THE UNIVERSITY OF BRITISH COLUMBIA

Opportunity Assessment of British Columbia's Agricultural Greenhouse Gas Reductions and Carbon Sinks

Report 3: Agroecosystem Models for GHG Emissions and Co-benefits

Opportunity Assessment of British Columbia's Agricultural Greenhouse Gas Reductions and Carbon Sinks

June 2021

Prepared for:
BC Ministry of Agriculture, Food and Fisheries

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UBC Sustainable Agricultural Landscapes Lab

The Sustainable Agricultural Landscapes Lab contributes to understanding the ecology of and management for an agricultural system that meets current needs without compromising the needs of future generations. A major focus is to evaluate the multiple environmental impacts and ecological interactions for various management options, and to provide a better understanding across a diversity of agroecosystems and social and economic contexts.

Funding

This projected was funded in part by the governments of Canada and British Columbia through the Canadian Agricultural Partnership, a federal-provincial-territorial initiative.

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Citation

In-text: Hanuszak et al. 2021

Reference list: Hanuszak, P., Li, C., Norgaard, A., Borden, K., Smukler, S. (2021). Report 3: Agroecosystem Models for GHG Emissions and Co-benefitsOpportunity assessment of British Columbia’s agricultural greenhouse gas reductions and carbon sinks. Report prepared for BC Ministry of Agriculture, Food and Fisheries.

Acknowledgements

This project was led by Anna Stemberger, Climate Change Specialist with the BC Ministry of Agriculture, Food and Fisheries. Considerable support was provided by members of the project delivery team, including Dieter Geesing, Lisa Zabek, and Julie Galloway from BC Ministry of Agriculture, Food, and Fisheries, and Alvaro Diaz from the Climate Action Secretariat of BC Ministry of Environment and Climate Change Strategy. Appreciations are also extended to Doug MacDonald and Corey Flemming of Environment and Climate Change Canada, and Dr. Brian McConkey and Arzeena Hamir of Farmers for Climate Solutions, for generously sharing their time and technical materials to advance this analysis.

Cover photograph

Measuring soil greenhouse gas emissions with a manual chamber set up in a blueberry field in Delta, B.C. Photo credit: Paula Porto, UBC Sustainable Agricultural Landscapes Lab.

Executive Summary

This is the third of three reports prepared by the Sustainable Agricultural Landscapes laboratory at the University of British Columbia as part of the project *Opportunity Assessment of Agricultural GHG Reductions and Carbon Sinks*. The objective of this report is to assess agroecological models for their ability to quantify greenhouse gas (GHG) benefits (reductions and sinks) and co-benefits resulting from the implementation of beneficial management practices (BMPs) in British Columbia. This work is intended to support the development of BMPs that can help meet GHG reduction targets. The specific objectives of this report are to:

- Compile a comprehensive list of potential models capable of quantifying agricultural GHG benefits and/or co-benefit.
- Evaluate models for suitability and effectiveness for modelling GHG benefits based on the following key criteria co-developed with the Ministry of Agriculture Food and Fisheries (AFF):
    - Capable of simulating a wide variety of cropping systems found in BC
    - Can be calibrated for BC's climate and soil properties and to accommodate project level simulations for ground-truthing
    - Could be used to meet the provincial and national reporting requirements
    - Could be integrated with other models to simulate environmental co-benefits and/or economic performance
    - Operable by non-scientific users.
- Provide a more detailed assessment of the most suitable models, that includes a list of their assumptions, required parameters and their limitations.
- Provide recommendations for developing a modelling approach for BC agriculture.

This report provides a brief background of the 40 agroecosystem models we reviewed, and details of a narrower list of 16 models, that include an overview of their scope and utility. From this set, we identified five models as most likely to meet the goals of AFF and describe them in detail: Holos, COMET-FARM, CFT-GHGs, DNDC.9.5v.CAN and DayCent/CENTURY. While these five models are the most suitable for simulating the outcomes of BMPs in agroecosystems in BC, we also identified limitations for each. Multiple models will

likely be needed to effectively simulate the GHG benefits and co-benefits for the numerous BMPs designed for BC's diverse agricultural production. The recommended modelling strategy for BC could potentially take shape in one or more of the following options:

1. Modify a ready-to-use empirical model to be compatible with a variety of production systems. For example, expanding the functions of Holos to include major field crops in BC, such as blueberry, tree fruits, and field vegetables.
2. Adapt and calibrate one or more of the process models, e.g. DayCent and DNDCv.Can, for a prioritized set of systems and BMPs in the BC context.
3. Use multiple, complementary models and integrate them in a platform that enables comparisons across BMP options, and ideally includes spatially explicit data and outputs.

A primary limitation for future modelling efforts in BC will be the lack of readily available, BC-specific, empirical data. There are a number of researchers in the province who have been engaged in collecting data for select crop and livestock systems and some BMPs, but it is unclear if these data will be appropriate for modelling either in terms of scope and quality. Developing guidance for the data required for modelling and the cyberinfrastructure to effectively catalogue it should be a high priority. With these data, readily available models could be strategically tested and evaluated to identify the most suitable for various production systems. Finally, establishing a set of BMP trials to validate the selected models would be critical for developing a robust, province-wide, long-term GHG emission modelling approach for the BC agriculture sector.

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List of Abbreviations

AAFC	Agriculture and Agri-Food Canada
ALUI	Agricultural Land Use Inventory
BC	British Columbia
BMP	Beneficial management practice
C	Carbon
COA	Census of Agriculture
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
CH_4	Methane
GHG	Greenhouse gas
GIS	Geographical information system
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land-use, land-use change, and forestry
AFF	BC Ministry of Agriculture, Food and Fisheries
N	Nitrogen
N_2O	Nitrous oxide
P	Phosphorus
UBC	University of British Columbia

1. Introduction

For the agricultural sector to help meet provincial and national greenhouse gas (GHG) emission targets, alternatives to current management practices need to be identified and adopted widely. Effective alternatives to current production practices, or beneficial management practices (BMPs), would ideally not only provide GHG benefits by reducing GHG emissions and/or sequestering carbon (C) but would also provide other economic and environmental co-benefits. Identifying BMPs that are able to meet multiple criteria is challenging given that agricultural GHG emissions and co-benefits are largely driven by complex ecological processes and field studies have been relatively limited.

At a national scale, there have been a number of BMPs developed (VandenBygaart et al. 2003, 2010, Drever et al. 2021) mainly for crops that are not grown widely in BC and for very different soil and climate conditions. While some research has been done to identify BMPs specifically for British Columbia's (BC) extremely diverse production systems, data are limited to only a few agricultural sub-categories as defined in the Canada's National Inventory (NI) and BC's Provincial Inventory (PI). Some examples of work by provincial scientists are BMPs developed for dairy forage (Bhandral et al. 2005, 2008), organic vegetables (Maltais-Landry et al. 2019) and orchards (Fentabil et al. 2016).

The number of BMPs in BC with empirical GHG data is limited and it remains unclear how these few BMPs will perform across the diversity of agroecological conditions found in the province, and the economic and environmental co-benefits are also largely unknown. While collecting empirical data is critical for developing BMPs for BC, agroecosystem models could also play an important role not only in the identification of BMPs but also for measurement, reporting and verification (MRV). Agroecosystem models can be employed to help predict the performance of BMPs in terms of GHG benefits as well as co-benefits for a wide range of systems and conditions.

1.1. Greenhouse gas benefit modelling for BC agriculture

Agroecosystem models are developed with varying levels of complexity, scale and intended use (Manzoni and Porporato 2009, Amatya et al. 2013, Maharjan et al. 2018) and typically consist of a collection of sub-models or processes that include soil, water, nutrient, crop, and ecosystem dynamics (Cherry et al. 2008, Maharjan et al. 2018). Due to the range in model complexity, as well as the temporal and spatial simulation scales, the scope of required inputs varies greatly from model to model. Typical data inputs include at the base level: land use, soil texture, topography, climate variables and management practices (Beckie et al. 1995, Pferdmenges et al. 2020) and underlying assumptions and process complexity. Empirical and mechanistic models vary significantly in the type and amount of data required as well as the number of parameters needed to operate the model (Cherry et al. 2008, Pferdmenges et al. 2020). Model input data and parameters are selected to be responsive to changes in management methods, crop selection, and predictions of climate scenarios in relation to the baseline scenario (Beckie et al. 1995, Cherry et al. 2008). Input data can be a combination of collected field data, experimental data, and generated model results that are then fed into the next modelling simulation (Cherry et al. 2008, Pferdmenges et al. 2020). Certain models have the capacity to be flexible with the data input requirements (Amatya et al. 2013). Flexibility is built into models where certain site-specific data is not available due to expense, time, and accessibility. In these scenarios, modellers can choose to use default values developed for the model in other production systems, measured data that most closely represents the system of interest, or estimations based on empirical data provided by the model developers (Beckie et al. 1995, Cherry et al. 2008, Amatya et al. 2013)

As with inputs, certain models have flexible outputs depending on the simulation the modeller chooses which may include changes to process parameters and assumptions, such as those associated with spatial variability. This has been designed for models that are used to inform management decisions or policy. Agricultural researchers, extension workers, producers and policy makers all engage with models as predictive as well as decision support tools. The broad-scale application and use of models requires that the model limitations be understood (Beckie et al. 1995, Amatya et al. 2013). Models are used to make a range of recommendations from site-specific nutrient planning to landscape-scale guidance such as national C budgets and GHGs emission guides (Basso et al. 2006, Jones et al. 2017, Maharjan et al. 2018). The diversity and degree of complexity of the models available reflect the determination to quantify and characterize agroecosystems for a broad range of objectives (Manzoni and Porporato 2009).

To accurately track or predict GHG benefits for BC agriculture, effective modelling of GHG emissions is needed for a wide range of current management practices under various conditions and their BMP alternatives, all while accounting for the environmental constraints of a changing climate over the coming decades. To this end, provincial GHG emission modelling for the BC agricultural sector must be initiated and sustained in the long term in a way that can iteratively amass GHG emission data with management and environmental information. Indeed, GHG emission data across the province is increasing in terms of quality (e.g., actual field measurements of GHG benefits of BMPs) and coverage (e.g., data from a diversity of BMPs and agriculture sub-sectors). These data will need to seamlessly integrate into a database that can be used by researchers looking to do GHG emission modelling and GHG benefit monitoring across the province.

1.2. GHG emission reduction models used in BC

Previous efforts led by CleanBC have shown a promising roadmap of using a model framework to support program/policy analysis. The energy-economy modelling report prepared by Navius Research (Peters, J., Hein, M., & Melton 2019) estimated how CleanBC policies would affect the province's economy and GHG emissions with a focus on technological choice and economic dynamic. The Forest Carbon Initiative (FCI), a joint effort by BC and the federal government, used forest C modelling to identify the key modules of the forest C budget, calculate the GHG reduction benefit between hypothetical baseline and project scenarios, and provide valuable information for the FCI to invest in beneficial forest management practices. A similar modelling approach would also be helpful to estimate agricultural GHGs benefits and support CleanBC reporting on GHG targets.

1.3. Report Objectives and Approach

As part of the project *Opportunity Assessment of Agricultural GHG Reductions and Carbon Sinks*, we completed a review of agroecosystem models and assessed their capability to predict the effects BMPs on GHG benefits in terms of emission reductions and C sequestration in agricultural lands in BC. This report aims to inform the establishment of a larger modelling effort in the Ministry of Agriculture, Food and Fisheries (AFF) that can enable strategic planning and

MRV of emissions benefits from BMP development. The specific objectives of this scoping report were to:

- Compile a comprehensive list of potential models capable of quantifying agricultural GHG benefits and/or co-benefits
- Evaluate models for suitability and effectiveness for modelling GHG benefits based on the following key criteria co-developed with the Ministry of Agriculture, Food and Fisheries (AFF):
    - Capable of simulating a wide variety of cropping system found in BC
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    - Could be used to meet the provincial and national reporting requirements
    - Could be integrated with other models to simulate environmental co-benefits and/or economic performance
    - Operable by non-scientific users
- Provide a more detailed assessment of the most suitable models, that includes a list of their assumptions, required parameters and their limitations
- Provide recommendations for developing a modelling approach for BC agriculture.

2. Agroecosystem model review

2.1. Developing models to meet IPPC reporting requirements

The IPCC provides guidelines (IPCC, 2006) for a tiered approach for developing national GHG inventories. The tiers are designed to enable countries to provide accurate emissions inventories with the data available. The tiered system starts with the most limited data and gets progressively more demanding in terms of data requirements and complexity which results in higher certainty estimates. Tier 1 employs a gain-loss method and default emission factors and other parameters provided by the IPCC which can be used together with spatially-explicit data. Tier 2 methods are similar to those of Tier 1 but rely on country-specific emission factors and parameters. Tier 3 methods can include models to improve the estimation of GHG emissions and removals by incorporating spatial and temporal components in dynamic simulations. Inventory compliers should follow seven general steps established by IPCC (Aalde et al. 2006) to implement a Tier 3 model-based inventory (**Figure 1**).

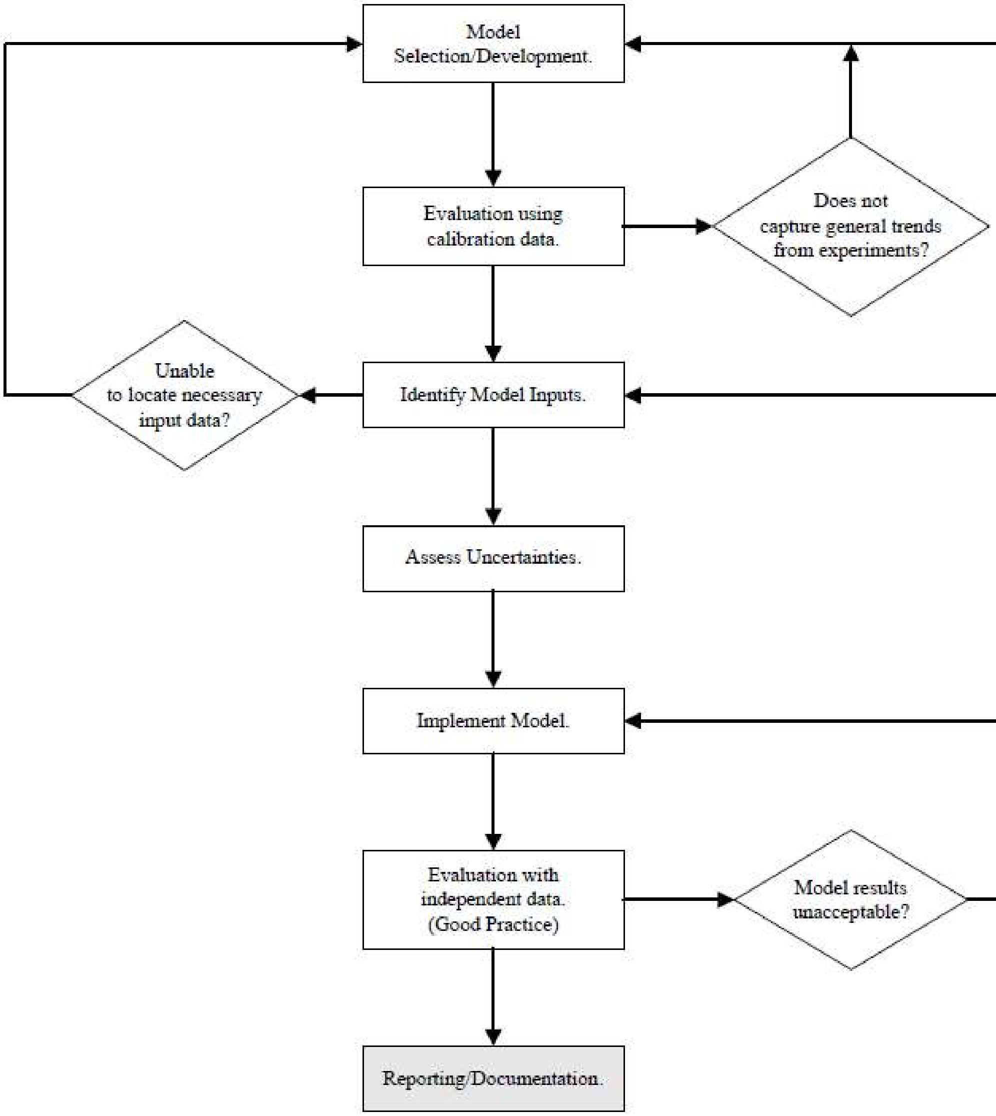

Figure 1. *Steps to developing a Tier 3 model-based inventory estimation system* (Aalde et al. 2006).

Tier 3 models and inventory measurement systems are fully integrated accounting systems driven by high-resolution activity data that provide multivariate inference across space and time using detailed time-series data sets. As part of the model selection and development, it is good practice to consider the availability of input data. Tier 3 methods are typically integrated mass-balance carbon pool accounting systems that operate as either empirical, process-based or other types of advanced models depending on data type availability, the scope, the costs and the required outputs. These models generally require system and location-specific calibration and validations. Tier 3 methods provide estimates of carbon pool and soil dynamics with greater certainty compared to lower-tier systems (Aalde et al. 2006). It is nonetheless necessary to conduct uncertainty analyses and provide a measure of confidence.

Tier 3 methods have been developed to work on a range of scales to conduct detailed scenario analysis of emissions estimates from specific areas of land using site-specific data and knowledge of management practices. An example of a Tier 3 model is version 3 of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3), which is used to estimate C stock changes, emission from and removals by managed forests, forest conversion to other land uses and land converted to forest land. To be applied in national inventory systems, the CBM-CFS3 is designed and implemented to fulfill the following requirements (Global Forest Observations Initiative 2014):

- Be able to represent accurately key flows of carbon, for example, flows from natural processes (growth and decay), harvesting, fire, pest attack
- Be parameterized using available or readily collectable data
- Have checks and balances to prevent unrealistic results
- Have tests to ensure that mass balance is guaranteed at all steps through the model
- Have inputs and outputs (flows) that match the carbon stock change.

In the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Winiwarter et al., 2019), IPCC recommended a detailed list of good practice regarding the selection of model, parameterization, implementation, QA/QC, and reporting on the use of models in GHG emission inventories. These guidelines should be followed for any development of models used for GHG inventory and BMP assessment in BC.

2.2. Scope and selection of models reviewed

The agroecosystem models examined in this review range in applications, complexity, and scale. While the models examined are not an exhaustive list of the numerous available biophysical and ecosystem models, they do represent those most likely to meet the goals of quantifying GHG benefits and potential co-benefits of BMPs either on their own or as part of a compilation of models. The major focus was to review models that were mainly designed to capture biogeochemical processes related to field production and thus apply to NIR/PI categories of: 1) Agriculture and 2) Land-Use, Land-use Change, and Forestry (LULUCF), and not the other agricultural-related categories of Energy or Transportation. Our review started with a broad overview of ecosystem models, which were then narrowed to 40 models related to agriculture (Appendix **Table A 1**). This list of models was further refined to 16 models that include the following initial criteria:

- Applicable to livestock and/or a large variety of crops found in BC (to accommodate, for example, berries, orchards and vineyards)
- Functional at multiple scales from the plot level to regions, watershed, or catchments
- Can simulate GHG emissions and soil C dynamics
- Available for use outside of the institution where it was developed
- Cited extensively in peer-reviewed literature
- Can be used to predict various co-benefits including nutrient and water dynamics
- Can be calibrated by locally developed empirical data.

Many of the models included in this review are well established in scientific literature and a select number are used by extension agencies, government organizations, and industry. While the majority of the models reviewed could predict GHG emissions or soil C sinks, we also included models that do not, but that were instead capable of modelling other processes that could help predict environmental co-benefits, primarily nitrogen (N) and phosphorus (P) nutrient dynamics and in some cases erosion, runoff and drainage. One of the primary outcomes of the models reviewed was crop yields. While economic outcomes were not part of this review, many of the components for assessing economic outcomes would be either required for parameterizing the models (e.g., fertilizer application rate) or be predicted as an outcome of the model (e.g., yield). The 16 models that fit the above criteria included in the review are listed in **Table 1** and summarized below. Details of their operating systems, training availability and target user can be found in (Appendix **Table A 2**).

Table 1. *List of 16 models included in this review, model version and their contact information. The top five selected models (described in section 3) are highlighted in green.*

Model	Model Name	Version	URL or Contact
ADAPT	Agricultural Drainage and Pesticide Transport	2.0.4	https://adaptframework.org/
ANIMO	Soil processes and nutrient leaching model	4.0	https://www.wur.nl/en/Research-Results/Research-Institutes/Environmental-Research/Facilities-Products/Software-and-models/ANIMO.htm
APEX	Agricultural Policy/Environmental eXtender Model	v.1501	https://epicapex.tamu.edu/apex/
APSIM	Agricultural Systems Modelling and Simulation	7.6	https://www.apsim.info
CANDY	Carbon and Nitrogen Dynamics Model	3.20.17.36	https://www.ufz.de/index.php?en=39725
CERES	Crop Estimation through Resource and Environment Synthesis		https://ecosys.versailles-grignon.inra.fr/ceres_mais/ceres.html
COMET-FARM	Carbon Management & Emissions Tool	2.3	http://comet-farm.com/
CFT	COOL FARM TOOL	0.11.06	https://coolfarmtool.org/
CropSyst	Cropping Systems Simulation Model	4	http://modeling.bsyse.wsu.edu/CS_Suite/CropSyst/index.html
DayCent	Daily CENTURY Model	DaycCent 4.5	https://www2.nrel.colostate.edu/projects/irc/
DNDC	DeNitrification-DeComposition Model	DNDC 95 and Manure DNDC	http://www.dndc.sr.unh.edu
DSSAT	Decision Support System for Agrotechnology Transfer	4.6	http://dssat.net
HOLOS	Holos software program	3.0.6	https://www.agr.gc.ca/eng/scientific-collaboration-and-research-in-agriculture/agricultural-research-results/Holos-software-program/?id=1349181297838
NLEAP	Nitrate Leaching and Economic Analysis Package	4.2	https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/technical/ecoscience/mnm/?cid=stelprdb1044740
RZWQM2	Root Zone Water Quality Model	4.1	https://www.ars.usda.gov/plains-area/fort-collins-co/center-for-agricultural-resources-research/rangeland-resources-systems-research/docs/system/rzwqm/
SALUS	System Approach to Land Use Sustainability	3	https://nowlin.css.msu.edu/salus/overview.html

Here we provide a brief introduction of the 16 models listed in **Table 1** and a summary of the types land use and scope of the systems that the models have been used for, and regions in which they have been applied (**Table 2**):

Agricultural Drainage and Pesticide Transport model (ADAPT): was developed for research and industry to simulate nutrient and pesticide transport in agroecosystems (Gowda et al. 2012). ADAPT simulates N and P at the plot or field level with a daily time-step (Gowda et al. 2012).

ANIMO (Agricultural Nutrient Model): is a soil process and nutrient leaching process-based model developed for researchers to examine grasslands, forests, and agricultural systems (Kroes and Roelsma 1998, Groenendijk and Kroes 1999). ANIMO can estimate GHGs and simulate C, N and P cycling and transformations.

Agricultural Policy/Environmental eXtender (APEX) model (Gassman et al. 2009), is an extension of the Environmental Policy Impact Calculator (EPIC; Wang et al., 2012; Williams, 1995). APEX is used to simulate water, sediment, nutrients, and pesticides across forest and agroecosystem landscapes. APEX uses a modified CENTURY model (Parton et al. 1994, Parton 1996) approach to simulate C and N (Parton et al. 1994, Amatya et al. 2013). APEX can simulate carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions but cannot currently model methane (CH_4) emissions.

Agricultural Systems Modelling and Simulation model (APSIM): was developed for researchers to simulate biophysical processes in agricultural systems (McCown et al. 1996, Keating et al. 2003, Holzworth et al. 2006, 2014). APSIM simulates C, N, and P dynamics at the plot level including the emissions of CO_2 and N_2O. APSIM is unable to simulate CH_4 emissions.

The Carbon and Nitrogen Dynamics Model (CANDY): was developed for researchers to simulate C and N dynamics in agricultural soils using process-based modelling techniques (Franko et al. 1995). CANDY is unable to simulate P dynamics and most GHGs.

Crop Estimation through Resource and Environment Synthesis model (CERES): was primarily developed as a crop growth model but also simulates soil water and N balances (Ritchie and Otter 1985, Godwin and Jones 1991, Beckie et al. 1995). The CERES model does not simulate CH_4 emissions but can simulate P dynamics using the DSSAT SOILP module.

Carbon Management & Emissions Tool (COMET-FARM): is an open-source web-supported decision support modelling platform that serves as a farm and ranch carbon and greenhouse gas accounting system (Paustian et al., 2012)**.** COMET-Farm was designed for use by extension agents, producers, and land managers. COMET-FARM uses DayCent/CENTURY nutrient and hydrological models (Paustian et al., 2012).

Cool Farm Tool (CFT): is another open-sourced web-supported decision support modelling platform that quantifies greenhouse gas emissions and biodiversity impacts from agriculture (Hillier 2013, Hillier et al. 2013, Kayatz et al. 2019). CFT was developed for producers, agroindustry and policy-makers. CFT is unable to simulate P dynamics.

Cropping Systems Simulation Model (CropSyst): is an open-sourced crop growth simulation model capable of modelling grasslands, forests, annual and perennial crops (Stöckle and Nelson 1993). CropSyst was designed for researchers to simulate N dynamics in an agroecosystem. CropSyst does not have the capabilities to simulate GHGs or P dynamics.

Daily CENTURY Model (DayCent): a field-scale biogeochemistry model which is a daily time-step version of the CENTURY model (Parton et al. 2001, Schimel et al. 2001). DayCent was developed to simulate water quality, runoff generation, plant growth, nutrient cycling, erosion, land use impacts, management practices, and the effects of climate change on agroecosystem components. DayCent is used by researchers, extension agents, and policy-makers to simulate and quantify C, N, P dynamics as well as GHGs.

DeNitrification-DeComposition Model (DNDC): is a process-based, field-scale C and N biogeochemistry model. DNDC simulates C and N dynamics based on energy balance, soil temperature and moisture regimes, soil C dynamics, N leaching, and emissions of GHGs (Brilli et al., 2017; Li et al., 1992; Gilhespy et al., 2014; Li et al., 2000; Smith et al., 2019).

Decision Support System for Agrotechnology Transfer (DSSAT): is an open-sourced crop growth simulation model developed for agriculture and forest soils (Tsuji et al. 1994, Oteng-Darko et al. 2013, Zha et al. 2014, Brilli et al. 2017, Maharjan et al. 2018). DSSAT can simulate and quantify C, N, P dynamics as well as GHGs. DSSAT modelling programs are used by researchers, educators, extension agents, industry, and policy-makers.

Holos software program: Holos is a whole-farm software program developed by Agriculture and Agri-Food Canada to help users estimate greenhouse gas emissions from animal agriculture operations (Little et al. 2008, Kröbel et al. 2012). Holos is designed to model both confined and pasture-based livestock operations of several different animals, encompassing a wide variety of annual, perennial, and grassland cropping systems. Holos estimates GHGs based on activities of the entire operation by using a "whole-system" approach, which sees components as not only individual parts but as part of a complex, integrated system. Holos accounts for emissions from animals, feed production (fertilizer application, tillage, pesticides, etc.), manure management, and practices that could sequester C such as planting trees to create shelterbelts or transitioning from annual to perennial crops (Amadi et al. 2016, Kröbel et al. 2016, Alemu et al. 2017).

Nitrate Leaching and Economic Analysis Package (NLEAP): is a simpler model than the others listed. NLEAP was developed to estimate nitrogen dynamics in the agricultural soils (M J Shaffer et al., 1991; M. J. Shaffer et al., 1991, Delgado et al., 1998; Shaffer et al., 2015, 2010). NLEAP focuses specifically on simulating N; therefore, it is mostly unable to simulate C and is completely unable to simulate P. NLEAP cannot be used to quantify or simulate GHGs emissions except N_2O. NLEAP has been modified by researchers at the AAFC research station to run on the commercial software, STELLA (Iseesystems, Lebanon, NH) and online. This version of the model is called NLEAP on STELLA (NLOS) (Bittman et al. 2001).

Root Zone Water Quality Model (RZWQM2): is a process-based model designed to simulate major physical, chemical, and biological processes around the root zone in agricultural soils (Ma et al. 2012b, 2012a, Jiang et al. 2019, Sadhukhan et al. 2019, Pferdmenges et al. 2020). RZWQM2 has the capability of quantifying and simulating C, N, and P dynamics as well as N_2O emissions.

System Approach to Land Use Sustainability model (SALUS): is a process-based model designed to simulate continuous crop, soil, water and nutrient conditions under different management strategies for multiple years (Basso et al., 2006; Maharjan et al., 2018). SALUS can simulate C, N and P dynamics in the soil as well as CO_2 emissions.

Table 2. *A summary of model land use, scope and regions that they have been applied.*

Model	Land-use	System parameterized	Scope	Regions applied
ADAPT	agriculture	---	nutrient and pesticide transport	USA
ANIMO	agriculture	grasslands, forest, and annual crops	nutrient transport	Europe
APEX	mixed	grasslands, forest, and annual crops	simulation of water, sediment, nutrients, and pesticides across landscapes	USA
APSIM	agriculture	annual crops*	simulate biophysical processes in agricultural systems	Australia
CANDY	agriculture	grasslands, annual crops and perennial crops	simulate carbon and nitrogen dynamics in arable soils	Germany
CERES	agriculture	annual crops	simulates the biogeochemical cycles of water, C and N in agroecosystems	France, Puerto Rico, Germany, China, India, Africa, USA, Switzerland
COMET-FARM	agriculture	annual and perennial crops, pasture, range and agroforestry system	farm and ranch carbon and greenhouse gas accounting system	USA
CFT	agriculture	annual and perennial crops, pasture, range and agroforestry system	quantifying greenhouse gas emissions and biodiversity impacts from agriculture	Switzerland, Germany, France, USA, Italy
CropSyst	agriculture	grassland, forest, annual crops, perennial crops	crop growth simulation model	USA, France, Italy, Syria, Spain, and Australia
DayCent	agriculture and forest soils	grassland, forest, annual crops	simulation of water quality, runoff generation, plant growth, nutrient cycling, erosion, the impact of land use, management practices, climate change	USA, Canada, Australia, New Zealand, and Europe
DNDC	agriculture and forest soils	grassland, forest, annual crops, perennial crops	simulation model of carbon and nitrogen biogeochemistry in agro-ecosystems	USA, Canada, Australia, New Zealand, Europe, China, Costa Rica, Japan, Thailand, Ireland, and India
DSSAT	agriculture and forest soils	annual crops, perennial crops and grasses	crop growth simulation model	Canada, United Kingdom, Brazil, Mexico, Burkina Faso, Italy, Spain

Model	Land-use	System parameterized	Scope	Regions applied
Holos	agriculture	annual crops, perennial crops and grasses, livestock	simulation model accounts for GHGs emission from livestock system at whole-farm scale	Canada and USA
NLEAP	agriculture	annual and perennial crops	determine potential nitrate leaching associated with agricultural practices	USA, Spain, Canada (NLOS)
RZWQM2	agriculture	annual crops, perennial crops and grasses	simulates major physical, chemical, and biological processes in an agricultural crop production system	Canada, USA, China
SALUS	agriculture	annual crops and grasslands	model continuous crop, soil, water and nutrient conditions under different management strategies for multiple years	USA, Italy

--- signifies missing information

2.3. Model temporal, spatial scales and components

The models reviewed in this report are primarily designed for plot-level simulation in which the plot represents either part of a field or the whole field as long as the management is the same (**Table 3**). Furthermore, the models were selected based on either a flexible[1] or daily time step[2]. These modelling features were selected to provide adequate scale and timing for plot-level experiments and observational studies that often occur at the season level.

The selected models range in capacity and capability to simulate GHGs and C, N, P dynamics (**Table 3**). Carbon in models can be grouped into three general C pools based on turnover rates in the soil: 1) microbial, also referred to as active or labile and has a seasonal to yearly turnover rate; 2) slow, which turnover rate in decades; and 3) passive, which has a turnover rate in hundreds to thousands of years). Other models, depending on the complexity and scale further break down those three carbon pools into numerous sub-pools. Nitrogen dynamics in models are generally simulated using two different methods. In the first method nitrogen

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[1] A user can select either daily or yearly simulation results (Amatya, et al., 2013). Most models have the capacity to run simultaneous scenarios and provide output files for each.

[2] The temporal scale of models influences the resolution of the model and its ability to answer certain questions or simulate different processes (Pferdmenges et al., 2020). Temporal scales of models include hourly, daily, and yearly time-steps. Models working with hourly time-steps are able to simulate single events in great detail whereas models working on yearly time-steps inherently have less resolution but are often used to answer different questions (Brilli et al., 2017; Pferdmenges et al., 2020).

dynamics are directly correlated to the carbon content in the soil. The second method of N dynamics is still influenced by the soil C content but is also influenced by other factors including soil temperature, volumetric soil water content, organic material composition and extent (Brilli et al., 2017). The second method is generally found in models that simulate at the plot level with a daily time-step. These models are developed to predict nuanced changes in nutrient dynamics. Lastly, P is a nutrient not widely simulated by most models. Only half of the models included in this review include modules for P dynamics. One approach of including either different nutrient dynamics methods or including a process not originally in the initial model is to group the model with another known model. A perceived benefit of using more than one model to assess or simulate a system is a more thorough understanding of the system at the cost of increased complexity, time and effort in terms of the modelling but also in terms of developing the empirical data required for parameterization and validation. Some models include all GHGs while others are selective and include either CO_2 and/or N_2O while only half of the models selected include simulations for CH_4.

Table 3. *Model properties overview indicating the modelling language, model type, spatial and temporal scale and capabilities for modelling elements and GHG emissions.*

					Primary Elements Modeled			**Greenhouse Gases**		
Model	**Language**	**Model type**	**Model scale**	**Time step**	**C**	**N**	**P**	CO_2	N_2O	CH_4
ADAPT	Fortran	mixed	Plot	daily	---	Y	Y	---	---	---
ANIMO	Fortran	process based	Plot	flexible	Y	Y	Y	Y	Y	Y
APEX	Fortran	mixed	plot, catchment	daily	Y	Y	Y	Y	Y	N
APSIM	C+	mixed	Plot	daily	~	Y	Y	Y	Y	N
CANDY	SQL	process-based	Plot	daily	Y	Y	N	---	Y	---
CERES	Fortran	process-based	Plot	daily	Y	Y	Y*	Y	Y	---
COMET-FARM	Fortran	mixed	Plot	daily	Y	Y	Y	Y	Y	Y
CFT	C+	mixed	Plot	daily	Y	Y	N	Y	Y	Y
CropSyst	C++	mixed	Plot	daily	---	Y	N	---	---	---
DayCent	Fortran	mixed	Plot	daily	Y	Y	Y	Y	Y	Y

					Primary Elements Modeled			**Greenhouse Gases**		
Model	**Language**	**Model type**	**Model scale**	**Time step**	**C**	**N**	**P**	CO_2	N_2O	CH_4
DNDC	C++	process based	Plot	daily	Y	Y	Y	Y	Y	Y
DSSAT	Fortran	mixed	Plot	flexible	Y	Y	Y	Y	Y	Y
Holos	---	empirical	Farm	yearly	---	---	---	Y	Y	Y
NLEAP	C+/ C++	process based	Plot	daily, monthly, or yearly	Y	Y	N	---	Y	---
RZWQM2	Fortran	process-based	soil profile	flexible	Y	Y	Y	---	Y	---
SALUS	C/Fortran	process-based	Plot	daily	Y	Y	Y	Y	---	---

--- signifies missing information

2.3.1. Carbon

The models reviewed were evaluated for soil C pools as well as soil C losses including sediment loss, leaching, and crop removal (**Table 4**). The majority of the models were capable of simulating the labile, slow, and passive soil carbon pools. For the models ADAPT, CFT, and CropSyst little information was readily available to evaluate the C dynamics and pools. APEX, COMET-FARM, and DSSAT use the DayCent soil organic pools modelling approach (Amatya, et al., 2013; Brilli et al., 2017; Parton et al., 1987, 1988, 1993, 1994; Vitousek et al., 1994). Very few models included soil C losses that were not GHGs emissions.

Table 4. *Soil carbon pool representation and carbon loss capabilities of each model.*

Model	**Soil carbon pools**			**C Losses**		**Crop Removal**
	Labile (soil microbial biomass and microbial products)	**Slow**	**Passive/ stable / inert**	**Sediment**	**Leaching**	
ADAPT	---	---	---	---	---	---
ANIMO	Y	Y	Y		Y	
APEX	Y	Y	Y	Y	Y	---
APSIM	Y	Y	Y	Y	---	---

Model	Soil carbon pools			C Losses		Crop Removal
	Labile (soil microbial biomass and microbial products)	Slow	Passive/ stable / inert	Sediment	Leaching	
CANDY	Y	Y	Y	---	---	---
CERES	Y	Y	Y	---	---	Y
COMET-FARM	Y	Y	Y	---	---	Y
CFT	---	---	---	---	---	Y
CropSyst	---	---	---	---	---	---
DayCent	Y	Y	Y	---	---	Y
DNDC	Y	Y	Y	---	---	---
DSSAT	Y	Y	Y	---	---	Y
Holos	Y*	Y*	Y*	---	---	Y
NLEAP	Y	Y	Y	---	---	Y
RZWQM2	Y	Y	Y	Y	Y	Y
SALUS	Y	Y	Y	---	---	Y

--- signifies missing information
* results do not differentiate the source of CO_2 emissions

2.3.2. Nitrogen

Nitrogen pools and processes vary in complexity between the models reviewed (**Table 5**). The main difference is the approach the models have taken to separate the N into different fractions and the number of fractions represented in the model (Kersebaum et al., 2007). Models that couple C and N processes have three N pools similar to the three C pools: microbial/labile, slow, and passive (Beckie et al. 1995, Kersebaum 2007, Brilli et al. 2017). The second method of nitrogen modelling takes into account the effects of temperature, soil moisture, NO_3-N and soil C (Beckie, et al., 1994).

In this review, the following N processes and losses were considered: absorption, assimilation, nitrification, denitrification, mineralization, immobilization, leaching, crop removal (**Table 5**). Most models reviewed could simulate the majority of N processes being evaluated. The main processes that were under-represented in the evaluation were absorption (clay-fixation) and dissolved organic nitrogen). Nitrogen transformations in the soil are dependent on the following factors: size and ratio of nitrifier and denitrifier microbial populations; organic matter composition and decomposition; land management; soil water dynamics; leaching and plant uptake (Diekkrüger et al. 1995, Amatya et al. 2013, Brilli et al. 2017). The complexity of soil N dynamics and the scale at which those transformations occur is often cited as a source of model error or limitation to the model.

Table 5. *Nitrogen pools, processes, loss accounting capabilities of each model, factors that are important for evaluating N_2O emissions but also key co-benefits.*

Model	Nitrate (NO_3-N)	Ammonium (NH_4-N)	Dissolved organic N	Mineral N	Organic N in solid matter	Adsorbed NH_4-N	Total N	Leached N	Crop uptake
ADAPT	Y	Y	Y	Y	Y	Y	Y	Y	Y
ANIMO	Y	Y	Y	Y	Y	Y	Y	Y	Y
APEX	Y	Y	Y	Y	Y	Y	Y	Y	---
APSIM	Y	Y	N	Y	Y	N	N	Y	---
CANDY	Y	Y	---	Y	Y	---	---	Y	Y
CERES	Y	Y	Y	Y	Y	N	---	Y	Y
COMET-FARM	Y	Y	Y	Y	Y	---	Y	Y	Y
CFT	---	---	---	Y	Y	---	---	Y	Y
CropSyst	Y	Y	---	Y	Y	Y	---	Y	Y
DayCent	Y	Y	Y	Y	Y	---	Y	Y	Y
DNDC	Y	Y	Y	Y	Y	Y	Y	Y	Y
DSSAT	Y*	Y*	---	---	---	---	---	Y*	Y*
Holos	N	N	N	N	N	N	N	N	N
NLEAP	Y	Y	Y	Y	Y	Y	Y	Y	Y
RZWQM2	Y	Y	Y	Y	Y	---	---	Y	Y
SALUS	Y	Y	---	Y	Y	---	---	Y	Y

--- signifies missing information

* results do not differentiate the source of N2O emissions

2.3.3. Phosphorus

Although many agroecological models exist, only some of them can simulate P dynamics (Pferdmenges et al., 2020). More than half of the models included in this review can simulate at some level phosphorus transformations and transport of P (**Table 6**). Given the need to identify BMPs with environmental co-benefits, and that P build-up in soils is an increasing concern to some regions BC, P was a key selection criterion. This has led to a high proportion of models capable of simulating P in this review. The following P transformations and losses were evaluated: surface application (manure and fertilizer), mineralization, immobilization, adsorption/desorption, leaching, runoff, and crop uptake (**Table 6**). ADAPT, APEX, and RZWQM2 share the same P transformation, transport, and losses processes (Pferdmenges et al., 2020). ANIMO simulates more transformations than what was covered in this review but included three inorganic pools (dissolved, adsorbed, and precipitated inorganic P) and three organic pools (dissolved, stable, and fresh organic P) (Groenendijk and Kroes, 1999; Pferdmenges et al., 2020). Models that can simulate surface transport of P in the form of losses and erosion include ADAPT, ANIMO, APEX, COMET-FARM, DayCent, DNDC, and RZWQM2.

Table 6. *Phosphorus pools, processes, loss accounting capabilities of each model.*

Model	**P fertilizer input**	**Organic P sources (crop residue, manure)**	**Labile P (soluble P)**	**Unavailable P (immobilized)**	**Crop uptake P**	**Surface P processes (erosion, leaching, etc.)**
ADAPT	Y	Y	Y	Y	Y	Y
ANIMO	Y	Y	Y	Y	Y	Y
APEX	Y	Y	Y	Y	Y	Y
APSIM	Y	Y	Y	Y	Y	N
CANDY	---	---	---	---	---	---
CERES	Y	Y	Y	Y	Y	---
COMET-FARM	Y	Y	Y	Y	Y	Y
CFT	---	---	---	---	---	---
CropSyst	---	---	---	---	---	---
DayCent	Y	Y	Y	Y	Y	Y
DNDC	Y	Y	Y	Y	Y	Y
DSSAT	Y	Y	Y	Y	Y	---
Holos	N	N	N	N	N	N

Model	**P fertilizer input**	**Organic P sources (crop residue, manure)**	**Labile P (soluble P)**	**Unavailable P (immobilized)**	**Crop uptake P**	**Surface P processes (erosion, leaching, etc.)**
NLEAP	---	---	---	---	---	---
RZWQM2	Y	Y	Y	Y	Y	Y
SALUS	Y	Y	Y	Y	Y	---

--- signifies missing information

2.3.4. Hydrological modules

One of the base components of all agroecosystem models is a hydrological module. The hydrological module is used to describe the distribution and movement of water into and through the soil profile. There is a range in mechanistic pathways that models can adopt to simulate water fluxes throughout the soil profile (Diekkruger et al., 1995). This multi-model review evaluates the following water processes and includes the mechanistic pathways when possible: soil matrix, macropores, surface water, infiltration, groundwater and streamflow (**Table 7**). Pathways for water in the soil matrix include but are not limited to Darcy's Law, the Richards equation, and storage routing (Diekkruger et al., 1995). Macropore transport was not included in most of the models evaluated. Where macropores are included in the models, by-pass flow is the general pathway utilized (Kroes et al., 2017; Pferdmenges et al., 2020). Surface water simulations are included in the majority of the models evaluated but no specific mechanistic processes were discussed. Infiltration methods varied widely in the models and include conceptual curve number approach, the Green and Ampt equation, and a capacity-based process. Few models included in this evaluation include ground water and stream flow as processes, as these are often features specifically found in watershed models.

Table 7. *Hydrological components of models and their general approach.*

Model	Matrix	Macropores	Surface Water	Infiltration	Groundwater	Streamflow
ADAPT	Darcy with Dupuit-Forchheimer assumptions	bypass flow	Yes	Curve Number, Green & Ampt	Darcy's law	no
ANIMO*	yes	bypass flow	Coupling with external hydrological model necessary (SWAP model)			
APEX*	storage routing	bypass flow	Yes	Curve Number, Green & Ampt	yes	yes
APSIM	Richards' equation	bypass flow	Yes	Advection-dispersion equation and SCS Runoff Curve Number	Darcy's law	---
CANDY	storage routing	unknown	Yes	capacity based	yes (as sink)	---
CERES	Darcy's Law	unknown	Yes	Curve Number	Darcy's Law	---
COMET-FARM	Richards equation	no	Yes	capacity based	no	no
CFT	yes	no	Yes	capacity based	yes	no
CropSyst	Richards equation	---	Yes	Yes	yes	---
DayCent	Richards equation	no	Yes	capacity based	no	no
DNDC	yes	bypass flow	Yes	Yes	---	---
DSSAT	storage routing	---	Yes	Curve Number	---	---
Holos	---	---	---	---	---	---
NLEAP	---	---	---	---	---	---
RZWQM2	Richards equation	bypass flow	Yes	Green & Ampt	Darcy's law	only as sink
SALUS	Darcy's Law	unknown	yes	Curve Number	Darcy's Law	---

--- signifies missing information

2.4. Model limitations and sources of error

Despite decades of development agroecosystems remain imperfect representations of complex systems (Cherry et al. 2008, Harris 2012). The scale and complexity of agroecosystem models lead to uncertainty in the parameterization and validation processes as well as errors in model outputs (Cherry et al., 2008; Schulz et al., 1999). Numerous model review papers exist that have evaluated agroecosystem models for different purposes and each with distinct objectives (Beckie et al. 1995, Diekkrüger et al. 1995, Rodrigo et al. 1997, Cherry et al. 2008, Manzoni and Porporato 2009, Amatya et al. 2013, Maharjan et al. 2018, Pferdmenges et al. 2020). Those evaluations resulted in quite similar conclusions in terms of limitations despite the different objectives.

Most of the agroecosystem models compared in previous reviews and this review have similar soil chemical processes included in the modules. The scale of models affects which biogeochemical processes are represented in the model. Generally, models operate on the soil profile to field spatial scale with a daily to monthly time-step (Manzoni and Porporato, 2009). Model operations are often empirically driven and do not include functions and processes that occur at pore-scale in the soil (Six et al. 2004, Blanco-Canqui and Lal 2009). Pore-scale processes include soil organic matter degradation and nutrient mineralization (Blanco-Canqui and Lal, 2004; Brilli et al., 2017; Manzoni and Porporato, 2009; Six et al., 2004). Further issues with modelling include the inaccurate characterization of soils as either heterogeneous or homogeneous pedons vertically throughout the profile or horizontally at the field or landscape scales. Thus, accurate modelling may be limited by the quality of basic soil property input data such as bulk density, soil texture or SOC. Other common issues that resulted in model weaknesses and errors found across most of the models include soil processes such as inaccurate water-filled pore space drainage and decomposition rates.

Inadequate representation of certain management practices including fertilization, tillage and irrigation were also often stated as a model limitation or weakness. Brilli et al., (2017) reviewed 9 agroecosystems models and found that most models do not include modules for grassland management that are not related to rangelands. Furthermore, that study also highlighted a lack of representation for ecosystem disturbances such as clearing and burning and their effects on soil processes particularly over longer time horizons (Brilli et al., 2017). A study by Maharjan et al., (2018) in which 16 agroecosystem models were reviewed found that despite the prevalence of tillage in agriculture and the perceived impacts on soil physical quality and vertical nutrient distribution within the soil profile no models adequately covered all of the known impacts of tillage. The Maharjan et al., (2018) study highlights one of many modelling components that require improvement to more accurately predict and simulate the impacts of specific agronomic practices. The following section will highlight limitations, weaknesses, and sources of error specific to the models being reviewed.

In a calibration and validation study performed by Gowda, et al., (2012) the model ADAPT was found to underpredict subsurface drainage in the calibration phase and overpredict total subsurface drainage in the validation process. Furthermore, the study found that ADAPT underpredicted nitrate losses during validation as well as over predicting plant N uptake (Gowda, et al., 2012).

A model calibration study by McGechan and Hooda (2010), underlined ANIMO's inability to accurately simulate inorganic P losses due to the model not including the leaching of inorganic P attached to mobile colloids. In a multi-model comparison calibration and validation study by Groenendijk et al., (2014) ANIMO was found to overestimate certain components of the N fluxes including leaching and biological fixation while underestimating crop N removal.

In a comparison study conducted by Amatya et al., (2013) it was noted that APEX does not include programming to run error and uncertainty analysis, a feature found in most other models discussed here. In a study by Pferdmenges et al., (2020) comparing 26 models, APEX was noted for using by-pass flow for macropores which limits the model's capacity to simulate particular P.

A review by Brilli et al., (2017) observed that APSIM's main weaknesses lay in the N cycle model structure where overestimations and underestimations of supply, leaching and emissions were commonly found in the studies evaluated. Furthermore, Brilli et al., (2017) noted that APSIM does not include NH_3 volatilization in the N cycle. A model performance evaluation study by Wolday and Hruy (2015) found that APSIM overestimates crop development and nutrient stress. Archontoulis et al. (2014) found that APSIM underestimated residual inorganic N at harvest.

A model simulation study by Franko et al., (1995) established that CANDY underestimated crop N uptake. Furthermore, CANDY does not include simulation routines for most of the greenhouse gases (**Table 2**).

A review by Thomas et al. (2013) highlighted the following limitations for the model CERES: no SOM representation below 20 cm, tillage effects not adequately represented, overestimation in N_2O emissions and no current validations for perennial crops. El Akkari et al.

(2020) found that CERES had difficulty simulating N translocation processes and crop uptake in belowground structures.

In an evaluation by Peter et al., (2017) COMET FARM was found to exclude emissions from machinery, fuel, pesticides and fertilizer types in its carbon emissions accounting when compared to similar decision support tools. Additionally, the model currently uses US soil data as a primary input and its capacity for being adapted to the Canadian context is unknown.

An assessment by Kayatz et al., (2019) found that CFT overestimated plant available water and does not include parameters for impermeable layers in the soil or capillary rise from groundwater. Kayatz et al., (2019) further highlight potential sources of errors in the CFT model that could be derived from the use of global gridded climate data as opposed to regional or site-specific meteorological data.

In a multi-model review by Maharjan, et al (2018) CropSyst when compared to the other models in the review did not include impacts on bulk density and other soil physical characteristics from management practices such as tillage. Further limitations to CropSysts use include no greenhouse gas simulations and a lack of a P pathway module**.**

A review by Thomas et al., (2013) highlights static bulk density as a source of error or weakness of the DayCent model as well. Brilli et al., (2017) observed that DayCent has been cited as frequently over and underestimating N emissions and SOC content.

In a review comparing N fate models, Amatya, et al., (2013), observed DNDC model limitations such as no water routing of particulate nutrients and no representation for nutrient losses to the air. A review by Brilli et al., (2017) found that soil structure in the DNDC model remains constant despite the presence of management modules that include tillage.

Brilli et al., (2017) highlighted residue management in the DSSAT model as a source of model weakness. Simulation of residue incorporation led to overestimations in SOC in a review study by Hartkamp et al. (2004).

A study by Minshew et al. (2002) found that NLEAP consistently underestimated NO_3-N leaching compared to observed values. Conversely, Beckie et al., (1995) found that NLEAP consistently overestimated NO_3-N levels in the upper soil horizons. In the same study, NLEAP was found to underestimate total soil water in simulations (Beckie et al., 1995).

In a study comparing two models, Smith et al. (2020) found that RZWQM2 overestimated runoff compared to the other model. A limitation of the RZWQM2 model is the lack of simulation capacity for most major GHG emissions (**Table 2**).

A limitation of the model SALUS is the lack of simulation capacity for most major GHG emissions. Furthermore, SALUS does not include pathways for soil carbon or phosphorus losses through surface erosion of sediment or leaching.

3. Modelling approaches best suited for BC

3.1. Five most suitable models

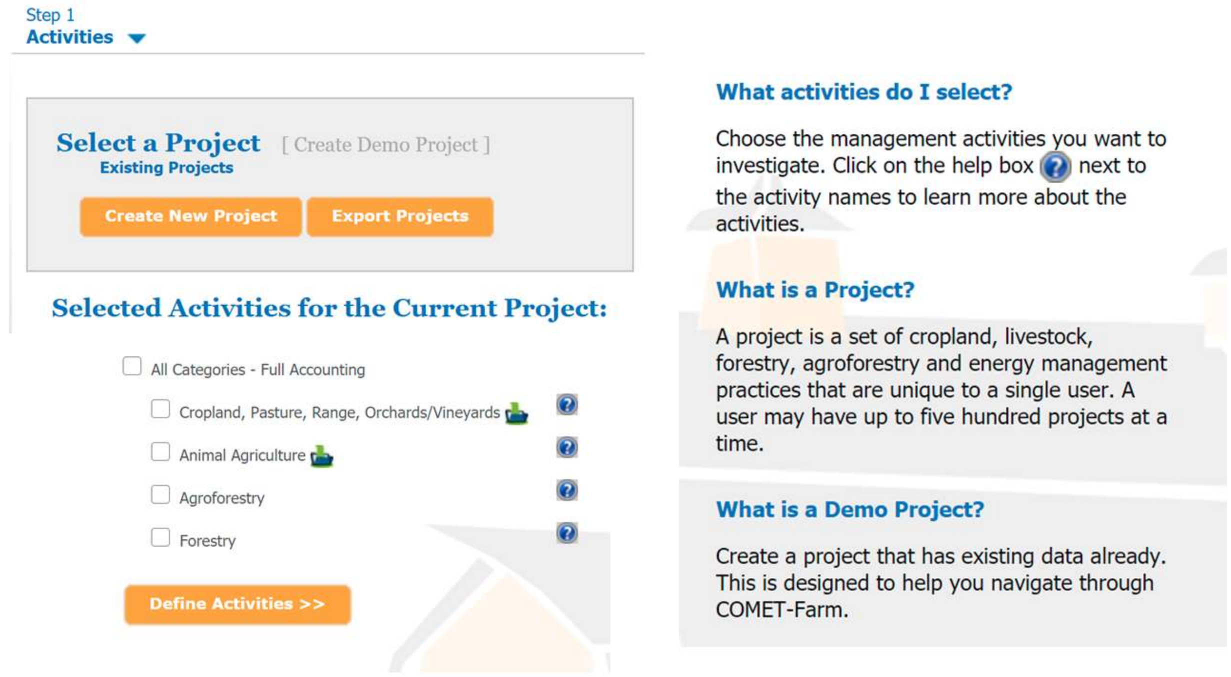
Using an additional 8 criteria (Table 8) we further refined our list of models to a set of five most suitable for simulating agricultural GHG benefits of BMP for agriculture in BC. These models all are likely to simulate at least one of the BMPs from the preliminary list of promising options we developed that would address a variety of agricultural emission sources (**Table 9**). Required input data of selected models are categorized and summarized in the appendix (**Table A 3**) and the limitations are summarized in **Table 10**.

Table 8. *Review criteria for suitability and effectiveness of simulating agricultural GHGs benefits of BMP for agriculture in BC.*

Selected Models	BMP GHG benefit simulation	Adapted for BC climate and soil?	Accessibility and platform for BC users	Accounting for GHGs from agriculture, LULUCF, and energy	Applicability to livestock and cropping systems	Temporal and spatial scale of the model simulation	Economic component	GHG emission reporting
Holos	Yes	Yes	Yes, free download on PC	Yes	Livestock and forage	Annual time step at farm scale	Yes	Net emission at farm scale
COMET-FARM	Yes	No	No, but the web-based application could potentially be adapted by BC	Yes	Cropland, pasture, range, livestock, orchards, and vineyards	Daily step simulation at entity scale	Yes	Net emission, eCO2, at farm scale
CFT-GHGs	Yes	No, but success in AB and Atlantic provinces	Yes, free for farmers and available for purchase for organization	Yes	Livestock and annual crop (applicability for perennial crops is being developed)	Annual simulation at field scale	No	Product-based carbon footprint
DNDCv.CAN	Yes	Yes	Yes, free download on PC	Only agriculture	60+ types of crops and the capability of creating entries for new crops	Daily step simulation at site or regional scale	No	Net emission, eCO2
DayCent / CENTURY	Yes	No, but great potential to adapt for BC	Yes, free download on PC.	Does not account for energy	Not calibrated to any specific crop	Daily or monthly simulation at field scale	No	Daily emission by gas type

Holos is likely to be more readily parameterized or even re-programmed for BC than other models because it was developed by Agriculture and Agri-Food Canada with soil and environmental properties included in the software at eco-district level based on climate data and Canadian soil types. Holos software program is a PC-based application and available for free download. The whole-farm approach of Holos accounts for GHG emissions from agriculture, LULUCF and energy sectors to provide annual net emission at the farm-scale. However, Holos was designed with a focus on GHG emissions from livestock operations and forage crop production. It has been recently programmed to simulate above- and below-ground C sequestration of shelterbelts (Kröbel et al. 2020). Vegetable production and non-forage perennial systems, such as orchards and vineyards, have not been modelled in Holos to our knowledge. Holos is also designed to be an exploratory tool to envision and test hypothetical farm management scenarios in the future rather than an accounting or GHG inventory tool. Therefore, the intended use of the model should be clearly defined before investing any further effort into model modification.

COMET-FARM is a carbon and GHG accounting system developed by USDA and Colorado State University using USDA entity-scale Methods (Eve et al. 2014). Users can access the COMET-FARM tool online (https://comet-farm.com/Home), where methodology documents, tutorials, and other resources are also available. Upon opening the web-based application, the first step is for users to create a project by selecting the activities they want GHG emissions for (**Figure 2**). Moving to step 2, an interactive map will appear to help users to locate the land parcels they are managing (**Figure 3**). This built-in GIS component can retrieve geo-referenced soil and environmental data of the selected land parcels. On the same page, user can enter their management data for historic (pre-2000), baseline (2000-2020), and a 10-year scenario in the future. Once the management data are entered for each of the selected activities and related land parcels, the different modules of COMET-FARM, field, livestock, and energy, will account for farm-scale net GHG emissions from the three major sectors, agriculture, LULUCF and energy. Different from Holos, COMET-FARM is applicable for a wide range of annual and perennial cropping systems, including orchards, and vineyards, and also pasture and rangeland for livestock systems. Although the current version of COMET-FARM only supports land in the US, this web-based application sets a great example for a user-friendly GHG accounting tool for BC to consider.



Step 1
Activities ▼

Select a Project [Create Demo Project]
Existing Projects

Create New Project | Export Projects

Selected Activities for the Current Project:

☐ All Categories - Full Accounting
☐ Cropland, Pasture, Range, Orchards/Vineyards
☐ Animal Agriculture
☐ Agroforestry
☐ Forestry

Define Activities >>

What activities do I select?

Choose the management activities you want to investigate. Click on the help box ? next to the activity names to learn more about the activities.

What is a Project?

A project is a set of cropland, livestock, forestry, agroforestry and energy management practices that are unique to a single user. A user may have up to five hundred projects at a time.

What is a Demo Project?

Create a project that has existing data already. This is designed to help you navigate through COMET-Farm.

Figure 2. *Project initiation page (Step 1) of COMET-Farm web application.*

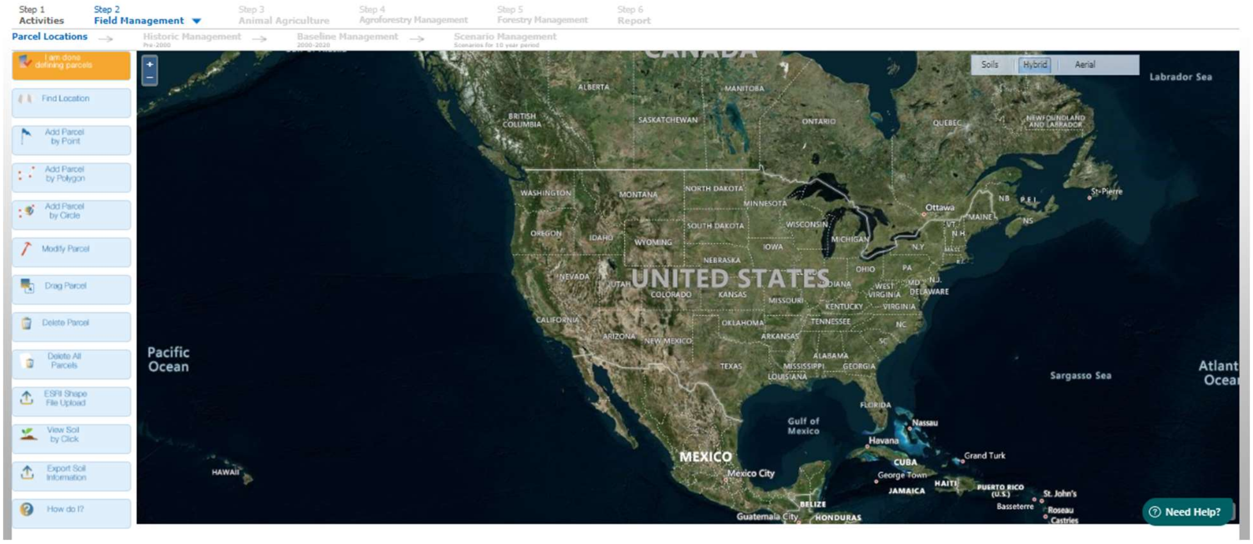


Figure 3. *Field management (Step 2) of COMET-Farm web application.*

The GHG component of the Cool Farm Tool (CFT) is an empirical model developed in the United Kingdom based on global datasets of GHG emissions and soil C sequestration. The CFT has been successfully adapted to quantify annual on-farm GHG emission for navy beans production in Ontario and Manitoba, and currently adapting for beef production in Alberta. The current version of CFT-GHGs covers mostly annual crop systems and livestock systems with the applicability for perennial crops being developed. In terms of functionality and required user inputs, CFT is the easiest one to use among all five selected models. However, the GHGs metric of CFT works on a per-product basis. This enables larger companies to assess and share with their consumers their GHG footprint but could limit the use of this model for other objectives unless conversions were made. In contrast, the whole-farm assessment of GHGs emission inventory carried out by Holos and COMET-FARM, CFT reports a product-based carbon footprint. For example, converting arable land to forest may affect the farm's net GHG emissions, but will not impact the carbon footprint of food produced by this farm.

DNDC.9.5.v.CAN is the Canadian version of DNDC model, a widely used and studied process model that simulates the daily dynamic of soil carbon and N pools at a site or regional scale. DNDC.9.5.v.CAN is applicable to over 60 types of crops and users can create entries for new crops if data for required parameters are available. While DNDC.9.5.v.CAN simulations can only account for the GHG emissions from agricultural production, DNDC, the parent model, has been adapted to simulate GHG emission from the change of land-use (Deng et al. 2020). As a process model, DNDC9.5.v.CAN requires input on extensive details of the site, soil properties, and crop management activities, and intensive parameterization which has been shown to produce accurate prediction but may limit usability.

DayCent is the daily-step version of the CENTURY model, which is used to simulate C and nutrient dynamics for different types of ecosystems including grasslands, agricultural lands, forests, and savannas. Similar to DNDC.9.5.v.CAN, DayCent is also a process model, which requires extensive input data to achieve optimal functionality. DayCent, like DNDC.9.5.v.CAN requires parameterization for specific climate and cropping systems. The CENTURY model has been used in combination with empirical data and Intergovernmental Panel on Climate Change (IPCC) Tier 1 and 2 methodologies to estimate GHG emission from agricultural land-use change for the Canadian national GHG inventory (McConkey et al. 2014). The core of COMET-FARM web tool is also adapted from DayCent. The algorithms and parameters of DayCent are well documented and fully open to the public, which gives it a great potential to be adapted for BC agriculture. With sufficient resources and technical support, adapting a process model, such as DayCent or DNDC.9.5.v.CAN, for BC crop and livestock systems with local environmental variables could likely be used to evaluate a number of BMP options and their MRV.

Table 9. *Limitations and sources of errors of the top five selected models.*

Models	Limitations	Source of errors
HOLOS	- Currently only applicable to livestock systems	- Fixed estimates for many variables based on Canadian average and/or expert opinion
CFT-GHGs	- Limited carbon sequestration accounting for livestock producers - Does not distinguish between pesticide type	- Overestimated plant available water and does not include parameters for impermeable layers in the soil or capillary rise from groundwater - Potential sources of errors due to the use of global gridded climate data as opposed to regional or site-specific meteorological data.
COMET-FARM	- Exclude emissions from LUC, crop residues, machinery, fuel, pesticides and fertilizer in its carbon emissions accounting - Uses US soils data as a primary input and its capacity for being adapted to the Canadian context is unknown - Does not distinguish between fertilizer type	- Input data represents general conditions derived from aggregate data sources, which only approximate the specific conditions at a particular field site
CENTURY/DayCent	- Unable to simulate energy use and related emission - Currently unable to simulate land-use change to perennial energy crops	- Tillage does not affect a static bulk density - Under/Overestimation of N emissions - Under/Overestimation of CO2 emissions
DNDCv.CAN	- Unable to simulate energy use and related emission - No water routing of particulate nutrients - No representation for nutrient losses to the air - Currently unable to simulate land-use change to perennial energy crops	- Tillage does not affect a static soil structure - Under/Overestimation of SOC - Over estimation of N leaching

In our *Report 2: Multi-criteria Framework for GHG Emissions and Co-benefits* we identified a preliminary set of BMPs that could provide GHG emission reductions and/or sinks in the Agriculture, LULUCF and/or Energy sectors. While the models that we reviewed here were primarily selected for their suitability to simulate GHG benefits from agricultural production that would be accounted for in Agriculture as N_2O and CH_4 emission reductions or in LULUCF as C sequestration in vegetation and soils, some of the models could also simulate CO_2 emission reductions in the Energy sector. It is however unlikely that the set of models we have selected here would be useful for evaluating all of our preliminary set of BMPs. As shown in **Table 10**, of our top five models, Holos could potentially simulate GHG outcomes for the largest number of BMPs (6 of 11) in our preliminary set but is very limited in terms of simulating co-benefits.

Alternatively, CFT has a more comprehensive set of functions which would enable the evaluation of a greater number of environmental co-benefit of the BMPs but would likely be effective at modelling on a few BMPs. Out of the five most suitable models, Holos, COMET-Farm, and CFT are capable of evaluating BMPs applicable to not only agricultural sources, but energy (e.g. electric tractors) and LULUCF (e.g. planting woody perennials on farm). None of these five models can evaluate the effect of preserving forests and retrofit greenhouses. To model preserving forests the CBM-CFS3 could be used. CBM-CFS3 has been used to simulate C stock change and GHG emission for forest management for reporting in the Canadian national inventory. To model the benefits of BMPs such as greenhouse retrofitting other energy or life cycle analysis models would need to be identified.

Table 10. *The capability of the top five models to evaluate BMPs for GHG benefits and co-benefits.*

Applicable model	**BMPs**	**Co-benefits that can be evaluated by the model**					
		Soil quality	**Water quality and conservation**	**Air quality**	**Biodiversity and pest management**	**Financial risks and benefits**	**Adapt-ation**
HOLOS	Rotational grazing Anaerobic digestion - renewable biogas Electric tractors Cattle feed additive - 3NOP Plant woody perennial Manure composting					X	
COMET-FARM	Plant woody perennial Rotational grazing Nitrification inhibitor - DCD		X	X			X
CFT	Plant woody perennial Electric tractors Nitrification inhibitor - DCD	X	X	X	X	X	
DNDC	Plant woody perennial Rotational grazing Cover crops Nitrification inhibitor - DCD	X	X	X			
CENTURY/ DayCent	Cover crops Rotational grazing Nitrification inhibitor - DCD	X	X	X			

3.2. Integrated modelling approach

Given that no one model is likely to effectively simulate both GHG benefits and all potential co-benefits, it may be important to use multiple models to evaluate BMP options. Furthermore, to compare multiple BMPs and/or tack their performance beyond the field scale, e.g., regionally or provincially, integrating modelling efforts with a geographical information system (GIS) to account for variation in soils and climate will be essential.

To account for both GHG benefits and co-benefits, multiple models could be run concurrently and their output collected and collated for comparisons. A tool such as the Multi-Criteria Framework we designed for this project[3] would be effective for this type of comparison as stakeholder values could also be integrated into the analysis. Alternatively, an integrated modelling framework (IMF) could be used to run multiple models simultaneously on a single platform. An example of an IMF is the Climate Change, Agriculture and Food Security Regional Agricultural Forecasting Toolbox (CRAFT) (Shelia et al. 2019). CRAFT was developed to provide a probabilistic risk analysis of climate change in cropping systems (Shelia et al. 2019). CRAFT is open source with a user-friendly interface that uses the models DSSAT, APSIM, SARRA-H and the Climate Predictability Tool (CPT) to assess multiple simulation scenarios using climate forecasts, management and field-collected data to produce maps as well as interactive visualizations. The IMF operates on the Microsoft .NET Windows platform and the design and structure of the platform provide easy adaptation for use with other models and spatial processing tools. This type of platform could be developed to enable comparisons of BMPs that include the simulation of GHG benefits (e.g. Holos) from one of the top five models and other models better suited for simulating co-benefits (e.g. water management with RZWQM2).

Another approach for integrating the simulation of outcomes from multiple BMPs would be to use a GIS. Given that performance of many BMPs is dependent on site conditions, a GIS would enable the integration of local soil and climate data with census data or other spatially explicit inputs. An example of this approach currently being developed within AFF is an air emissions model (Boulton et al., 2014, Foyle, personal communication, 2021). This GIS-based

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[3] For details see *Report 2: Multi-criteria Framework for GHG Emissions and Co-benefits*

air emission inventory model accounts for air pollutants, e.g. particular matters (PM), ammonia (NH_3), and volatile organic carbons (VOC), from a variety of agricultural sources, such as fuel consumption, energy use, pesticide application, and soil and cropping. An empirical model was developed for each source of emissions to calculate spatially resolved emission using GIS-based activity data, e.g. Agriculture Land-use Inventory (ALUI) and Agricultural Census. Emission factors of particular sources and types of gases are extracted from published studies applicable to BC (Boulton et al., 2014). Emission factors and geospatially referenced activity data function as one of the empirical model components in the air model that simulate emissions annually (Boulton et al., 2014). The level of details being considered in each model component is dictated by the amount of supportive scientific information available. A similar approach could be used to estimate GHG benefits and co-benefits of current agricultural practices and their associated BMPs. There is likely a strong synergy between the ongoing development of this air model and the development of modelling for agricultural GHG emissions in BC. There are, however, some key limitations to this type of integration:

1. The empirical equations for many agricultural practices and associated BMPs are still not well developed, particularly for BC, e.g. fruit production;
2. This empirical modelling approach has limited capability to simulate long-term GHG emissions or synergies among BMPs;
3. For most BMPs, there is no system in place that meets international reporting requirements for collecting spatially explicitly activity data.

4. Recommendations

4.1. Develop a diversity of approaches

Most of the 16 models we reviewed for simulating GHG benefits also adequately simulated N while few models included sufficient modules for C and P routines. Less than half of the models include representation for all of the GHGs (ANIMO, COMET-FARM, CFT, Daycent, DNDC, DSSAT). Of those models, CFT does not include a P module. Most of the models were designed to run at the plot scale while a few such as DNDC include a user-friendly GIS interface (Amatya et al. 2013). COMET-FARM and CFT are both web-based which provides access to many potential users (Paustian et al. 2012, Maina et al. 2014, Ziegler et al.

2016) COMET-FARM is built from the same modelling processes as DAYCENT (Paustian et al., 2012).

Of the 16 models reviewed here in detail, these five seem to meet our more specific criteria for simulating BMPs for BC agriculture: Holos, COMET-FARM, CFT-GHGs, DNDC.9.5.v.CAN and DayCent/ CENTURY. These models all have features and components that can simulate conditions of the agroecosystems located in the province. Each of the models however had some limitations. The results of this review suggest that no model considered is ideal, and further comparison and actual testing of the more promising models for BC should be a priority next step. Multiple models will probably be needed to effectively simulate the GHG benefits and co-benefits for numerous BMPs designed for BC's diverse agricultural production. The ideal modelling strategy for BC could potentially take shape in one of but not restricted to the following options:

1. Modify a ready-to-use empirical model to be compatible with a variety of production systems. For example, expanding the functions of Holos to include major field crops in BC, such as blueberry, tree fruits, and field vegetables.
2. Adapt and calibrate one or more of the process models, e.g. DayCent and DNDCv.Can, for a prioritized set of systems and BMPs in the BC context.
3. Use multiple complementary models and integrate them in a platform that enables comparisons across BMP options, and ideally includes spatially explicit data and outputs.

Based on our analysis and interactions with AFF we have refined the criteria that models should be selected by. We suggest that the end product should meet the following requirements:

1. Capable of simulating GHG reduction from most crop and livestock systems in BC
2. Can be integrated with a geospatial database of BC's soil, climate, and land use
3. Consistent with methodology recognized by ECCC for provincial and national reporting
4. User-friendly interface for farmers and farm advisors to conduct farm-level analysis and program reporting
5. Contains an economic component to support provincial policy analysis.

4.2. Steps for developing a modelling approach in BC

To develop an effective modelling approach for BC a detailed strategy should be developed. Our recommendations for steps that should be included in this strategy are:

1. **Develop GHG emissions database**: Developing a database to house and securely share empirical data would substantially enhance the utility of future modelling efforts. These data would include production outcomes for crop or livestock systems (e.g. yield), management information (e.g. inputs), economics (e.g. costs of inputs), soil properties, GHG emissions and other environmental impact data (e.g. leaching). Targeted input variables for the database could be selected once the models have been identified. The BC Agricultural Climate Adaptation Research Network (ACARN) has developed a database infrastructure that would be suitable for housing this type of data. Compiling and sharing previous data collected by researchers across the province would substantially enhance the development and testing of models.
2. **Detailed testing of models**: While a number of models have been identified that show promise for BC's diverse agricultural production, testing, using empirical datasets would be necessary to ensure they are meeting the outlined criteria before making any selection. A number of researchers across the province have been running experiments to quantify BMP benefits that could provide the data required for parameterization and validation. These data could be used by modellers to quantitatively assess the efficacy of the models capable of multiple outcomes or combinations of models. A best practice would be to compare more than one model using multiple parameters to assess the accuracy of predicted outcomes.
3. **User evaluation**: Models should also be evaluated by targeted end-users to identify if certain models are more likely to meet needs, both in terms of usability and utility of the outputs. This would require a clearer picture of how the models are likely to be used and by whom.
4. **Model selection**: BMP options that are most likely to benefit from a modelling effort should be identified and models selected that would meet the greatest number of criteria for a particular production system or set of BMPs.
5. **Targeted BMP trials**: Field trials should be established for the prioritized BMPs to develop the parameterization and validation data required to model their performance. Ideally, these trials would be developed to encompass a range of soil and climatic conditions where the BMPs would be deployed.

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Appendix

Table A 1. *Complete model list, including the scale and land-use that they were designed for.*

Acronym	Model Name	Version	Model Scale	Land-use	URL or Contact
ADAPT	Agricultural Drainage and Pesticide Transport	2.0.4	plot	agriculture	https://adaptframework.org/
AGROSIM	Agroecosystem Simulation Model	12.93	plot	agriculture	***
ANIMO	Soil processes and nutrient leaching model	4.0	plot	agriculture	https://www.wur.nl/en/Research-Results/Research-Institutes/Environmental-Research/Facilities-Products/Software-and-models/ANIMO.htm
APEX	Agricultural Policy/Environmental eXtender Model	v.1501	plot, region, watershed	mixed	https://epicapex.tamu.edu/apex/
APSIM	Agricultural Systems Modelling and Simulation	7.6	plot, region	agriculture	https://www.apsim.info
AquaCrop	Crop-water productivity model	6.0	plot	agriculture	http://www.fao.org/aquacrop
CANDY	Carbon and Nitrogen Dynamics Model	3.20.17.36	plot	agriculture	https://www.ufz.de/index.php?en=39725
CERES	Crop Estimation through Resource and Environment Synthesis	2.0	plot	agriculture	https://ecosys.versailles-grignon.inra.fr/ceres_mais/ceres.html
CENTURY	---	5.0	plot, region	grasslands, agricultural lands, forests and savannas	https://www.nrel.colostate.edu/projects/CENTURY-model-information/
COMET-FARM	Carbon Management & Emissions Tool	2.3	plot	agriculture	http://comet-farm.com/
CFT	COOL FARM TOOL	0.11.06	plot	agriculture	https://coolfarmtool.org/
CQESTER	---	2.0	plot	agriculture	https://www.ars.usda.gov/pacific-west-area/pendleton/columbia-plateau-conservation-research-center/docs/cqestr/

Acronym	Model Name	Version	Model Scale	Land-use	URL or Contact
CREAMS	Chemicals, Runoff, and Erosion from Agricultural Management Systems	***	plot, region, watershed	land-use impacts on water, sediment, and nutrients	https://www.tucson.ars.ag.gov/unit/Publications/PDFfiles/312.pdf
CropSyst	Cropping Systems Simulation Model	4.0	plot	agriculture	http://modeling.bsyse.wsu.edu/CS_Suite/CropSyst/index.html
DAISY	---	5.2	plot	agriculture	https://daisy.ku.dk/
Daycent	Daily CENTURY Model	DaycCent 4.5	plot	grasslands, agricultural lands, forests and savannas	https://www2.nrel.colostate.edu/projects/irc/
DNDC	DeNitrification-DeComposition Model	DNDC 95 and Manure DNDC	plot, region	agriculture and forest soils	http://www.dndc.sr.unh.edu
DSSAT	Decision Support System for Agrotechnology Transfer	4.6	plot, region	agriculture and forest soils	http://dssat.net
EPIC	Environmental Policy Integrated Climate Model	V.0810	plot	agriculture	http://epicapex.tamu.edu/
Expert_N	---	5.0	plot	agriculture	https://soil-modeling.org/resources-links/model-portal/expert-n
GLEAMS	Groundwater Loading Effects on Agricultural Management Systems	3.0	plot	pesticide and nutrient loading in groundwater	https://www.ars.usda.gov/southeast-area/tifton-ga/southeast-watershed-research/research/models/gleams-model/
HERMES	---	2.0	plot	agriculture	***
Holos	Holos software program	3.0.6		agriculture	https://www.agr.gc.ca/eng/scientific-collaboration-and-research-in-agriculture/agricultural-research-results/Holos-software-program/?id=1349181297838
LPJmI	Lund-Potsdam-Jena managed Land	3.0	regional, global	mixed	https://www.pik-potsdam.de/en/institute/departments/activities/biosphere-water-modelling/lpjml
MACRO	---	***	soil profile	agriculture and forest soils	***

Acronym	Model Name	Version	Model Scale	Land-use	URL or Contact
MONICA	Model of Nitrogen and Carbon in Agroecosystems	2.0	plot	agriculture	https://github.com/zalf-rpm/monica/wiki
NLEAP	Nitrate Leaching and Economic Analysis Package	4.2		agriculture	https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/technical/ecoscience/mnm/?cid=stelprdb1044740
Nlos	NLOS Soil Nitrogen Simulation Model	1.0	plot	agriculture	http://www.nlos.ca
NTRM	Nitrogen, Tillage and Residue Management Model	***	plot	agriculture	***
Opus	---	***	plot, catchment	mixed	https://www.ars.usda.gov/plains-area/fort-collins-co/center-for-agricultural-resources-research/water-management-and-systems-research/docs/opus/
PaSim	Pasture Simulation model	5.3	plot	grasslands	https://www1.clermont.inra.fr/urep/modeles/pasim.htm
Roth C	Rothamsted Carbon model	RothC10N	plot	agriculture and forest soils	http://www.rothamsted.ac.uk/sustainable-soils-and-grassland-systems/rothamsted-carbon-model-rothc
RZWQM2	Root Zone Water Quality Model	4.1	soil profile	agriculture	https://www.ars.usda.gov/plains-area/fort-collins-co/center-for-agricultural-resources-research/rangeland-resources-systems-research/docs/system/rzwqm/
SALUS	System Approach to Land Use Sustainability	3.0	plot	agriculture	https://nowlin.css.msu.edu/salus/overview.html
SARRAH-H	System of Agroclimatological Regional Risk Analysis	3.3	plot	agriculture	https://sarra-h.teledetection.fr/ModeleSARRAH_En.html
SPACSYS	---	4.0	plot	agriculture	https://www.rothamsted.ac.uk/rothamsted-spacsys-model
STICS	Simulateur mulTIdiscplinair	8.3.1	plot	agriculture and pasture	http://www6.paca.inra.fr/stics

Acronym	Model Name	Version	Model Scale	Land-use	URL or Contact
	e pour les Cultures Standard)				
SWAP	Soil-Water-Atmosphere-Plant	4.0.1	plot	agriculture and forest soils	https://www.swap.alterra.nl/
SWAT	Soil & Water Assessment Tool	SWAT +	catchment, continent	watershed, river-basin evaluations	https://swat.tamu.edu/
SWIM	Soil and Water Integrated Model	***	catchment	regional land-use change evaluation	https://www.pik-potsdam.de/en/institute/departments/climate-resilience/models/swim
EX-ACT	FAO				http://www.fao.org/3/a-i8075e.pdf
Diaterre (French)	ADEME				https://www.ademe.fr/sites/default/files/assets/documents/86159_7739diaterre_4p.pdf
CALM	UK				https://ec.europa.eu/eip/agriculture/en/find-connect/projects/calm-%E2%80%93-useful-online-carbon-calculator-land
CFF					https://www.adm-global.org/productionsupporttools/Ecodesign_CarbonCalculator.html
Alberta Quantification Protocol (even though with-drawn)					https://open.alberta.ca/dataset/b99725e1-5d2a-4427-baa8-14b9ec6c6a24/resource/db11dd55-ce34-4472-9b8b-cb3b30214803/download/6744004-2012-quantification-protocol-conservation-cropping-april-2012-version-1.0-2012-04-02.pdf

---not acronyms

*** information unavailable

Table A 2. *Model system components, operating systems, training availability and intended user.*

Model	Open access (Y/N)	Commercial (Y/N)	System requirements	Training Support (Y/N)						Intended User
				User manual	Direct (email, workshops, etc.)	Videos	Case Studies	Dummy data-sets	Github	
ADAPT	Y	Y	Windows, Mac or Linux -runs the .NET Framework or Mono	---	Y	Y			Y	Extension, Industry
ANIMO	N	N	PC/MS-DOS, SUN/UNIX, VAX/VMS	Y	Y	Y	Y	N		Researcher
APEX	Y	---	Windows, Linux	Y	Y					Researcher, Extension
APSIM	Y	Y	Windows, Linux and OSX	Y	Y	Y	Y	Y	Y	Researcher
CANDY	Y	---	---	Y	Y	Y	---	Y	---	Researcher
CERES	Y	---	MS DOS, Windows, and Unix systems (including Linux)	Y	Y	Y	---	Y	---	Researcher
COMET-FARM	Y	Y	none, system is online	Y	Y	N	N	N	---	Extension, Producer, Land Manager
CFT	Y	Y	none, system is online	Y	Y	Y	Y	N	---	Producer, Industry and Policy-makers
CropSyst	Y	---	MS DOS, Windows and Windows 95 versions	Y	Y	N	N	N	---	Researcher
DayCent	Y	---	---	Y	Y	N	Y	Y	---	Researcher, Extension, Policy-makers
DNDC	Y	---	Windows	Y	Y	---	Y	Y	---	Researcher

DSSAT	Y	Y	Windows, Linux and iOS platforms	Y	Y	---	Y	Y	---	Researcher, Teacher, Extension, Industry, and Policy-makers
NLEAP	Y		MS DOS, online	Y	---	---	Y	---	---	Researcher, Extension, Policy-makers
RZWQM2	Y	---	Windows 7 and later	---	Y	---	Y	---	---	Researcher, Extension
SALUS	---	---	Windows, Linux and iOS platforms	---	---	---	---	---	---	Researcher

Table A 3. *Table of input parameters for five most promising models: HOLO, COMET-Farm, CFT-GHGs, DNDCv.CAN and DayCent/CENTURY.*

Selected Models	Required Input Parameters/Data						
	Weather/ climate data	**Site information**	**Soil properties**	**Crop management activities**	**Livestock management activities**	**Energy use**	**Land use**
Holos	- Monthly average temperature (ºC) - Annual total precipitation (mm) - Potential Evapotranspiration (mm)	- Year - Ecodistrict - Province - Topography	- Direct and indirect soil N2O emission factor - % of annual soil N2O emission allocated monthly - Emission factor for volatilization - Fraction of N lost by leaching - Soil texture and soil type - Fraction of N by volatilization	- N and P fertilizer rate (kg/ha) - Crop type and yield - Tillage intensity - Area of irrigation - Herbicide usage	- Feed type, feed additives, ration mix - Pasture and grazing usage, duration, and quality - Herd size and composition (age and sex) - Type of operation and manure handling system - Barn housing usage - Feedlot type and capacity	- Fertilizer and herbicide production (kg CO2/kg) - Swine, dairy, house beef (kWh/head), and poultry (kWh/placement/yr) - Diesel and gas (kg CO2/GJ) - Manure spreading (GJ/1000 L) - Irrigation (kg CO2/ha) - Electricity (kg CO2/kWh)	- Type of tree; age, length, rows of tree planting - Area of annual crops, perennial, grassland, and fallow
COMET -FARM	- Data retrieved from USDA soil database via an interactive	- Location and size of land parcel	- Data retrieved from USDA soil database via an	- Rate, timing, type and application method for fertilizer and	- Herd size and composition	- Integrated with the crop and	- Land-use type and size

Selected Models	**Required Input Parameters/Data**						
	Weather/ climate data	**Site information**	**Soil properties**	**Crop management activities**	**Livestock management activities**	**Energy use**	**Land use**
	map application		interactive map application	manure applications - Irrigation method and application rate - Residue management - Crop or pasture management practices since 2000 - Type of tillage system - Cropping sequence, planting and harvest date	- Manure management system - Type of grazing system - Feed character and supplement	livestock management components	
CFT-GHGs	N/A	- Baseline year - Harvested yield and market yield - Product and co-product, and relative economic value of co-product to main product (%)	- Soil texture - Organic matter content (%) - Moisture content - Drainage	- Crop type and crop area - Cover crop and % of area change - Number of pesticide application, category, application rate, and active ingredient (%) - Tillage change and % of area with practice change	- Feed quality and quantity - Manure management system - Herd size and composition (age and sex)	- Fuel consumption - Electricity consumption	- % area converted - To/from forest, grassland, arable - Tree species, tree type, density, size last year (DBH), size this year (DBH), trees planted

Selected Models	Required Input Parameters/Data						
	Weather/ climate data	Site information	Soil properties	Crop management activities	Livestock management activities	Energy use	Land use
			- pH	- Fertilizer type, nutrient, application rate, unit, method, emission inhibitors, and production - Crop residue amount (DM weight) and management options			
DNDCv. CAN	- Daily max. & min. temperature (ºC); daily precipitation (mm);	- Latitude and longitude, total year of simulation	- Soil texture, bulk density (g/cm^3), slope (%), and microbial activity, pH, and salinity	- Crop type, planting and harvest date, and fraction of aboveground plant residue left	- Number of grass cutting, dates of each cut, cut part, and cut fraction	N/A	- Land-use type and size
	- Atmospheric CO2 and NH3 concentration and annual increase rate of atmospheric CO2 (ppm/yr)	- Number of cropping systems, duration of each cropping system	- Soil Organic Carbon at surface soil (kg C/kg), SOC profile, depth of top soil with uniform SOC (m), SOC decrease rate below top soil	- Max. harvested biomass (kg C/ha), C/N ratio of harvested biomass, N demand (kg N/ha), and water demand (g H2O/g DM)	- Grazing hours per day and grazing intensity (heads/ha)		
	- Daily average wind speed, daily solar radiation; daily average relative humidity		- By-pass flow rate, water logging problem, highest groundwater table depth (m)	- Number of fertilizer application, dates, depth, amount, inhibitor, controlled release, and type	- Number of grazing event and start/end dates		
	- N concentratio		- Fraction of macro-	- Plastic film methods,			

Selected Models	**Required Input Parameters/Data**						
	Weather/ climate data	**Site information**	**Soil properties**	**Crop management activities**	**Livestock management activities**	**Energy use**	**Land use**
	n in rainfall (ug N/m^3)		pores, depth of water retention layer (m), - C/N ratio and fraction of litter and humus - Initial NO3 and NH4 concentration at surface soil (mg N/kg)	dates, and covered fraction - Irrigation dates, amount, and methods - Number of manure application, dates, amount, type, C/N ratio, and method - Cumulative thermal degree days and optimum temperature (°C) of crop growth - Leaf area index and vascularity - Flooding events dates and number - Number of tillage, dates, and method			
DayCent /CENTURY	- Daily max. & min. temperature and daily precipitation - Monthly precipitation skewness and standard deviation	- Latitude and longitude - Slope	- Initial organic C, N, P, S aboveground, in surface, and below ground (g/m^2) - Average thermal diffusivity of soil, max/min soil temperature (deg C),	- Management events, dates, and repeating sequence - Fraction biomass harvested above- and belowground; fraction of residue as live and dead.	- Fraction of live shoots and dead plants removed by grazing - Fraction of consumed C, N, P, S excreted in faeces and urine	N/A	- Type of forest and C/(N,P,S) ratio of leaves, roots, wood, and branches. - Gross monthly forest biomass and organic C potential

Selected Models	Required Input Parameters/Data						
	Weather/ climate data	Site information	Soil properties	Crop management activities	Livestock management activities	Energy use	Land use
			and depth interval (cm)				production (g biomass and C/m^2/month)
	- Daily solar radiation		- Number of soil layers and thickness of each layer	- Fraction of shoots, plant residue, and litter removed by fire	- C, lignin (g/m^2), and C/(N,P,S) ratio of added organic matter		- Leaf area index and monthly death rate fraction of leaves
	- Daily average wind speed		- Bulk density and % sand-silt-clay of all layers	- Irrigation type and amount of water applied (cm)			- Symbiotic N fixation rate (g N fixed/g C growth)
	- Average duration of rain event		- Faction water flow across layers, fraction of water loss by drainage, and surface runoff coefficient	- Fertilizer application rate (g/m^2) of N, P, S, and fraction of NO3 and NH4			- Fraction of C,N,P,S removed from the system as roots, branches, wood, and leaves.
	- Daily average relative humidity		- Saturated hydraulic conductivity (cm/sec) and min. volumetric soil water content below wilting point for each layer				- Fraction of C,N,P,S transferred to soil pool as roots, branches, wood, and leaves.
			- Field capacity, wilting point,				- Decomposition rate and C

Selected Models	Required Input Parameters/Data						
	Weather/ climate data	Site information	Soil properties	Crop management activities	Livestock management activities	Energy use	Land use
			baseflow of top layer - Max. P sorption potential and pH - Initial mineral C, N, P, S in each layer (g/m^2)				allocation fraction of root, wood, and ranches - Type of tree removal event