates farms for 25 years of weather data. From these results, the impact of different weather conditions (e.g. unusually wet, dry, hot, cold) on GHG emissions can be estimated. Simulation options include projecting impact of future weather conditions, subject to climate change, on GHG emissions and nutrient flows. IFSM weather files can be constructed from NOAA recorded data or generated using PRISM.[211] Information from the farm and equipment parameter files can be modified in dialogue boxes through the software program.[212] Additionally, modeling routines can be modified for predicting impacts in other systems like compost management.[213] Reports summarize the results in different formats with different levels of detail.[214] The model is calibrated primarily for the northern U.S., but may be applicable to other regions.

The massive data set provides information for comprehensive studies. One study evaluated the impact of production options on the reduction or elimination of long-term phosphorus accumulation in the soil and increased profit. Another study illustrated the impact of feed choices on reduction of volatile nitrogen loss and increased profit.[215] A third study explores the impact of conventional and organic management practices on soil phosphorus accumulation and erosion. Recent studies have determined national environmental impacts of beef cattle and dairy production for the U.S[216, 217, 218].

IFSM is currently well supported through the USDA. The latest release was in early 2022 and upcoming releases expand the model to include energy produced through solar panels and nutrient flows using nutrient extraction technologies.[219]

---

[209] Jégo, Guillaume. C.A. Rotz, G Bélanger, G. F. Tremblay, E. Charbonneau, and D. Pellerin. (2015). Simulating forage crop production in a northern climate with the Integrated Farm System Model. Can. J. Plant Sci. 95: 745757 doi:10.4141/CJPS-2014-375

[210] Rotz, C.A. (2005). The Integrated Farm System Model: A Tool for Whole Farm Nutrient Management Analysis.

[211] Rotz, C.A. Personal communication. January 26, 2022.

[212] Rotz, C.A. (2005). The Integrated Farm System Model: A Tool for Whole Farm Nutrient Management Analysis.

[213] Bonifacio, H.F., C.A. Rotz, and T. L. Richard. (2017) Process-based model for cattle manure compost windrows: part 1. model description. ASABE. Vol. 60(3): 877-892.

[214] Rotz, C.A. (2005). The Integrated Farm System Model: A Tool for Whole Farm Nutrient Management Analysis.

[215] *Id.*

[216] Rotz, C. A., S. Asem-Hiablie, S. Place and G. Thoma. 2019. Environmental footprints of beef cattle production in the United States. Agric. Systems 169:1-13.

[217] Rotz, C.A., R. Stout, A. Leytem, G. Feyereisen, H. Waldrip, G. Thoma, M. Holly, D. Bjorneberg, J. Baker, P. Vadas and P. Kleinman. 2021. Environmental assessment of United States dairy farms. J. Cleaner Prod. (2021), doi: https://doi.org/10.1016/j.jclepro.2021.128153.

[218] Veltman, K., C. A. Rotz, L. Chase, J. Cooper, P. Ingraham, R. C. Izaurralde, C. D. Jones, R. Gaillard, R. A. Larsson, M. Ruark, W. Salas, G. Thoma, and O. Jolliet. 2018. A quantitative assessment of beneficial management practices to reduce carbon and reactive nitrogen footprints and phosphorus losses of dairy farms in the Great Lakes region of the United States. Agric. Systems 166:10-25.

[219] Rotz, C.A. Personal communication. January 26, 2022.

Weaknesses

IFSM provides simulations for dairy, beef, and crop only production systems but does not have capacity to simulate vegetable, other livestock production systems, or diversified farms.[220] The IFSM does not account for field spatial representation.[221] Nor does it include forest management or biodiversity in its simulations.[222]

The model can benefit from field calibration to assure suitable prediction of yield, N-uptake, and crop quality. The model may also be limited in the types of cropping systems it can accept. For example, it cannot fully represent triple-cropping practices.[223] The model does not consider impacts of snow cover which affects soil heat fluctuations.[224] IFSM does not account for pest or weed pressure, but yield could be adjusted to represent crop loss.[225] Although it is primarily designed as a research tool for long-term simulations,[226] it has some educational applications, but is limited in value as a decision support tool[227] i.e. it is not necessarily designed with the intent to inform PES programs and was not intended to be used for regulatory or similar purposes.[228]

IFSM is good for whole-farm (not including forestry) analysis. However, the tool is not suitable for, nor is it designed to conduct, a watershed-level water quality analysis, but it could feed into a watershed water quality analysis model.

Opportunities

The software is available for free to anyone at any time. Download instructions can be found at https://www.ars.usda.gov/northeast-area/up-pa/pswmru/docs/ifsm-download-instructions/.

---

[220] Rotz, C.A. (2005). The Integrated Farm System Model: A Tool for Whole Farm Nutrient Management Analysis.

[221] Ghebremichael, L.T., P.E. Cerosaletti, T.L. Veith, C.A. Rotz, J.M. Hamlett, and W.J. Gburek. (2007). Economic and Phosphorus-Related Effects of Precision Feeding and Forage Management at a Farm Scale. J. Dairy Sci. 90:3700–3715. doi:10.3168/jds.2006-836

[222] Rotz, Alan, M. Corson. D. Chianese, F. Montes, S. Hafner, H. Bonifacio, and C. Cioner. (2018) The Integrated Farm System Model Reference Manual Version 4.4

[223] Belflower, J.B., J. K. Bernard, D. K. Gattie, D. W. Hancock, L.M. Risee and C. A. Rotz. (2012). A case study of the potential environmental impacts of different dairy production systems in Georgia. Agricultural Systems Volume 108, April 2012, Pages 84-93. doi:10.1016/j.agsy.2012.01.005

[224] Jégo, Guillaume. C.A. Rotz, G Bélanger, G. F. Tremblay, E. Charbonneau, and D. Pellerin. (2015). Simulating forage crop production in a northern climate with the Integrated Farm System Model. Can. J. Plant Sci. 95: 745757 doi:10.4141/CJPS-2014-375

[225] Rotz, C.A. Personal communication. January 26, 2022.

[226] Jégo, Guillaume. C.A. Rotz, G Bélanger, G. F. Tremblay, E. Charbonneau, and D. Pellerin. (2015). Simulating forage crop production in a northern climate with the Integrated Farm System Model. Can. J. Plant Sci. 95: 745757 doi:10.4141/CJPS-2014-375

[227] Rotz, C.A. (2022). “Software for Evaluating the Environmental Impact of Dairy and Beef Production Systems.” Livestock and Poultry Environmental Learning Community.

[228] Rotz, C.A. (n.d.). “The Integrated Farm System Model: Software for Evaluating the Performance, Environmental Impact and Economics of Farming Systems.” USDA ARS. https://www.ars.usda.gov/ARSUserFiles/np212/LivestockGRACEnet/IFSM.pdf

Data can be leveraged to conduct more comprehensive studies, and some organizations are offering incentives for participation which will add to its dataset.[229] A well or newly established organization could gather Vermont farm data to create representative Vermont-specific farming operation scenarios. It can be used to assess the impact of different management strategies, like precision feed management, on water quality, whole farm phosphorus budgets, and farm viability.[230] IFSM's intended use is as a research tool and the output focuses on the environmental and economic impacts of a limited range of farming systems. The model could be improved by expanding its ability to generate estimates for different types of production systems and the positive environmental benefits agriculture provides. IFSM could be expanded and applied to PES programs with strong technical assistance as a way to predict changes based on soil type, field management, and weather.

### Threats

The model will need to be calibrated as new agricultural technologies emerge. Currently, the model can account for different types of manure injection, but not nitrogen inhibitors.[231] Like most models dealing with complex systems, engaging with it is somewhat knowledge intensive. Utilization of the model requires dedicated staff that have the training and skills to use it correctly along with good understanding of farming practices.[232] Likewise, the availability and quality of data entered into the model depends on farmer time and record-keeping, which may influence the quality of the model's outputs. IFSM is currently maintained and improved by one USDA staff member located at the Pasture Systems and Watershed Management Research Unit in State College, Pennsylvania. IFSM may no longer be supported in the future by the USDA if new staff are not trained or other models developed at other institutions supersede it. Furthermore, keeping IFSM current means updating the model as the software packages it relies on evolves.

*For more comprehensive information on IFSM refer to:*

Ghebremichael, L.T., P.E. Cerosaletti, T.L. Veith, C.A. Rotz, J.M. Hamlett, and W.J. Gburek. (2007). Economic and Phosphorus-Related Effects of Precision Feeding and Forage Management at a Farm Scale. J. Dairy Sci. 90:3700–3715. doi:10.3168/jds.2006-836

McLean, Andrew. (2012). Modeling Best Management Practices on Representative Farms in Southeastern Pennsylvania Using the Integrated Farm System Model. A Thesis. Pennsylvania State University Graduate School. College of Engineering. https://etda.libraries.psu.edu/files/final_submissions/77

---

[229] PASA. (2022). Grazing Dairy Footprint Study. https://pasafarming.org/soil-institute/farm-based-research/grazing-dairy-footprint-study/

[230] Ghebremichael, L.T., P.E. Cerosaletti, T.L. Veith, C.A. Rotz, J.M. Hamlett, and W.J. Gburek. (2007). Economic and Phosphorus-Related Effects of Precision Feeding and Forage Management at a Farm Scale. J. Dairy Sci. 90:3700–3715. doi:10.3168/jds.2006-836

[231] Rotz, Alan, M. Corson. D. Chianese, F. Montes, S. Hafner, H. Bonifacio, and C. Cioner. (2018) The Integrated Farm System Model Reference Manual Version 4.4

[232] Rotz, C.A. Personal communication. January 26, 2022.

Rotz, Alan, M. Corson. D. Chianese, F. Montes, S. Hafner, H. Bonifacio, and C. Cioner. (2018) The Integrated Farm System Model Reference Manual Version 4.4

Rotz, C. A., S. Asem-Hiablie, S. Place and G. Thoma. 2019. Environmental footprints of beef cattle production in the United States. Agric. Systems 169:1-13.

Rotz, C.A., R. Stout, A. Leytem, G. Feyereisen, H. Waldrip, G. Thoma, M. Holly, D. Bjorneberg, J. Baker, P. Vadas and P. Kleinman. 2021. Environmental assessment of United States dairy farms. J. Cleaner Prod. (2021), doi: https://doi.org/10.1016/j.jclepro.2021.128153.

Veltman, K., C. A. Rotz, L. Chase, J. Cooper, P. Ingraham, R. C. Izaurralde, C. D. Jones, R. Gaillard, R. A. Larsson, M. Ruark, W. Salas, G. Thoma, and O. Jolliet. 2018. A quantitative assessment of beneficial management practices to reduce carbon and reactive nitrogen footprints and phosphorus losses of dairy farms in the Great Lakes region of the United States. Agric. Systems 166:10-25.

# APPENDIX 6: DNDC (DeNitrification-DeComposition)[233]

## Summary

The DNDC process-based model simulates carbon and nitrogen biogeochemistry in agro-ecosystems on a daily time-step.[234] In addition to inventorying emissions from $N_2O$, nitric oxide, dinitrogen, ammonia, $CH_4$ and $CO_2$, DNDC can be used for predicting crop growth, soil temperature and moisture, carbon dynamics, and nitrogen leaching.[235] DNDC can be used for IPCC Tier 3 methodology since it simulates interactions between soil-plant-atmospheric processes.[236]

The model has two components: the first consists of "the soil climate, crop growth and decomposition sub-models, [to predict] soil temperature, moisture, pH, redox potential (Eh) and substrate concentration profiles driven by ecological drivers (e.g., climate, soil, vegetation and anthropogenic activity)," while the second consists "of the nitrification, denitrification, and fermentation sub-models" to predict emissions from plant-soil systems.[237] The model includes land-use type options for "upland crop field, rice paddy field, moist grassland/pasture, dry grassland/Pasture, wetland, and tree plantation."[238] There are also separate Forest-DNDC and Wetland DNDC models that simulates biogeochemistry in forests and wetlands, as well as a Manure-DNDC model that expands on DNDC's calculations for manure additions to soils to include simulated emissions estimates for different manure management scenarios.[239]

Accurately running a simulation with the tool requires three groups of data: "soil characteristics, daily climate, and crop profile and management. The soil characteristics cover a long set of soil properties such as clay content, organic carbon concentration, initial nitrate and ammonium concentrations, field capacity, wilting point, bulk density, porosity and etc."[240]

---

[233] Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, "The DNDC Model," (n.d.) https://www.dndc.sr.unh.edu/. [*hereinafter* UNH].
[234] IPBES, "Policy Support Tool: DNDC DeNitrification-DeComposition," (n.d.), https://ipbes.net/policy-support/tools-instruments/dndc-denitrification-decomposition.
[235] Conservation Technology Information Center, "The Denitrification-Decomposition (DNDC) Model," (2022), https://www.ctic.org/DNDC_Information. [*hereinafter* CITC].
[236] Ward Smith, Personal Interview, February 22, 2022. [*hereinafter* Smith Interview].
[237] *See* CITC.; *also see* Sarah L. Gilhespie et al., "First 20 years of DNDC (DeNitrification DeComposition): Model evolution," *Ecological Modelling* (2014), https://www.sciencedirect.com/science/article/pii/S0304380014004190# . [*hereinafter* Gillespie et al.]: "*Component 1 linked ecological drivers to soil environmental variables and consisted of the soil climate, crop growth and decomposition sub-models. Component 2 linked soil environmental factors to trace gases and consisted of the already known denitrification sub-model and furthermore, the two new sub-models for nitrification and fermentation.*"
[238] Institute for the Study of Earth, Oceans and Space University of New Hampshire, "User's Guide for the DNDC Model," 18 (2012), https://www.dndc.sr.unh.edu/model/GuideDNDC95.pdf.
[239] *See* UNH.; *also see* Chengsheng Li et al., "Manure-DNDC: A biogeochemical process model for quantifying greenhouse gas and ammonia emissions from livestock manure systems," *Nutrient Cycling in Agroecosytems*, (2012), https://link.springer.com/article/10.1007/s10705-012-9507-z. [*hereinafter* Manure DNDC].
[240] Yelin Deng et al., "Incorporating dentrification-decomposition method to estimate field emissions for Life Cycle Assessment," (2017). [*hereinafter* Yelin Deng et al.]

Strengths

Some users of the tool report that it has an attractive interface, and that the tool's outputs are similarly accessible to a wide range of users.[241] DNDC can simulate processes for a range of land uses across varying "climatic zones, soil types, and management regimes."[242] Numerous studies have verified DNDC's accuracy in comparison to observations, including several global studies where it performed well in multi-model comparisons.[243] DNDC's daily time-step modelling makes it more accurate than other tools like CENTURY with a monthly time-step.[244]

DNDC has been found to be more accurate than IPCC methods, which are intended for a much wider scale, and is considered to be "more site specific as it is built according to complex models of soil science."[245] In at least one study DNDC was found to be more accurate than DAYCENT for measuring soil organic carbon,[246] but the models are generally comparable in performance.[247]

Though DNDC is more technically demanding than tools like Holos, DNDC can generate more outputs and can accommodate a much wider range of management practices including 4R (*for definition, see footnote*[248]) and conservation practices.[249] A recently revised version of DNDC simulates carbon change over 2m soil profile depth and vertically stratifies this change in 1 cm increments.[250]

Weaknesses

The primary DNDC model does not include parameterization for field trees, hedges, agroforestry, forestland, wetlands, settlements, or other non-cultivated lands.[251] Furthermore, the DNDC's predictions for N2O emissions from organic manures, and in the absence of additional nitrogen fertilisation, are sometimes reported to be too low.[252]

---

[241] *See* Gillespie et al.

[242] *Id.*, at 8.

[243] Changsheng Li, "Calibrating, Validating, and Implementing Process Models for California Agriculture Greenhouse Gas Emissions," 7, (2014), https://ww2.arb.ca.gov/sites/default/files/2020-05/1dndcproposal.pdf.

[244] *See* Smith Interview.

[245] *See* Yelin Deng et al.

[246] Wentian He et al., "Measuring and modeling soil carbon sequestration under diverse cropping systems in the semiarid prairies of western Canada," *Journal of Cleaner Production*, (2021), https://www.sciencedirect.com/science/article/pii/S0959652621037926.

[247] *See* Smith Interview.

[248] "4R Nutrient Stewardship provides a framework to achieve cropping system goals…the 4R concept incorporates the: **R**ight fertilizer source at the **R**ight rate, at the **R**ight time and in the **R**ight place."; Nutrient Stewardship, "What are the 4Rs," (2017), https://nutrientstewardship.org/4rs/.

[249] *Id.*

[250] *Id.*

[251] *Id.* At 14.

[252] *See* Gillespie et al.; However, this is not always the case, *see* Wentian He et al., "Assessing the effects of manure application rate and timing on nitrous oxide emissions from managed grasslands under contrasting climate in Canada," *Science of the Total Environment*, (2020), https://www.sciencedirect.com/science/article/pii/S0048969719353665.

Users have noted difficulty understanding the user manual and stated that restricted access for the DNDC source code makes it difficult to understand the reasoning for changes and code modifications and their impact.[253] "There are also issues with availability of input parameters for specific situations."[254] DNDC has also been identified by some users (but not all, *see footnote*[255]) as "notably extreme in [it's] very high data requirements" and the time required for analysis is "very long."[256] As a result, the skill level necessary to use DNDC effectively is very high.[257]

Opportunities

The Canadian DNDC model is available for free through GitHub, though the US model developed by the University of New Hampshire is accessible through Dr. William Salas (cost unknown).[258]

Separate Forest and Wetland DNDC models have been developed that can be used to provide calculations to supplement whole-farm accounting.[259] Similarly, a Manure-DNDC model can simulate emissions from different manure management systems of storage, application, and biodigestion.[260] The different land use models have not yet been used together to design a single, comprehensive whole-farm assessment, but they could be.[261]

Though DNDC was initially designed to estimate emissions on individual farms, researchers in California were able to reliably simulate regional emissions by linking DNDC to a GIS database.[262] The tool's library of default settings can accommodate 62 crops and 12 soil types, enabling users to "model a wide range of sites and situations without the need for considerable amounts of rarely measured input data.[263] Furthermore, many of these inputs can also be user-defined to accommodate a greater range of possibilities."[264]

---

[253] *Id.*; The user can sign and agreement that the model is being used for research purposes, *see* Ward Smith, Personal Interview, February 22, 2022.

[254] *Id.*

[255] "DNDC has moderate inputs requirements. It uses a cascade water flow approach such that we don't need detailed hydraulic parameters and the crop inputs are simple compared to most crops models (DSSAT, APSIM, STICS, etc). I would certainly say the input requires are no more than moderate," and "The base US model takes at most 0.5 seconds per year or 5 seconds for 10 years on a home laptop. I don't think this is "very long" so I again disagree. Computational power is not a major limitation since large projects should have hardware available." *See* Ward Smith, Personal Interview, February 22, 2022.

[256] Anass Toudert et al., "Carbon Accounting Tools for Sustainable Land Management," World Bank Group, 15 (2018), https://openknowledge.worldbank.org/handle/10986/31062.

[257] *Id.*

[258] *See* Smith Interview.

[259] *Id.*

[260] *See* Manure DNDC.

[261] *See* Smith Interview.

[262] *Id.*, at 13.

[263] *See* Gilhespie et al.

[264] *Id.*

In Canada, a DNDC-Management Factor Tool (DNDC-MFT) was developed which links soil, climate, and agricultural activity data to estimate the impacts of changes in agriculture management on N2O emissions and soil organic carbon change.[265]

Threats

As with other tools, DNDC's accuracy comes at the expense of complexity and it is necessary to employ experienced users with a sophisticated understanding of the tool, as well as a strong understanding of agronomy and soil science, to use it effectively.[266] It may therefore be difficult to train enough technicians to deploy the model across the state of Vermont.[267] (for an estimate on training demand for technicians, *see footnote.*[268])

Furthermore, the accuracy of DNDC models relies on the accuracy of the data used and Vermont may need to undertake a large research effort to compile sufficient and accurate information.

---

[265] Smith, W.N., Grant, B.B., Desjardins, R.L., Worth, D., Li, C., Boles, S.H., Huffman, E.C. (2010). A tool to link agricultural activity data with the DNDC model to estimate GHG emission factors in Canada, 136(3-4), 301-309, https://profils-profiles.science.gc.ca/en/publication/tool-link-agricultural-activity-data-dndc-model-estimate-ghg-emission-factors-canada-0.

[266] *See* Smith Interview.

[267] *Id.*

[268] *Id.* "It could only take one or two skilled people to implement the model, but they would require training, less training if they have already used other process-based models. I think it's important for any modeler, even if they use a simple empirical model, to still have good background/knowledge of agronomy and soil processes, such that they can determine if the results across contrasting soils, climate and management are reasonable."

## APPENDIX 7: EPIC (Environmental Policy Integrated Climate) & (APEX) Agricultural Policy Environmental eXtender

### Summary

The Environmental Policy Integrated Climate (EPIC) and Agricultural Policy Environmental eXtender (APEX) tools are two variations of a model developed by the Blacklands Research and Extension Center in Temple at Texas A&M University.[269] Both are process-based biogeochemical models that function on a daily time-step and perform IPCC tier 3 simulations.[270]

EPIC was initially developed to assess the impacts of erosion on farm productivity, but was later expanded to assess other processes related to agricultural management[271] and can now also simulate water quality, nitrogen cycling, carbon cycling (based on the CENTURY model), climate change, and the effects of $CO_2$.[272] Weather information for EPIC/APEX modelling uses WXGN Software that "uses standard deviation instead of skew coefficient for temperature generation; this eliminates erroneous values generated in areas where the mean monthly temperature is at or near zero."[273]

In comparison, APEX builds on EPIC by linking hydrological modeling and has components for routing water, sediment, nutrients, and pesticides across complex landscapes and channel systems to the watershed outlet as well as groundwater and reservoir components.[274] Whereas EPIC has no spatial dimension, "APEX places EPIC into a spatial context, where it can model hydrological flows using algorithms similar to those used in the SWAT model and thus estimate runoff as well as transport and deposition of soil sediment, nutrients, and pesticides."[275] APEX was developed to facilitate multiple subarea scenarios and/or management strategies, which cannot be simulated in EPIC[276] and is the base tool for the Farm-PREP model–developed by

---

[269] Phillip W. Gassman et al., "The Agricultural Policy Environmental Extender (APEX) Model: An Emerging Tool for Landscape and Watershed Environmental Analyses," *Iowa State University: Center for Agricultural and Rural Development*, (2009), https://www.card.iastate.edu/products/publications/pdf/09tr49.pdf.

[270] Xiuying (Susan) Wang et al., "APEX Model Upgrades, Data Inputs, and Parameter Settings for Use in CEAP Cropland Modeling," *USDA/NRCS*, 3 (2011), https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs143_012924.pdf. [*hereinafter* Wang].

[271] *See* Wang at 3.

[272] Texan A&M AgriLife, "EPIC & APEX Models," *Blackland Research & Extension Center*, (n.d.), https://epicapex.tamu.edu/about/epic/. [*hereinafter* EPIC & APEX].

[273] Texan A&M AgriLife, "Software|WXGN," *Blackland Research & Extension Center*, (n.d.), https://epicapex.tamu.edu/software/wxgn/ . "*The release of WXGN is restricted to those researchers and individuals working with the modeling team to enhance scientific understanding or application of the model. We encourage those with interest or modification of the model to contact us epicapex@brc.tamus.edu.*"

[274] *See* EPIC & APEX.

[275] Lydia P. Olander & Karen Haugen-Kozyra, "Using Biogeochemical Process Models to Quantify Greenhouse Gas Mitigation from Agricultural Management Projects," *Duke University: Nicholas Institute*, 12-15 (2011), https://nicholasinstitute.duke.edu/sites/default/files/publications/using-biogeochemical-process-paper.pdf. [*Hereinafter* Olander & Haugen-Kozyra].

[276] *See* Wang at 6.

Stone Environmental–that the Vermont Agency of Agriculture Food and Markets (VAAFM) uses to measure phosphorus reductions.[277]

APEX was also selected to estimate the edge of field benefits for the USDA Conservation Effects Assessment Project (CEAP), and APEX's cropland results were also aggregated in the Soil and Water Assessment Tool (SWAT).[278]

The most recent versions of the tools are EPIC v.1102 and APEX v.1501.[279] Updates occur over the course of several years, but APEX is more frequently updated than EPIC because the developers receive greater outside support for APEX.[280]

This summary will include information about both EPIC and APEX because the two tools are closely related and either can have their separate advantages for modelling Vermont agriculture emissions at the whole-farm level[281]—while EPIC could provide more convenient functionality, APEX could be better suited for modelling when measuring edge of field target variables.[282] Additionally, APEX is already employed by the USDA for CEAP and SWAT, and APEX is also already used by VAAFM and can have important applications for Vermont agri-environmental policy like Payment for Ecosystem Services programs.

Strengths

EPIC and APEX include measurements for 150 different crops—including an extensive list of vegetable crops[283]—and forested areas, as well as a tracking mechanism for production costs and crop income for simulating economic outcomes.[284] The tools have been tested and validated by the developers across the US[285] and have the capacity to perform simulations for hundreds or thousands of years.[286] The models' original development for evaluating management practices also gives them a strong foundation in measuring soil productivity and quality.[287]

Furthermore, both models receive robust backing from federal agencies for financial and policy support, as well as from technical staff and Texas A&M University for helping users

---

[277] Stone Environmental, "The Farm-P Reduction Planner (Farm-PREP): An Integrated Tool for Optimizing Field Practices to Achieve Farm-Scale Nutrient Reductions," (n.d.), https://www.stone-env.com/assets/resources/6d35ca97df/E_17054-FarmPREP.pdf.

[278] See Wang at 6.

[279] Texan A&M AgriLife, "Manuals and Publications," *Blackland Research & Extension Center*, (n.d.), https://epicapex.tamu.edu/manuals-and-publications/.

[280] Jaehak Jeong & Phillip Gassman personal interview, March 8, 2022. [*hereinafter* Jeong & Gassman interview].

[281] *Id.*

[282] *Id.*

[283] *See* Olander & Haugen-Kozyra at 12-15.

[284] EPIC Development Team, "Environmental Policy Integrated Climate Model: User's Manual Version 0810," *Blackland Research & Extension Center*, 5 (2015), https://epicapex.tamu.edu/media/vw3pbx0b/epic0810-user-manual-sept-15.pdf. "*The FLIPSIM whole farm economic model has been coupled with EPIC to perform economic analyses of irrigated agriculture in Texas.*"

[285] *See* Jeong & Gassman interview.

[286] *Id.*

[287] *Id.*

resolve technical challenges, including through an online EPIC/APEX modelling forum on Google Groups.[288]

EPIC can perform simulations for stored carbon and nitrogen based on the CENTURY model.[289] In a study comparing EPIC to other tools—including DNDC and Daycent—EPIC stood out for being the only tool in the study that accounted for GHGs from upstream fertilizer and pesticide production.[290]

APEX includes a model for extensive grazing and confined area feeding, though the simulation can only accommodate one herd in a subarea at any given time.[291]

Weaknesses

EPIC is designed to simulate fields, farms, or small watersheds that are homogenous across factors for climate, soil, land use, and can simulate "an extensive array of tillage systems and other management practices," so conducting a whole-farm measurement requires individual simulation of multiple fields rather than a single measurement comprised of multiple fields.[292] The tools also do not currently model for enteric emissions, though seed grazing land source code is being integrated into the not-yet-available APEX v.1905 model.[293]

Users of APEX indicate that it can be technically tedious since potentially a large number of corresponding model parameters may need to be predefined or calibrated to properly represent the area of interest. [294] Additionally, the source code is poorly documented and is very difficult to access.[295]

In one assessment that compared models that were developed to specifically focus on carbon and nitrogen dynamics, APEX and EPIC were found to have lower resolution in the ecology of different cropping systems.[296]

Opportunities

Both models are already used by federal and state agricultural programs, making any outcomes from modelling Vermont emissions compatible with those pre-existing programs. Specifically considering APEX, the high expertise-level required to effectively use the tools

---

[288] *Id.*; *See* Google Groups, "EPIC/APEC Modeling Forum," https://groups.google.com/g/agriliferesearchmodeling.

[289] *Id.*

[290] *See* Olander & Haugen-Kozyra at 12-15.

[291] *Id.*

[292] *Id.* at ii.

[293] *See* Jeong & Gassman interview.

[294] Kiuyang Want & Jaehak Jeong, "APEX-CUTE 4 User Manual," *Texas A&M AgrifLife Research*, (2016), https://temp-web1.brc.tamus.edu/media/gtnivg5p/apexcute-user-manual_v46.pdf.

[295] *See* Jeong & Gassman interview.

[296] Christina Tontito et al., "Quantifying Greenhouse Gas Emissions from Agricultural and Forest Landscapes for Policy Development and Verification," *Advances in Agricultural Systems Modeling, Volume 6*, (2016), https://repository.si.edu/bitstream/handle/10088/32927/Tonitto-etal-GHGmodelReview16.pdf?sequence=1&isAllowed=y.

could be mitigated because of Vermont Technical Assistance Providers' familiarity with Farm-PREP and VAAFM's established relationship with Stone Environmental.

Also, regarding the tools' required technical sophistication, developing a more user-friendly interface—similar to the work already done on Farm-PREP—could make them more broadly deployable for Vermont agriculture initiatives, both for measuring emissions and for a potential PES program.[297]

Other opportunities include ongoing developments of the tools—in addition to the forthcoming integration of grazing land source code to simulate enteric emissions in APEX v.1905, developers are also working to give bigger scale perspectives for agricultural impacts to air and groundwater quality.[298]

Threats

As discussed, the tools' sophistication could make it difficult to train enough staff to use this tool across Vermont. Also, like other models, the quality of outputs depends on the quality of inputs and routinely updating to reflect changes in management technologies, cropping systems, and climate and calibrated as new data becomes available.

---

[297] *See* Jeong & Gassman interview.

[298] *Id.*

## APPENDIX 8: COOL-Farm

### Summary

The Cool Farm Tool (CFT) is owned and managed by the Cool Farm Alliance, an international organization of consumer goods producers, retailers, non-governmental organizations, fertilizer producers, and small and medium-sized enterprises.[299] CFT was developed in 2008[300] and put online in 2013[301] as open-source software.[302] CFT is a decision support tool that models estimates of greenhouse gases (GHGs), biodiversity, and water footprint.[303] GHG reduction and carbon sequestration are calculated on a per field basis with calculations from over 100 global data sets, peer reviewed studies, and IPCC methods,[304] derived mostly from IPCC Tier 1 and Tier 2.[305] Biodiversity calculations capture the ability of the farm to support biodiversity through four dimensions and 11 species groups.[306] CFT Water metrics measures irrigation use and optimization for crop yield and freshwater conservation.[307]

### Strengths

A unique strength of this tool is its international reach which provides a standard tool and results for easy comparison.[308] CFT has many corporate stakeholder members which increases the likelihood of its use and development. It was designed to have a high degree of applicability to what occurs on farms and be user-friendly for farmers. To calculate product carbon footprint, it accounts for carbon sequestration[309] (above and below ground)[310], nitrogen inhibitors,[311] wastewater from processing[312], etc. CFT accounts for GHG emissions from a wide variety of

---

[299] Kayatz, Benjamin, G. Baroni, J. Hillier, S. Lüdtke, R. Heathcote, D. Malin, C. van Tonder, B. Kuster, D. Freese, R. Hüttl, M. Wattenbach. (2019). Cool Farm Tool Water: A global on-line tool to assess water use in crop production. Journal of Cleaner Production. Vol 207. 1163-1179. doi.org/10.1016/j.jclepro.2018.09.160.

[300] *Id.*

[301] CFT. 2019. “Methods Papers.” Greenhouse Gases. https://coolfarmtool.org/coolfarmtool/greenhouse-gases/

[302] Hillier, Jonathan, C. Walter, D. Malin, T. Garcia-Suarez, L. Mila-i-Canals, P. Smith. (2011). A farm-focused calculator for emissions from crop and livestock production. Environmental Modelling & Software. Vol 26 (9) 1070-1078 doi.org/10.1016/j.envsoft.2011.03.014.

[303] CFT. 2019. Dashboard. https://coolfarmtool.org/coolfarmtool/

[304] CFT. 2019. “Methods Papers.” Greenhouse Gases. https://coolfarmtool.org/coolfarmtool/greenhouse-gases/

[305] Vetter, Sylvia, D. Malin, P. Smith, J. Hillier. (2018). The potential to reduce GHG emissions in egg production using a GHG calculator – A Cool Farm Tool case study. Journal of Cleaner Production. Vol. 202. 1068-1076. doi.org/10.1016/j.jclepro.2018.08.199.

[306] CFT. 2019. Biodiversity. https://coolfarmtool.org/coolfarmtool/biodiversity/

[307] CFT. 2019. Water. https://coolfarmtool.org/coolfarmtool/water/

[308] Aschbacher, Michaela. Personal communication. February 16, 2022.

[309] CFT. 2019. “Methods Papers.” Greenhouse Gases. https://coolfarmtool.org/coolfarmtool/greenhouse-gases/

[310] Aschbacher, M. Personal communication (March 23, 2022).

[311] Cool Farm Alliance. 2016. “The Cool Farm Tool Data Input Guide -- Crops.” http://coolfarmtool.wpengine.com/wp-content/uploads/2016/09/Data-Input-Guide.pdf

[312] Hillier, Jonathan, C. Walter, D. Malin, T. Garcia-Suarez, L. Mila-i-Canals, P. Smith. (2011). A farm-focused calculator for emissions from crop and livestock production. Environmental Modelling & Software. Vol 26 (9) 1070-1078 doi.org/10.1016/j.envsoft.2011.03.014.

livestock sources and manure storage methods, including grazing[313] and can be applicable to diversified farms.[314] Biodiversity scores are based on expert opinion and additional points are awarded when scientific documentation supports it.[315] To calculate blue and green water footprints, CFT Water utilizes local climate data[316] and the FAO56 standard to simulate soil water dynamics (e.g., runoff, interception, the effect of organic matter)[317]. CFT aims to keep current with changes made to IPCC guidelines[318] and is transparent about changes with well-documented, publicly accessible updates document.[319]

CFT is currently being used and co-developed by the 131[320] members of the Cool Farm Alliance and is a well-documented tool with over 30 scientific publications published.[321] The CFT corroborates other research,[322] such as that conducted by Lal published in 2004[323] and Ledo.[324] Cool Farm Alliance created an Innovation Hub to increase the scientific rigor of CFT by engaging in research partnerships.[325] Current research partners include University of Aberdeen, University of Oxford, University of Cambridge, GFZ German Research Centre for Geosciences, and Wageningen University and Research.[326] Cool Farm Alliance offers a free E-Learning course on CFT.[327]

---

[313] Vetter, Sylvia, D. Malin, P. Smith, J. Hillier. (2018). The potential to reduce GHG emissions in egg production using a GHG calculator – A Cool Farm Tool case study. Journal of Cleaner Production. Vol. 202. 1068-1076. doi.org/10.1016/j.jclepro.2018.08.199.

[314] Aschbacher, Michaela. Personal communication. February 16, 2022.

[315] CFT. 2019. Biodiversity. https://coolfarmtool.org/coolfarmtool/biodiversity/

[316] Cool Farm Alliance. 2017. "CFT Water Assessment Description." http://coolfarmtool.wpengine.com/wp-content/uploads/2017/07/CFA-Water-Description.pdf

[317] CFT. 2019. "Methods Papers." Water. https://coolfarmtool.org/coolfarmtool/water/

[318] Cool Farm Alliance. 2019. "Cool Farm Tool: Updates to the 2019 IPCC Guidelines for Greenhouse Gas Inventories." News & Resources. https://coolfarmtool.org/2022/01/cool-farm-tool-updates-to-the-2019-ipcc-guidelines-for-greenhouse-gas-inventories/

[319] Cool Farm Alliance. 2019. "Updating the Cool Farm Tool Calculation – CFT Version 1.0 Release Plan." News & Resources. https://coolfarmtool.org/2021/07/updating-the-cool-farm-tool-calculation-cft-version-1-1-release-plan/

[320] Aschbacher, M. Personal communication (March 23, 2022).

[321] Kayatz, Benjamin, G. Baroni, J. Hillier, S. Lüdtke, R. Heathcote, D. Malin, C. van Tonder, B. Kuster, D. Freese, R. Hüttl, M. Wattenbach. (2019). Cool Farm Tool Water: A global on-line tool to assess water use in crop production. Journal of Cleaner Production. Vol 207. 1163-1179. doi.org/10.1016/j.jclepro.2018.09.160.

[322] Hillier, Jonathan, C. Walter, D. Malin, T. Garcia-Suarez, L. Mila-i-Canals, P. Smith. (2011). A farm-focused calculator for emissions from crop and livestock production. Environmental Modelling & Software. Vol 26 (9) 1070-1078 doi.org/10.1016/j.envsoft.2011.03.014.

[323] Lal, R. (2004). Carbon emissions from farm operations. Environ. Int. 30 981-990. doi.org/10.1016/j.envint.2004.03.005

[324] Ledo, Alicia, R.Heathcote, A.Hastings, P.Smith, J.Hillier. (2018) Perennial-GHG: A new generic allometric model to estimate biomass accumulation and greenhouse gas emissions in perennial food and bioenergy crops. Environmental Modelling & Software. 102 292-305. doi.org/10.1016/j.envsoft.2017.12.005

[325] Cool Farm Alliance. 2019. "Overview." Research Partnerships. https://coolfarmtool.org/research/research-partnerships/

[326] Cool Farm Alliance. 2019. "Overview." Innovation Hub. https://coolfarmtool.org/research/innovation-hub/

[327] Cool Farm Alliance. 2019. "Free E-Learning Course on the Cool Farm Tool." News & Resources. https://coolfarmtool.org/2021/06/free-e-learning-course-on-the-cool-farm-tool/

Weaknesses

CFT only calculates the impact of pesticides on radiative forcing (GHG) and not its other impacts on air, water, or soil,[328] and also does not account for social impacts. However, a cost balance for income and expenses can be made on an individual assessment level. Other aspects such as biochar, feed additives, closed environments (e.g., greenhouses and soilless growing operations) are not yet available but are currently in development.[329] Although CFT accounts for conversion into and out of forest, it does not account for working woodlot forest management.[330] Not all data requirements or management options are posted online. Although CFT can calculate GHGs for many crops, it is not a streamlined process yet as a whole-farm assessment.

The biodiversity tool is currently only for the temperate forest and Mediterranean and semi-arid biome, while tropical forests still need to be finalized. This might not cover every, but most of the production regions worldwide.[331] The maximum biodiversity score is only attainable if the farm implements all recommended practices and has all habitat types i.e. is a mixed farm.[332] Biodiversity thresholds have not yet been established.[333] CFT Water requires assessments of all fields for whole farm or basin assessment, uses well water grass crop as reference point (uses single crop coefficient curve to adjust for other crops), and does not calculate a grey water footprint.[334]

Future iterations of CFT Water are expected to provide additional GHG assessments (including fertigation options), expand crop type selection, estimate potential catchment water scarcity, increase soil water balance parameters details, and aggregate information at the whole farm level.[335] CFT estimates GHGS based on annual averages and is not able to calculate GHGs on a daily basis.

CFT is not a lifecycle assessment (LCA) tool but can be used as a tool for LCA analysis.[336] Although CFT is robust in its analysis of Tier 1 and Tier 2, it uses a simplified version of Tier 3 (multi-factorial empirical model) which quantifies the impact of nitrogen

---

[328] Cool Farm Alliance. 2016. “The Cool Farm Tool Data Input Guide -- Crops.” http://coolfarmtool.wpengine.com/wp-content/uploads/2016/09/Data-Input-Guide.pdf

[329] Aschbacher, Michaela. Personal communication. February 16, 2022.

[330] Cool Farm Alliance. 2016. “The Cool Farm Tool Data Input Guide -- Crops.” http://coolfarmtool.wpengine.com/wp-content/uploads/2016/09/Data-Input-Guide.pdf

[331] Aschbacher, M. Personal communication (March 23, 2022).

[332] Cool Farm Alliance. 2016. “CFT Biodiversity Metric Description.” http://coolfarmtool.wpengine.com/wp-content/uploads/2016/10/CFT-Biodiversity-Method-Description.pdf

[333] CFT. 2019. Biodiversity. https://coolfarmtool.org/coolfarmtool/biodiversity/

[334] Cool Farm Alliance. 2017. “CFT Water Assessment Description.” http://coolfarmtool.wpengine.com/wp-content/uploads/2017/07/CFA-Water-Description.pdf

[335] *Id.*

[336] Cool Farm Alliance. 2019. “Is the Cool Farm Tool compliant with standards such as the WRI GHG Protocol ISO, PAS2050, Carbon Trust, Life Cycle Analysis, the International Dairy Federation etc?” News & Resources. https://coolfarmtool.org/faqs/is-the-cool-farm-tool-compliant-with-standards-such-as-the-wri-ghg-protocol-iso-pas2050-carbon-trust-life-cycle-analysis-the-international-dairy-federation-etc/

application, soil carbon sequestration, emissions from residue management, energy, and other sources. [337, 338] As with all models, there are degrees of uncertainty in output related to calculations and algorithms. CFT is working toward reducing uncertainties and documenting them for user reference. The CFT does not account for soil C stock changes as a result of plant biomass changes i.e. under perennial forage.[339] However, it does account for soil C stock changes from switching land use from arable to grassland.[340] Due to $N_2O$ release variability from fertilizer on poorly drained soils under different tillage managements (no-till vs till), the CFT is not able to model this scenario.[341] Like other agricultural GHG models, CFT exhibits "substantial uncertainties for studies which display large soil $CO_2$ emissions/sequestration or direct $N_2O$ emissions."[342] Therefore, the best application of CFT may be for an initial assessment to identify best mitigation practice options. In some cases, the tools may be too general to capture nuances in management i.e. does not accommodate 'it depends' scenarios. CFT cannot meet every goal of every organization.

Opportunities

It is free for farmers[343] and is non-prescriptive as it shows impact of changes and identifies fields where the biggest impact can be made. There is opportunity to use the CFT GHG tool to model GHG reductions and carbon sequestration. The biodiversity tool metrics are applicable in Vermont.[344] However, CFT does not provide a price associated with management changes that impact GHG, biodiversity, or water quality. CFT can be a tool for organizations, like Mars and PepsiCo who want to broaden their focus from practices to outcomes.[345] As with one of northern Europe's leading meat companies, Atrias' 32 pig farms, The Cool Farm Tool can be used on food product packaging to inform consumers of carbon footprint associated with primary production and other factors in association with production of the product.[346] Other

---

[337] Hillier, Jon. (2013). The Cool Farm Tool. Powerpoint presentation. https://www.fao.org/fileadmin/user_upload/epic/docs/workshops/Technical_consultation/Presentations/CFT_intro.pdf

[338] Aschbacher, M. Personal communication (March 23, 2022).

[339] Hillier, Jonathan, C. Walter, D. Malin, T. Garcia-Suarez, L. Mila-i-Canals, P. Smith. (2011). A farm-focused calculator for emissions from crop and livestock production. Environmental Modelling & Software. Vol 26 (9) 1070-1078 doi.org/10.1016/j.envsoft.2011.03.014.

[340] Aschbacher, M. Personal communication (March 23, 2022).

[341] Hillier, Jonathan, C. Walter, D. Malin, T. Garcia-Suarez, L. Mila-i-Canals, P. Smith. (2011). A farm-focused calculator for emissions from crop and livestock production. Environmental Modelling & Software. Vol 26 (9) 1070-1078 doi.org/10.1016/j.envsoft.2011.03.014.

[342] *Id.*

[343] CFT. 2019. Dashboard. https://coolfarmtool.org/coolfarmtool/

[344] Cool Farm Alliance. 2016. "CFT Biodiversity Metric Description." http://coolfarmtool.wpengine.com/wp-content/uploads/2016/10/CFT-Biodiversity-Method-Description.pdf

[345] Cool Farm Alliance. 2019. "Leverage points to scale regenerative agriculture and GHG emission reductions." News & Resources. https://coolfarmtool.org/2021/06/leverage-points-to-scale-regenerative-agriculture-and-ghg-emission-reductions/

[346] Cool Farm Alliance. 2019. "Finish Brand First to Communicate Pork Carbon Footprint On-Pack." News & Resources. https://coolfarmtool.org/2021/12/finish-brand-first-to-communicate-pork-carbon-footprint-on-pack/

businesses like Stonyfield and Ben & Jerry's (Unilever) are using CFT with farmers in a pilot program to reduce GHG emissions and encourage regenerative agriculture.[347] The results of CFT indicate areas of improvement, but do not make recommendations. Future improvements could include a list of practices that would help minimize GHG footprints and improve biodiversity. Furthermore, as is occurring in Australia in response to new European and Asian export requirements, businesses are partnering with each other and farmers to mitigate GHG emissions and using the CFT to document changes.[348] The CFT offers an opportunity for shared learning as it creates a robust database and this can help inform cost-effective approaches.[349]

To meet the goals of organizations that use CFT, other models or additional questions can be utilized. For example, CFT can be used with EX-ACT to model crop productivity, farm economics, and optimization of decreasing GHG emissions.[350] Because of its wide-use and easy integration with other models, CFT can be used to inform policy decision or in PES programs. Currently, Agreena and Soil Capital are using CFT to inform monetization of carbon and sustainability.[351, 352]

Threats

As with any modeling system, the model needs to be maintained, calibrated with new data, and expanded to support new management techniques, technology, or cropping systems. Currently, maintenance of CFT is supported to respond to changes in standardized methods or farmer operational changes. Rigorous scientific review of model outputs may delay implementation until verification is complete. CFT seems to be most widely utilized in scenarios where there are research, business, or compliance incentives to do so. A unique threat to CFT is that its development priorities may be influenced by its members as many of its members are primary funders so its development may be influenced by market forces as agricultural and policy actions can sometimes be dependent on commercial interests.[353] Thus, if stakeholders

---

[347] Cool Farm Alliance. 2019. "Farmer Interviews: The Cool Farm Tool as an Enabler of Regenerative Agriculture." News & Resources. https://coolfarmtool.org/2021/12/farmer-interviews-the-cool-farm-tool-as-an-enabler-of-regenerative-agriculture/

[348] Cool Farm Alliance. 2019. "Learnings from the COOL SOIL INITIATIVE: Using the Cool Farm Tool to Drive Transformation at Scale in Soil Health and Farmer Resilience." News & Resources. https://coolfarmtool.org/2021/10/learnings-from-the-cool-soil-initiative-using-the-cool-farm-tool-to-drive-transformation-at-scale-in-soil-health-and-farmer-resilience/

[349] Cool Farm Alliance. 2019. "Leverage points to scale regenerative agriculture and GHG emission reductions." News & Resources. https://coolfarmtool.org/2021/06/leverage-points-to-scale-regenerative-agriculture-and-ghg-emission-reductions/

[350] Hillier, Jonathan, C. Walter, D. Malin, T. Garcia-Suarez, L. Mila-i-Canals, P. Smith. (2011). A farm-focused calculator for emissions from crop and livestock production. Environmental Modelling & Software. Vol 26 (9) 1070-1078 doi.org/10.1016/j.envsoft.2011.03.014.

[351] Aschbacher, Michaela. Personal communication. February 16, 2022.

[352] Cool Farm Alliance. 2021. "CFA Annual Meeting 2021 – A Day of Solutions in Action." News & Resources. https://coolfarmtool.org/2021/05/cfa-annual-meeting-solutions-in-action/

[353] Aschbacher, Michaela. Personal communication. February 16, 2022.

choose to develop their own tool, funding could drop for CFT and relevancy may decrease if it loses widespread international use.

Additionally, its global reach may limit its adaptability to the needs (practices and terminology) of particular regions. However, an application programming interface (API) provides a method of compatibility with other systems. As is true for many modeling software, it is rare that a farmer would utilize this tool without support, financial incentive, or regulatory requirement. Like any payment for ecosystem programs, programs that support changes on farms with CFT may not be able to offer compensation past a limited time which can impact farm planning, incentive to invest, and program permanence.

Results from management changes can take years to manifest and this may be a source of frustration for farmers, regulators, or purchasers of farm products that want more immediate results. Utilization of the model requires learning how to use the tool or working with dedicated staff that have the training and skills to use it correctly. Cool Farm Alliance has reduced this barrier with a free e-learning course. Likewise, the quality of the model's outputs depends on the availability and quality of data entered into the model which depends on farmer time and records.

*For more information on strengths and limitations of the Cool Farm water model:*

Kayatz, Benjamin, G. Baroni, J. Hillier, S. Lüdtke, R. Heathcote, D. Malin, C. van Tonder, B. Kuster, D. Freese, R. Hüttl, M. Wattenbach. (2019). Cool Farm Tool Water: A global on-line tool to assess water use in crop production. Journal of Cleaner Production. Vol 207. 1163-1179. doi.org/10.1016/j.jclepro.2018.09.160.

## APPENDIX 9: *Table 1*-Model Input Requirements

| Program | Scale / Location Designation | Crop history (number of years of rotation, tillage, fertilizer management, etc.) | Manure management (storage types) | Fuel use (none, only on farm or off-farm too) |
|---|---|---|---|---|
| **Holos** | Eco-District | 1 year farm history | Y | On farm and off-farm |
| **DayCent** | Long/latitude (point-based or gridded data) | Crop or pasture yield and field management practices beginning in 2000, earlier information can be entered if available | N | N |
| **Comet-Farm** | Select field location | General pre-2000 information, management practices post-2000 | Y | On farm only with Comet-Energy |
| **Comet-Planner** | County | 1 year | N | Y for combustion system improvement, only if practice is selected |
| **Integrated Farm System Model (IFSM)** | Select farm location | 1 year of crop history (yield, inputs, field management) | Y | On farm and off-farm |
| **DNDC** | Long/latitude (point-based or gridded data) | Current field management practices | Y, in Manure-DNDC | N |
| **EPIC/APEX** | Long/latitude | Current field management practices | Y (in APEX) | On farm and off-farm |
| **Cool-Farm** | Long/latitude. User inputs average yearly temperature | 1 year of crop history (yield, inputs, tillage) | Y (but not length of storage) | On farm and off-farm |
| **Ex-Act*** | Regional | Current and (speculated) future management | Y | On farm and off-farm |
| **SIT (Ag and LULUCF modules)*** | State, sector | Crop production data for each year | Y | No (reflected in other modules) |

## APPENDIX 10: *Table 2*-Model Inputs

| **DNDC** | **IFSM** | **DayCent** | **Holos** | **EPIC** | **APEX** |
|---|---|---|---|---|---|
| Site and climate | Crop and soil | Daily max/min air temp/precipitation as input parameter files | Site boundaries | Sites | Sites |
| Soil | Grazing | Surface soil texture class | Farm management | Subarea | Subarea |
| Farming management | Machinery | Land cover | Stocking numbers | Soils | Soils |
| Crop | Tillage and planting | Land use data | Crop management | Field operation schedules | Field operation schedules |
| Tillage | Crop harvest | Tillage |  | Weather | Weather |
| Fertilization | Feed storage | Fertilization |  | User determines number of projection years | User determines number of projection years a |
| Manure management | Herd and feeding | Grazing and cutting |  |  |  |
| Plastic film use | Manure management | Irrigation |  |  |  |
| Flooding | Economic parameters | Harvest type and date |  |  |  |
| Irrigation |  | Organic matter applications |  |  |  |
| Grazing and cutting |  |  |  |  |  |

**APPENDIX 10: *Table 2*-Model Inputs (cont'd)**

| COMET-Farm | COMET-Planner | COOL-Farm:Crop | COOL-Farm: Livestock |
|---|---|---|---|
| Field Boundary | County | Crop type and planting date | Herd size and composition |
| Historical data since 2000 | NRCS Practice(s) (dropdown) | Crop year | Milk production, fat content, and protein content |
| Crop Rotations | Acres of practice(s) | Harvest date & yield | Grazing time by cow category |
| Planting, harvest dates, & yields | | Growing area | Feed type and amount |
| Tillage System | | Soil information (texture, SOM, moisture, drainage, pH) | Manure storage type |
| Rate, timing, type of manure and fertilizer applications | | Rate and method type of fertilizer applications (with or without N inhibitor) | On-farm energy use (electricity and fuel) |
| Irrigation method and rate | | Rate, timing, and method type of pesticide applications | Transportation of goods on and off farm |
| Residue management (burning) | | Fertilizer and pesticide production region for upstream GHG region calculations | - |
| Herd size and composition | | Changes in land use (into/out of forest or grassland) | |
| Manure management system | | Irrigation method and rate | |
| Optional: Fuel & electricity use, through COMET-Energy tool | | Tillage practices | |
| | | Cover crop practices | |
| | | Residue management (dropdown options) | |
| | | Fuel and electricity use | |
| | | On-farm energy use (electricity and fuel) | |
| | | Transportation of inputs and harvest (optionally) | |
| | | Wastewater | |
| | | Transportation of inputs and harvest (optionally) | |
| | | Wastewater | |

**APPENDIX 10: *Table 2*-Model Inputs (cont'd)**

| EX-Act* | SIT (Ag Module)* | SIT (LULUCF Module)* |
|---|---|---|
| Geographic area | Emission factors by animal type | Carbon emitted from or sequestered in aboveground & belowground biomass |
| Climate & soil characteristics | Animal population numbers | Carbon sequestration factor for urban trees |
| Duration of project | Typical animal mass | Total urban area |
| Deforestation | Volatile solids production | Urban area tree cover |
| Afforestation/reforestation | Maximum potential CH4 emissions | Direct N2O emission factor for managed soils |
| Non-forest LUC | Kjeldahl nitrogen excreted | Total synthetic fertilizer applied to settlements |
| Agronomic practices | Crop production | Emission factors for CH4 and N2O emitted from burning forest and savanna |
| Tillage practices | Fertilizer utilization | Combustion efficiency of different vegetation types |
| Water & nutrient management | Emission factors for limestone and dolomite | Average biomass density |
| Manure application | Total limestone and dolomite applied | Area burned |
| Grassland management practices | Emission factors from urea fertilizer | Grass, leaves, and branches constituting yard trimmings |
| Feeding practices | Total urea applied to soils | Yard trimmings and foods scraps landfilled, 1960-present |
| Forest degradation | Residue/crop ratio | Yard trimming management and initial carbon content |
| Drainage of organic soils | Residue burning management and efficiencies | Carbon emitted from or sequestered in mineral and organic soils on cropland and grassland |
| Peat extraction | | |
| Fertilizer & agro-chemical use | | |
| Fuel & electricity use | | |

## APPENDIX 11: *Table 3*-Model Parameters

| **Program** | **Modeling approach** | **Scope of analysis** | **Time-step** | **Model calibrated** |
|---|---|---|---|---|
| **Holos** | Bookkeeping (Emissions factors) | Whole Farm | Yearly | Canada Eco-districts |
| **DayCent** | Process-based | Crop, fields | Daily | International |
| **Comet-Farm** | Process-based & bookkeeping (Emissions factors) | Whole farm, by category (cropland/pasture/range/orchard/vineyard, animal agriculture, agroforestry, and forestry) | Daily | National |
| **Comet-Planner** | Bookkeeping (Emissions factors) | By crop (number of acres) | Yearly | National |
| **Integrated Farm System Model** | Process-based | Whole Farm | Daily | Primarily northern US and southern Canada, applicable to broader US & Canada |
| **DNDC** | Process-based | Field C&N cycling | Daily | International |
| **EPIC/ APEX** | Process-based | Whole Farm | Daily | International, but only for select nations |
| **Cool-Farm** | Bookkeeping (Empirical and emissions factors) | Whole farm by crop or livestock product; biodiversity at a whole-farm scale | Annual | International |
| **Ex-Act*** | Bookkeeping (Emissions factors) | Fields, whole Farm, sector, state | Annual | Regional (sub-continent) |
| **SIT (Ag and LULUCF modules)*** | Bookkeeping (Emissions factors) | State, sector | Annual | State |

## APPENDIX 11: *Table 3*-Model Parameters

| Program | Farm type | Climate zones | Soil types | Weather source |
|---|---|---|---|---|
| **Holos** | 18 types of crops, beef, dairy, swine, poultry, other livestock | Applied by Eco-district | Canadian Soil Information System National Ecological Framework | Canadian Soil Information System National Ecological Framework |
| **DayCent** | Major crops and grassland | Site-specific uses weather station, national uses PRISM, for global or others can use any user desired databases | Can be site-specific, SSURGO, user can use any desired database. | Site-specific uses weather station, national uses PRISM, for global or others can use any user desired databases |
| **Comet-Farm** | Diverse (crops, livestock, orchards, etc.) | Site-specific | Site-specific, SSURGO | PRISM |
| **Comet-Planner** | Cropland, grazing, woody, cropland to herbaceous cover, restoration of disturbed lands | County, Major Land Resource Areas | County, Major Land Resource Areas | PRISM |
| **Integrated Farm System Model** | Main crops, dairy, and beef | Site-specific, user can input weather data | User inputs soil texture & can modify soil characteristics | Recorded data or PRISM |
| **DNDC** | Crops and livestock | Site-Specific | Site-Specific | User determined |
| **EPIC/ APEX** | Extensive Crops | Site-Specific | Site-Specific | WXGN Software |
| **Cool-Farm** | Emission footprint can be generated separately by crop (main crops and some speciality (apples, strawberries, etc.)) or livestock, aggregates for whole-farm assessment | User chooses temperate or tropical (used for GHG emissions) | n/a, user inputs texture, SOM, moisture, drainage, and pH | ERA 5, for water module |
| **Ex-Act*** | Crops, livestock, aquaculture | Regional | Regional | Harmonized World Soil Database and CGIAR Consortium for Spatial Information |
| **SIT (Ag and LULUCF modules)*** | Crops, livestock | State | State | Pre-loaded federal data |

**APPENDIX 11: *Table 3*-Model Parameters (cont'd)**

| Program | Weather time (number of years model uses) | Conducts economic analysis (based on default 10 year averages, etc.) (yes/no) | Suitable for diversified farm operations (y/n) | Capacity to include forest |
|---|---|---|---|---|
| **Holos** | 30 | Y | Y | Can extrapolate from lineal tree plantings and riparian zones |
| **DayCent** | User determined | N | Y | Y |
| **Comet-Farm** | 10 | N | Y | Y |
| **Comet-Planner** | 1 | N | Y | Y |
| **Integrated Farm System Model** | 1 to 25 | Y, user inputs costs | N | N |
| **DNDC** | User defined | N | Y | Separate forest and wetland DNDC-models could be used in conjunction |
| **EPIC/ APEX** | n/a | Y, user inputs costs | Y | Y |
| **Cool-Farm** | 1 | N | Y, User can aggregate crop and livestock data for whole-farm assessment | As land use change |
| **Ex-Act*** | Unknown | N | Y | Yes |
| **SIT (Ag and LULUCF modules)*** | Unknown | N | Y | Y |

**APPENDIX 12: *Table 4*-Model Output**

| Program | Scale | GHG emission reduction | Enteric emissions (y/n) | Carbon sequestration (y/n) | Water quality |
|---|---|---|---|---|---|
| **Holos** | IPCC 2 & 3 | CO2, CH4, N2O | Y | Y | Forthcoming in next version |
| **DayCent** | IPCC 3 | CO2, CH4, N2O, NOX, N2 | N | Y | Some NO3 leaching, but lacks hydrological model |
| **Comet-Farm** | IPCC 1, 2, & 3 | C, CO2, CO, N20, CH4 | Y | Y | N |
| **Comet-Planner** | IPCC 1, 2, & 3 | CO2, N2O, CH4 | n/a, no corresponding NRCS standard | Y | N |
| **Integrated Farm System Model** | IPCC 3 | CO2, N2O, CH4, NH3, NOx, N2 | Y | Y | Y, (N leaching and P loss by erosion) |
| **DNDC** | IPCC 3 | N2O, NO, N2, NH3, CH4 & CO2 | Y, in Manure-DNDC | Y | Y |
| **EPIC/APEX** | IPCC 3 | CO2, NO2, N2O, N2, O2, | N | Y | Y |
| **Cool-Farm** | IPCC 1 & 2 | CO2, N2O, CH4 | Y | Y | N |
| **Ex-Act*** | IPCC 1 & 2 | CH4, N2O, and selected other CO2 emissions | Y | Y | N |
| **SIT (Ag and LULUCF modules)*** | IPCC 1 & 2 | CO2, N2O, CH4 | Y | Ag module No; LULUCF module Yes | N |

## APPENDIX 12: *Table 4*-Model Output (cont'd)

| Program | Biodiversity | Compares to alternative cropping scenarios (y/n) | Compares to alternative weather scenarios (y/n) | Water footprint (y/n) | Pesticide impacts (y/n) |
|---|---|---|---|---|---|
| **Holos** | N | N, user can do by running multiple simulations | N, user can do by comparing output by year | Forthcoming in next version | Y, GHG emissions, no toxicological impacts |
| **DayCent** | N | Y | Y | N | N |
| **Comet-Farm** | N | Y | N | N | N |
| **Comet-Planner** | N | Y | N | N | N |
| **Integrated Farm System Model** | N | N, user can do by running multiple simulations | N, user can do by comparing output by year or multiple climate simulations | Y | Y, as GHG emission and economic cost |
| **DNDC** | N | N, user can do by running multiple simulations | N, user can do by comparing output by year | Y | N |
| **EPIC/APEX** | N | N, user can do by running multiple simulations | N, user can do by comparing output by year | Y | Y |
| **Cool-Farm** | Y (whole farm) | N, user can do by running multiple simulations | N | Y | Y, GHG emissions, no toxicological impacts |
| **Ex-Act*** | N | N | N, user can do by comparing output by year | N | Y, GHG emissions, no toxicological impacts |
| **SIT (Ag and LULUCF modules)*** | N | N | N | N | N |

## APPENDIX 13: *Table 5*-Model Use and Usability

| Program | Model support | Level of support | Program available for free (y/n) | Used by other programs |
|---|---|---|---|---|
| **Holos** | Agriculture and Agri-Food Canada | Robust | Y | LogiAg |
| **DayCent** | Colorado State University | Robust | Y | Is an underlying soil carbon model for COMET |
| **Comet-Farm** | Colorado State University, USDA | Robust | Y | Many programs use COMET-Farm methodology |
| **Comet-Planner** | Colorado State University, USDA | Robust | Y | Cali. Health Soils Program; American Farmland Trust's CaRPE tool; Climate Smart Commodity grant program |
| **Integrated Farm System Model** | ARS USDA | Robust short-term, long-term unknown | Y | Primarily Research, some university courses, UW/ Organic Valley LCA |
| **DNDC** | UNH/Geosolutions | Robust | Y | Primarily Research |
| **EPIC/APEX** | Blacklands Research and Extension Center | Robust, long-term | Forthcoming in next version | Conservation Effects Assessment Project (CEAP), Soil and Water Assessment Tool (SWAT), VT Pay-for-Phosphorus Program |
| **Cool-Farm** | Cool Farm Alliance | No long-term guaranteed funding, but robust industry support and university collaboration | Y for farmers | Atria, geoFootprint, Stoneyfield, and others. For a complete list of members see: https://coolfarmtool.org/cool-farm-alliance/members/ |
| **Ex-Act*** | FAO | Robust | Y | FAO, VT Carbon Budget |
| **SIT (Ag and LULUCF modules)*** | EPA | Robust | Y | EPA, State Inventories |

**APPENDIX 13: *Table 5*-Model Use and Usability (cont'd)**

| Program | User-friendly | Application | Data privacy |
|---|---|---|---|
| **Holos** | High | General estimates | n/a, tool is downloaded, not based in cloud |
| **DayCent** | Moderate | Primarily research | n/a, tool is downloaded, not based in cloud |
| **Comet-Farm** | Moderate | General estimates | Y, data entered is not used, shared, or viewed by the USDA. |
| **Comet-Planner** | High | General estimates | Y, data entered is not used, shared, or viewed by the USDA. |
| **Integrated Farm System Model** | Moderate | Primarily research | n/a, tool is downloaded, not based in cloud |
| **DNDC** | Low | Primarily research | n/a, tool is downloaded, not based in cloud |
| **EPIC/APEX** | Low | Primarily research | n/a, tool is downloaded, not based in cloud |
| **Cool-Farm** | High | Corporate tracking and reporting | Y, if shared data anonymized. For privacy policy see: https://app.coolfarmtool.org/privacy/ |
| **Ex-Act*** | Moderate | General estimates | n/a, tool is downloaded, not based in cloud |
| **SIT (Ag and LULUCF modules)*** | High | General estimates | n/a, tool is downloaded, not based in cloud |