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Canadian farm-level soil carbon change assessment by merging the greenhouse gas model Holos with the Introductory Carbon Balance Model (ICBM)

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ABSTRACT

The farm-level model Holos, developed to explore mitigation options for greenhouse gas emissions (GHG) from Canadian farming systems, includes soil carbon change as a prominent component. Soil carbon was assumed to be constant, except where there was recent change in land use or management (e.g., conventional vs. reduced vs. no tillage). The factors associated with the changes were derived using CENTURY model simulations. To make Holos more responsive to farm management (e.g., crop rotation and residue management) and inter-annual climate variation, it was decided to replace the carbon change factors with the Introductory Carbon Balance Model (ICBM), a simple two carbon pool model driven by inputs from above- and belowground crop residues and manure. We showcase how the model will simulate the impact of crop rotation management decisions on soil carbon change, focussing on the choice of crop and crop residue retention, but considering also tillage and fertilization management. We argue that simulating carbon change at each field involved in the rotation is advantageous because it allows to test the rotation resilience with respect to inter-annual climate variation as well as to validate the model outputs using measurements of scientific long-term field experiments. We propose to report the farm-level carbon change results ranging from annual to centennial time frames which would be in line with the reporting requirements in carbon credit programs, while giving the user the capability to project and test new crop rotation systems using long-term carbon change forecasts.

1. Introduction

Farming systems world-wide have demonstrated astonishing yield increases in recent decades, but the emphasis in farming systems has now expanded to encompass not only food production but also stewardship of the environment. Intensive (or industrialized) farming, with its stresses on nature and landscape values (Breland and Eltun, 1999), needs to be re-oriented towards an elevated balance of economic, rural development and environmental protection (Ten Berge et al., 2000). Policymakers in the European Union (Pacini et al., 2004) and elsewhere have developed economic incentives to foster agri-environmental stewardship (Antle et al., 2003), but these often depend on farm system models to analyze the benefits and trade-offs of management decisions. However, such modeling studies often miss the holistic viewpoint by focussing on a limited number of simulated environmental impacts (e.g., contamination and nutrient losses) (Pacini et al., 2004), thus possibly distorting the policy- or decision-making processes. For a farm-system model to be holistic, scientific knowledge needs to be combined with objectives of stakeholders (farmers, agro-industry, public sector, and environmental groups) to arrive at designs that can be tested and tuned under real conditions (Ten Berge et al., 2000). Such models could reveal management options not yet considered (Sterk et al., 2007).

Greenhouse gas (GHG) mitigation research often focusses on single components within the farm system or on individual goals of the farm manager without taking into account the complexity of interrelationships (Schils et al., 2007). At the same time, farmers need to be continually adapting to changing environmental stresses, societal needs, and economic limitations (Schils et al., 2007). To respond to this conundrum, Janzen et al. (2006) proposed a virtual farm approach that resulted in the creation of the Holos-model, a farm-level GHG emission assessment tool specific for Canadian conditions (Little et al., 2008). In alignment with Pannell et al. (2000) considerations, Holos employed simple algorithms (e.g., emission factors and other simplified approaches) to generate approximate estimates for many aspects of the farm system simultaneously, rather than focussing in detail on one specific facet. The goal was to capture important processes and influences directly pertinent to farming systems, rather than to develop highly complex, demanding simulations (Pannell et al., 2000).

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The Holos model was conceptualized as a farm-level "Virtual Farm" model that links descriptors (farm characterization) and algorithms (e.g., IPCC Tier 2 emission factors) to generate whole-farm greenhouse gas (GHG) emission estimates (Janzen et al., 2006; Little et al., 2008). In addition to estimating GHG emissions, Holos allows users to contemplate GHG mitigation strategies, making it an exploratory tool (Little et al., 2008). Based on 30-yr climate normals, Holos calculates average annual GHG emissions from enteric fermentation, manure management, cropping systems and energy use, taking into account carbon dioxide, nitrous oxide, and methane emissions, as well as carbon sequestration from tree plantings and changes in land use and management (Little et al., 2008). Land use and management options considered are tillage (conventional, reduced, no-till), fallowing, perennial crops and grassland breaking and seeding (Little et al., 2008). Soil carbon change factors were derived through Century model scenarios runs for different zones of Canada (McConkey et al., 2007).

Following Pannell et al. (2000)'s definition, our model development is constrained and directed by deadlines and deliverables, the quality and completeness of available national databases, the size of our development team, and the scientific expertise of contributing scientists. Aside from building a tool to investigate our own questions and potential solutions, our goal was to allow non-scientists a way of exploring similar questions or solutions without requiring the scientific background needed to develop the algorithms. In this sense, while our initial target audience was the science community, we sought also to enfold decision makers in industry and producer organizations; municipal, regional, and national planning and policy; teachers in schools, colleges, and academia; as well as producers themselves (Kröbel et al., 2013). For producers, our aim was not to instruct daily decisions, but rather to project long-term environmental consequences of choosing potential options (Pannell et al., 2000; Janssen and van Ittersum, 2007).

Farm system modeling traditionally considers alternative farm configurations reflecting innovation, effects of policy changes, and scientific application (Janssen and van Ittersum, 2007). Farm setup and management adapt to changes in technology, off-farm income, policy, human capital, demographics, social setting, economic environment (Pannell 1996; Zimmermann et al., 2009), and now also to changes in climate. Management decisions, thus, reflect the goals and aspirations of a single household, determined by available resources, possible activities and external constraints imposed by environment, economy, and social networks (Kruseman et al., 1995). Empirical models are ill-equipped to deal with most of these drivers, as they rely on time-series of observed past behavior (Gibbons et al., 2006; Janssen and van Ittersum, 2007). Non-linear dynamic models may be required to simulate the complexity of agricultural farming systems to be useful for decision making and estimate the effect of management decisions on soil fertility (Bontkes and van Keulen, 2003).

Greenhouse gas emissions from agriculture are mainly diffuse — not confined to a single source (Schils et al., 2007). Farm-level GHG assessments (often focussing on animal production systems) often assume that there is no change of soil carbon storage in their assessments (Gibbons et al., 2006; Olesen et al., 2007; Schils et al., 2007; Rotz et al., 2010; O'Brien et al., 2014), but soil carbon change can contribute greatly to (or negate substantial parts of) the overall farm GHG budget (Beauchemin et al., 2011). For instance, Gan et al. (2012) found that soil carbon change in continuous wheat production versus fallow-wheat production systems was able to temporarily offset GHG emissions. Furthermore, data from long-term experiments in northern Europe shows that GHG emissions associated with production and transport of N fertilizer use can be compensated for by increased NPP (Net Primary Productivity), where each kg of N applied can increase SOC stocks by 1–2 kg (Kätterer et al., 2013). Diversifying crop rotations (Gan et al., 2011a,b,c) and including forages in a rotation (Breland and Eltun, 1999; Bolinder et al., 2010) can enhance soil carbon stocks and fertility further, and thus prolong the emission offsets through additional carbon storage in the soil (Liebig et al., 2010). Accordingly, increasing carbon stocks is often quoted as one of the most cost-effective opportunities to offset GHG emissions (Antle et al., 2002) and many management options have been proposed to achieve this (e.g., Gan et al., 2011b).

To improve the reliability and flexibility of Holos in simulating soil carbon responses to management, we intend to replace the coefficients now used with an embedded, interactive model. The objective of this paper is to present an updated version of this model – the Introductory Carbon Balance Model (ICBM) – for Canadian farm conditions, describe the conceptual assumptions required to incorporate ICBM, present optional input data sources, and offer examples of model outputs with respect to carbon change.

2. Methodology

2.1. The Holos model

Holos 2.1 is a farm-level model and software tool that estimates GHG emissions on an annual time step for cropping systems, tree plantings, and land use and management changes and on a monthly time step for livestock operations. The software requires the user to select the farm location, either through a map or a drop-down menu of ecodistrict numbers. Choosing the appropriate ecodistrict (a subcategory of the National Ecological Framework of Canada (Marshall et al., 1999)) populates default inputs (which the user can override) for climate normals (growing season precipitation, potential evapotranspiration, and monthly average temperature), as well soil type, texture, topography, and yield. The user can select from a choice of 23 annual crops, four different types of perennial crops, summer fallow (land left unplanted for a growing season), grassland (native or seeded), and eight types of tree plantings. Holos also allows the user to define crops or trees not included by default in the software program. The user can select from four distinct livestock operations (beef, dairy, sheep and swine) and other types of livestock or poultry, and provide pertinent production details.

The cropping inputs required by the user are listed in Table 1. Yield is required to calculate aboveground and belowground residues, which in turn are used to estimate N added to soil for calculating direct and indirect N_2O emissions. Yield responses to management (e.g., fertilizer rate) are not explicitly predicted by Holos but are provided by the user. Crop residue ratios, residue nitrogen content, and crop moisture content are crop specific defaults provided by the model, but the user can override these defaults. Similarly, the model provides default crop and region specific emission factors for herbicide application and energy (fuel) consumption from machine operations, but these can be modified by the user. The CO_2 emission factor for energy use in irrigation is an adjustable constant. Default nitrogen and phosphorus fertilization rates are provided but can be modified. Fertilizer inputs are used to estimate N_2O emissions (for N fertilizer) and to estimate emissions from energy used to produce the fertilizers, using coefficients which can be modified. Emissions from soil carbon change are assumed to be negligible, unless there have been recent management changes (area of perennial crops, permanent grassland, and fallow, or changes in tillage system), which

Table 1
Required cropping input parameters for Holos version 2.1.[1]

Input parameter	Unit	Crops	Perennials	Fallow[2]	Grassland
Area	(ha)	x	x	x	x
Yield	(kg ha^{-1})	x	x		
Year seeded			x		x[3]
Year broken					x
Nitrogen application	(kg N ha^{-1})	x	x	x	x
Phosphorus application	(kg P_2O_5 ha^{-1})	x	x	x	x
Irrigation	Yes/no	x	x		x
Herbicide	Yes/no	x	x	x	x

[1] Holos also requires the user to define current and past tillage system and year of change if different.
[2] The user must input area of past fallow and year of change if different from present.
[3] If the user chooses native pasture, the year of seeding is not required.

need to be described by the user along with the year of adoption. The user can also modify provided values for herbicide and energy consumption emission factors for fallow areas. Native grassland systems are assumed to be at equilibrium levels with respect to soil carbon (Smith, 2014). The shelterbelt option calculates aboveground living tree biomass (as a carbon sink) from stand age and row spacing, but assumes constant soil carbon and belowground biomass.

The minimum livestock input requirement is the number of animals, but updating the other optional inputs given in Table 2 is recommended, as the default values may not be representative for individual farms. Additional detailed inputs (not shown in Table 2) include the ability to change emission factors for manure systems and to customize diets (user-defined total digestible nutrients and crude protein content for cattle and sheep; and feed intake and crude protein content for swine). Different housing options are available depending on the livestock system and range from confinement to various grazing areas. Manure storage options encompass several solid and liquid systems (including compost) and direct manure deposition on pasture. The user can also define a custom manure handling option.

User-provided initial and final body weight is used to calculate an average weight for cattle and sheep other than feedlot animals. Feedlot cattle and sheep require the input of initial weight and average daily gain. Animal energy requirements and feed intake are derived from the energy requirements for maintenance, activity, growth, pregnancy, and lactation. Volatile solid production is based on feed intake and feed digestibility and, with the methane conversion factor of the handling system, is used to calculate manure methane emissions. Manure nitrogen is estimated from feed intake, the protein content of the diet, and the nitrogen retention of the animal (e.g., milk and meat). Manure nitrous oxide emissions are calculated with an emission factor specific to the manure handling system. Indirect nitrous oxide emissions are also estimated. Manure nitrogen from handling systems other than direct application on land is adjusted for storage losses and is assumed to be land-applied once per year. Direct and indirect emissions from this land-applied manure nitrogen are estimated, but, as with synthetic fertilizer, crop yield response to the manure is not simulated by the model.

Outputs of the software tool encompass all greenhouse gas emissions (CO_2, CH_4, and N_2O) calculated for each crop, tree planting and land use change, and livestock type input, and is provided as an annual summary in CO_2 equivalents or by individual GHG. For livestock, the user can also investigate monthly results. An uncertainty class, ranging from 20% to greater than 60%, is provided for each output to indicate approximate confidence levels. For life cycle calculations, the software also provides estimates of crop and animal productivity, and also an estimate of dry matter intake and nitrogen use efficiency for cattle, pigs, poultry, sheep, and others (Beauchemin et al., 2010). The software also provides several charts for the calculated results, one of which can be refreshed after changes have been made to the current farm so results are immediately displayed for comparison. Results of individual runs can be exported to a spreadsheet for further analysis.

Carbon change estimates were previously based on changes in land use or management involving tillage, fallow, perennial cropping systems or grassland, with the move towards perennial crops/grassland having the most benefit in carbon gain (Fig. 1). To develop these curves, scenarios were run for three different soil textures (coarse, medium, fine) in nine different reporting zones for Canada, using the CENTURY

Table 2
Required livestock input parameters for Holos version 2.1.

	# of animals	Initial weight (kg)	Final weight (kg)	Average daily gain (kg)	Milk production (kg d^{-1})	Milk fat content (%)	Milk protein (%)	Wool production (kg $yr.^{-1}$)	Housing	Diet	Diet additive[*]	Manure system
Beef												
Cows/calves	x	x	x		x	x	x		x	x	x	x
Stockers and grassers	x	x		x					x	x	x	x
Backgrounders	x	x		x					x	x	x	x
Finishers	x	x		x					x	x	x	x
Bulls	x	x	x						x	x	x	x
Dairy												
Lactating cows	x	x	x		x	x	x		x	x	x	x
Calves	x											x
Young heifers	x	x	x						x	x	x	x
Bred heifers	x	x	x						x	x	x	x
Dry cows	x	x	x						x	x	x	x
Bulls	x	x	x						x	x	x	x
Swine												
Lactating sows	x									x		x
Starters	x									x		x
Growers	x									x		x
Finishers	x									x		x
Dry sows	x									x		x
Boars	x									x		x
Sheep												
Ewes	x	x	x					x	x	x		x
Rams	x	x	x					x	x	x		x
Feedlot	x	x		x					x	x		x
Poultry												
Layers (wet manure)	x											
Layers (dry manure)	x											
Broilers	x											
Turkeys	x											
Ducks	x											
Geese	x											
Other												
Other	x											

* Diet additive = additives to feed that supplement potentially-deficient constituents (e.g., vitamins, amino acids, fatty acids, minerals). Such feed additives can have an impact on enteric methane production in the rumen.

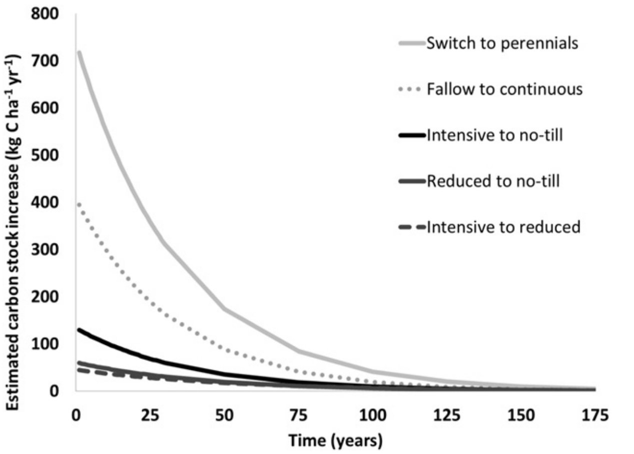

Fig. 1. CENTURY model estimated carbon stock increases over time for different agricultural management options in the semi-arid prairies of Canada.

model (McConkey et al., 2007). As non-linear curves were employed to describe carbon change, the year of management change (tillage practice, areas of perennials and of fallow, grassland establishment or cultivation) needed to be specified. For example, the rate of carbon gain from elimination of fallow diminished with increasing time after the change. The CO_2 removals (or emissions) from calculated gains (or losses) in carbon stock were added to the overall GHG budget of the farm.

2.2. Introductory carbon balance model

The Introductory Carbon Balance Model (ICBM) is a dynamic model based on first-order kinetics that calculates temporal changes in soil C stocks. The underlying philosophy is to have a structure as simple as possible for describing soil organic C dynamics, in a decadal time frame (30 to 50 years), and to estimate parameters from information that is usually available at a farm or regional scale (Andrén and Kätterer, 1997). Since its release, ICBM (or parts of its components) has been applied in different ecosystems and climatic regions. Model applications range from large scale national soil carbon inventories at the IPCC Tier II level (Andrén et al., 2008; Lokupitiya et al., 2010; Borgen et al., 2012) to incubation studies (Kätterer and Andrén, 2001). It has now been used in Canada for about a decade and significant progress has been made to validate and refine the model on data from long-term field experiments. Bolinder et al. (2006), for instance, reported that the performance of ICBM was comparable to the more complex CENTURY model, a finding confirmed by VandenBygaart et al. (2009). Lemke et al. (2010) found that ICBM simulated carbon trends well in a 37 year long-term trial in Swift Current, Saskatchewan. Ellert and Janzen (2006) utilized the ICBM model to understand carbon and nitrogen isotope behavior in a long-term rotation in Lethbridge, Alberta, and found that the model, with adaptions, reflected soil carbon stock change after cultivation and under contrasting cropping systems.

The initial version of the model considered two soil C pools, one young and one old, each with specific decay rates and was calibrated using data from the Swedish long-term Ultuna frame trial in Uppsala for the period 1956–1991 (Andrén and Kätterer, 1997). The decay rate for the young C pool was based on litter bag studies (for straw and roots), while the decay rate for the old C pool was determined by optimizing its value for a bare fallow treatment present at the calibration site. This version is part of a wider array of analytically solved C (and N) models (Kätterer and Andrén, 2001) and is continuously refined as new data and concepts are explored. We are implementing ICBM into Holos based on a version of the model that considers several young C pools, ICBM/3. This version also has one old C pool but considers three, instead of only one, young (Y) soil C pools: Y_l and Y_r, that represent debris derived from above- and below-ground crop residues, respectively, and, Y_m, a pool that accounts for the additions of manure or other organic amendments (Fig. 2). Required are nine input parameters or driving variables:

- I_i, which determines the annual C input to each of the three young pools;
- h_i, the humification coefficient that is specific for each of the young pools;
- r_e, a soil climate-and management parameter that aggregates the external influences on soil biological activity;
- k_Y and k_O, the decomposition constants of the three young pools (0.8 yr^{-1}) and the old C pool (0.00605 yr^{-1} under reference conditions), similar to the initial ICBM version.

The ICBM version to be incorporated into Holos includes other Canadian-specific coefficients developed for cereals, soybeans and forage in short term (3 to 5 years) rotations (Bolinder et al., 2007a), for oilseed and pulse crops (Gan et al., 2009) and for root crops (Bolinder et al., 2015) to estimate annual crop residue C inputs. These coefficients are driven by net primary productivity (NPP) which are estimated from agronomic yields and also take into account rhizodeposition, i.e., extra-root material including root exudates and other material derived from root-turnover. Extra-root C components are included in the calibration of the humification coefficient for roots, h_r (see below). Annual C inputs from manure or other organic amendments (Y_m) are estimated from application rates, total C and dry matter contents. All of the annual C inputs to soil enter and proceed through the respective Y pools (Fig. 2).

The humification coefficient (h) follows approximately the early definition made by Hénin and Dupuis (1945), and in ICBM it is used to determine the fraction of each Y pool that is stabilized and enters the old pool, O (Fig. 2). In the original version of ICBM, which used only one Y pool for both above- and below-ground crop residues, the default value $h = 0.125$ (Andrén and Kätterer, 1997). This value is being refined by including data from other long-term experiments; for example, recent studies suggest it may be controlled by soil texture (Poeplau et al., 2015a,b). The use of an ICBM version with separate coefficients for above- vs. belowground crop residues is driven by recent observations that roots contribute about twice as much C to stable soil C (Kätterer et al., 2011 and references cited therein). This part of the model is currently subject to a re-calibration and the values will be continuously incorporated into Holos. For current scenarios, we used $h = 0.125$ for aboveground and $h = 0.310$ for belowground crop residues. The value for h_m, corresponds to that of solid farm manure and is set by default to 0.310 (Kätterer et al., 2008) but further refinement will be considered in future versions.

Decomposition rates are modified by a factor (r_e) which is the product of three response functions derived from soil temperature (r_T), water content (r_W) and tillage practices (r_C) (Fortin et al., 2011). The r_e factor is multiplied by the first-order decomposition rates of the soil C pools in ICBM (Fig. 2). Site-specific typical values for Canadian Agricultural Ecoregions vary from 0.75 to 1.50 (Bolinder et al. (2008), though a much wider range is expected when using input-data with a higher spatial resolution. Usually, r_e is calculated from standard daily climatic records but it is expressed as a mean annual average value when running ICBM simulations. Soil properties and crop characteristics are also involved to make the parameter more site-specific. When the crop characteristics are excluded (i.e., no transpiration) r_e represents the conditions in a bare fallow (Bolinder et al., 2008). Fallow remains a common practice in Canada, particularly in the Prairie Provinces, although its use has declined drastically in recent years. The intra- and long term inter-annual variations of Canadian climate were addressed by Bolinder et al. (2007b, 2013). For use in Holos, the tillage-factor (r_C) will be adapted to reflect Canadian-specific knowledge assembled from long-term field experiments across the country (VandenBygaart et al., 2003).

In the initial design of the model (Andrén and Kätterer, 1997), a different humification coefficient for manure was used, based on a

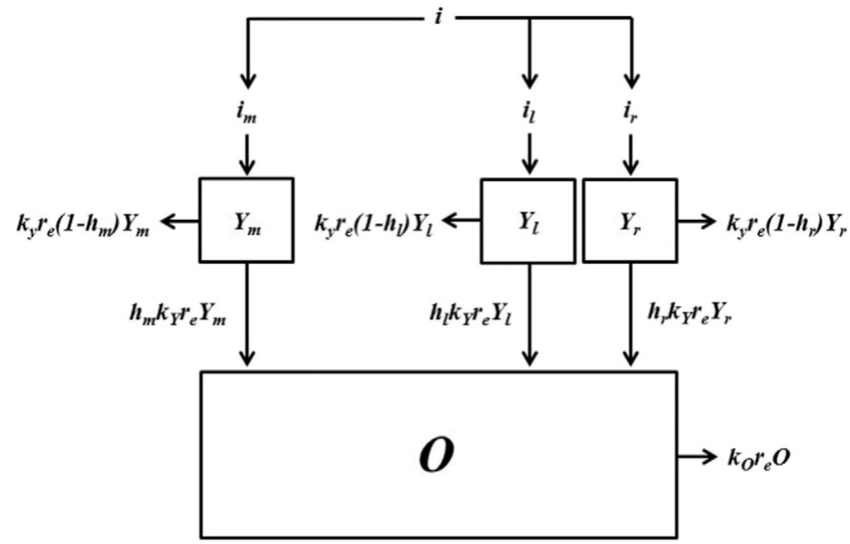

Fig. 2. Structure of the Introductory Carbon Balance Model (ICBM/3) version: i = annual C inputs to soil, k_Y and k_O = first-order decomposition rate constants for the young (Y) and old (O) C pools, h = humification coefficient, r_e = soil climate-management parameter. The subscripts l and r refers to above- and below-ground plant residues and m to manure (see the text for more details).

weighted average h-value for crop residues (above- and below-ground) and manure entering the young pool. Kätterer et al. (2008) subdivided the young pool into distinct pools for crop residues and manure and Poeplau et al. (2015b) divided the crop residues further into above-ground below-ground residues, resulting in the three-young-pool version in this paper. Kätterer et al. (2011) found that h for below-ground crop residues was 2.3 times higher than for above-ground crop residues in a long-term (50 years) Swedish field experiment. Poeplau et al. (2015b) confirmed that using these more specific h values improved the ICBM model performance when simulating other Swedish and Italian long-term field experiments.

However, the value of 0.310 used for below-ground crop residues presented here should not be viewed as final. There is a need to refine and validate this humification coefficient across a wider range of soil, climate and management conditions. The sensitivity of the model to each of the parameters has been stressed in several publications (e.g., Andrén and Kätterer, 1997; Andrén et al., 2008). A detailed sensitivity analysis of the model to both the fixed parameters and the driving variables were presented by Kätterer et al. (2008). Other publications have dealt with the sensitivity of the model to climatic data, soil properties, and other specific factors (Fortin et al., 2011; Bolinder et al., 2013).

2.3. Incorporation of ICBM into Holos

The ICBM model simulates annual changes in soil carbon stocks, and by virtue of its underlying algorithms these stocks move towards an equilibrium state over time. Therefore, given constant climate (constant r_e factor) and crop yield (constant crop residue C input), each cropping system will tend towards its specific equilibrium state. Long-term changes like general yield increases (e.g., new crop cultivars) or increasing temperatures (e.g., from enhanced radiative forcing), however, will cause a continual re-adjustment of the equilibrium state.

ICBM requires inputs of climatic and edaphic properties not always available to potential users. Furthermore, history matters in soil carbon simulations: current soil carbon responses depend on practices and conditions in the past. Estimated initial starting carbon stocks, if inaccurate, may distort simulations of future carbon changes. The model has been developed, calibrated and validated using data of soil carbon measurements (including initial stocks) from long-term field experiments. Most of its applications have also been site-specific (field plots), where measurements or reasonable estimates of initial soil carbon stocks can be made. However, ICBM can also be used for large scale applications with multiple locations. In such cases, exact measurements of initial carbon stocks are not necessarily available and various assumptions are then made about the initial conditions. For instance, Borgen et al. (2012) calculated reference soil carbon stocks (initial conditions) with the ICBM equilibrium equation using a ley cropping system receiving manure (Norwegian national soil carbon budget), with the assumption that it was the most representative historical management. Lokupitiya et al. (2010) also used the equilibrium equations to determine reference soil carbon stocks in a large scale application for croplands in the U.S.; a mean value for C inputs and climatic conditions during the study period by county was used to derive the initial conditions.

ICBM runs in Holos will use the equilibrium equations to estimate current carbon status by considering a 30-yr period (dating back to 1985). The user therefore needs to provide information about management changes within this historical 30-yr period. The equilibrium state will be calculated by averaging the estimated crop residue inputs of the complete rotation, and this will be used as a default starting value for each field of the rotation. However, it is considered to allow a user to provide an initial soil organic carbon stock in place of the default value.

2.3.1. Data requirements and design

Holos uses the publicly available soil-landscape polygons of Canada (SLC) database (Soil Landscapes of Canada Working Group, 2010) as a basis for many default parameters. The SLC database describes soil properties such as classification, texture, profile, depth, slope, and water holding capacity; Holos considers only the ~4800 polygons in agricultural regions (about 5% of Canada's total land area) (Vanin et al., in preparation). Default climate data were generated from monthly climate normals (1980–2010) for minimum and maximum temperature, precipitation, and potential evapotranspiration from a $10 \times 10\ km^2$ grid (daily) climate database of Canada for each SLC (Newlands et al., 2011). The use of monthly climate normals removes the climate variability factor from the model simulation but allows Holos to provide these climate data as representative defaults to the user for simulating long-term averages. The user can over-ride the defaults to provide year-specific values or to investigate climate change scenarios (possibly also climate extremes). Looking forward, climate normals can also be used in automated simulations of randomized daily weather where model applications demand it.

Crop residue (C) inputs in rotations differ from year to year, depending on crop, management practices (e.g., fertilizer rate), and climate.

Individual phases of crop rotations are allotted to different parcels of land ('fields') in successive years, with each field having a unique carbon status. Holos will therefore simulate soil carbon changes on each 'field' assigned to the respective crop in a given year. To reduce information entry, Holos will also allow the user an option to treat the entire 'farm' (all 'fields together') as one unit, with the phases assigned in appropriate proportion. For example, if the producer chooses a 5-year rotation, the entire land area is divided by Holos into 5 equally-sized fields.

2.3.2. Case studies

As a case study, we used measured yields of a fallow–wheat–wheat (*Triticum* spp.) rotation in the "Old Rotation" study in Swift Current, Saskatchewan, started in 1967 (Campbell et al., 1983, 2005). This system was recently analyzed with respect to carbon change (Congreves et al. 2015), and the authors reported a measured gain in carbon of 90 kg C ha^{-1} over 42 years (fallow–wheat–wheat with N and P fertilization), using an estimated carbon stock baseline of 30.5 Mg C ha^{-1} for a soil depth of 0–15 cm, on land previously under a fallow-spring wheat rotation with minimal fertilizer addition since 1922. Using the previous carbon change estimation method in Holos, no carbon stock change would have been calculated as there is no land use change from fallow systems to continuous systems (e.g., there is still fallow incorporated in the rotation) and no reduction in tillage.

As the goal of our new carbon model addition was to represent the effect of management change, we eliminated the impact of the previous land use by calculating the rotations carbon stock equilibrium state of 43.25 Mg C ha^{-1} in the 0–25 cm depth. This steady-state was maintained for 10 years [Period (A), Fig. 4], using the average of the first 6 years as representative yields for the calculation of the equilibrium state. From there on, the model was run using measured yield and straw values (below ground residues were estimated) and measured climate data to simulate soil carbon change for illustrative experimental plots that represent each phase of the rotation in one year.

Our model is intended to simulate greenhouse gas from the diverse crop rotations used in Canada. We therefore created cropping scenarios for three different locations in Canada (Fig. 5), using a potato rotation (*Solanum tuberosum* L.), a wheat rotation, and a corn rotation (*Zea Mays*), as common crop rotations (e.g., historic period A) in Prince Edward Island [Fig. 5 (1)], Alberta [Fig. 5 (2)], and Ontario [Fig. 5 (3)], respectively. None of these rotation choices would have created a carbon change output using the old Holos method. Historical daily weather for the time period 1970–1979, including maximum and minimum air temperatures, total precipitation and potential evapotranspiration data were taken from Bolinder et al. (2007b). The data from three climate stations in different Agricultural Ecoregions (AE) were retained: Charlottetown (AE = 130), Melfort (AE = 149) and Peterborough (AE = 134) and used in examples 1 through 3 (Fig. 5), respectively.

The soil properties used were taken from Bolinder et al. (2008), with data for soil series Charlottetown (clay = 0.05%, sand = 0.80% and SOC = 1.30%), Whitewood (clay = 0.21%, sand = 0.42% and SOC = 2.80%) and Harriston (clay = 0.13%, sand = 0.38% and SOC = 1.13%), that were associated with each of the three climate station records, respectively. These climate data and soil properties were than used to calculate the ICBM soil climate-and management parameter as described in Bolinder et al. (2008) with a fixed mean small-grain cereal yield and considering a constant tillage management.

Each of the rotations underwent a management change: undersowing was introduced to the potato rotation, perennial alfalfa was introduced to the wheat rotation, and soybean was introduced to the corn rotation. In the latter case, we added a scenario where corn stover was removed or retained. The average dry matter yield at Charlottetown was 8 Mg ha^{-1} for potato, 4 Mg ha^{-1} for barley (*Hordeum vulgare* L.) and for 3 Mg ha^{-1} undersown barley; at Melfort 3 Mg ha^{-1} for wheat and 4 Mg ha^{-1} for alfalfa (*Medicago sativa*); at Peterborough 9 Mg ha^{-1} for grain-corn and 3 Mg ha^{-1} for soybeans. The above- and below-ground crop residues were calculated with relative annual plant C allocation coefficients (Bolinder et al., 2007a,b, 2015; Gan et al., 2009).

3. Results

The simulation results presented in this study provide only partial model validation because we replaced a measured starting value (as usually done in carbon modeling studies) with an approximated equilibrium value. The reason for doing so, as explained earlier, is that the Holos is intended for use also outside the scientific community (e.g., producer decision support), where historic soil carbon contents are often unknown and where carbon change estimates are utilized in sustainability assessments of producer management decisions. The results we simulated, therefore, are based on an assumed equilibrium state in disregard of prior land use in order to disentangle management-induced carbon change from carbon change arising from lingering historical effects.

In our Swift Current example (Fig. 4), each simulated plot (representing each rotation phase) clearly shows the fallow years and higher wheat yields (and therefore crop residue inputs) following the fallow year. Two of the plots immediately show a downwards trend in soil carbon stock, but one plot has a slight increase. This continued until some drought years around 1990, which induced a drop in soil carbon stock. All three plots recovered in the following years, but in only one of the three plots does the recovery go beyond the initial soil carbon level.

In the last years of the simulation, two of the plots gained soil carbon, but the remaining plot lost more carbon than the other two plots gained, resulting in an average loss of 95 kg C ha^{-1}. This is due to all phases of the rotation being present in each year, and the loss in one plot is due to this being the fallow year. When calculating the carbon stock change over a 10, 20, and 30 yr period, the systems gained carbon when assessing the last 10 yr period, but lost carbon when assessing 20 or 30 yrs (Table 3). Unfavorable growing conditions in the 1990s caused a decrease in soil carbon stock, which the system then recovered from, thus creating a positive balance in the last 10 yrs.

In simulations for the whole period (37 yrs), we found that one plot gained 256 kg C ha^{-1}, while the other two lost 599 and 50 kg C ha^{-1}, respectively, resulting in an average loss of 131 kg C ha^{-1} (Table 3). However, this result could be biased towards the performance of the last year, so if, for instance, a drought year diminished plant growth (i.e., causing an additional fallow year), we would find a higher carbon loss than is representative for the system. Thus, in our example, we would calculate an average annual system performance and find that the system is essentially in equilibrium (−3.5 kg C ha^{-1} $yr.^{-1}$). Congreves et al. (2015) found that the system, using measured data points for validation, had gained 90 kg C ha^{-1} over a 42 year period, confirming that our assumed starting equilibrium was representative of the investigated system, and that the simulation correctly predicted the system to be near equilibrium.

In the rotation scenarios we created, we were able to demonstrate how the choice of crops and residue management in a rotation influence the carbon content. In the PEI rotation, the continuous barley/potato/

Table 3
Estimated changes in soil carbon stocks of three plots in a fallow-wheat-wheat rotation of the "Old rotation" experiment in Swift Current, Saskatchewan.

	Plot 1**	Plot 2	Plot 3	Average
	kg C ha^{-1}			
Change of the last year*	651	142	−1078	−95
Change of the last 10 yrs	710	63	−410	121
Change of the last 20 yrs	−1041	397	−1014	−553
Change of the last 30 yrs	−984	124	618	−81
Change of whole experiment (37 yrs)	−599	−50	256	−131

* Negative values represent a loss in soil carbon stock.
** Each plot represents a rotation phase, so that while one plot is in fallow, one is in wheat after fallow, and one is in wheat after wheat.

potato rotation started with low carbon level as the harvest of all three crops returned little residue material to the soil. Undersowing barley increased carbon addition, prompting an increase in soil carbon. Most of this additional carbon was decomposed in the following two potato years (Fig. 5.1), but the system still gained 329 kg C ha^{-1} over 12 yrs (Table 4). Increasing the frequency of undersown barley further (every second year) increased carbon stock by an additional ~800 kg C ha^{-1} during a further 12 yr period.

In the Alberta rotation, initial carbon stock of the fallow/wheat/wheat rotation equilibrated at a similar level as our Swift Current long-term rotation described earlier. In this scenario, we switched the rotation to undersown wheat alternating with 3 consecutive years of alfalfa. Such a radical shift in crop production could occur when increasing the carbon stocks becomes a primary goal, while still utilizing the land for grazing/pasture purposes. However, while the undersown wheat generally increased the carbon content temporarily, the harvest of alfalfa actually prevented the carbon stock from further increasing, instead returning it to almost original levels in the third year with only 139 kg C ha^{-1} gained over a period of 11 yrs (Fig. 5.2). Switching instead to continuous wheat cropping and annual crop residue return to the soil increased the carbon stock by an additional ~2000 kg C ha^{-1} over a period of 12 yrs (Table 4).

Our third scenario looked at a continuous corn system in Ontario with a high soil carbon stock, where the return and incorporation of the corn residues is the main driver behind the maintenance of such a carbon stock level. When switching the rotation to an alternation of corn (with residue returned) and soybean, carbon stock levels started to plummet, losing 2821 kg C ha^{-1} over a period of 12 yrs (Table 4). After returning to continuous corn thereafter, we applied two scenarios, one where 70% of the crop residues were returned, and another where all crop residues were removed (e.g., for biofuel feedstock) (Fig. 5(3)). Both alternatives resulted in a further decrease of the carbon stock, but as expected, the drop was larger when residues were removed (additional ~4000 kg C ha^{-1} lost over 11 yrs), while the partial return limited the additional loss to ~1200 kg C ha^{-1} (Table 4).

4. Discussion

Our literature research, and our own test within this study demonstrates that the ICBM model is a viable and instructive addition to the Holos model, much in line with the usage of other peer-reviewed algorithms in the model architecture. Our simulation examples (e.g., Figs. 3 & 4) indicate that including the ICBM model in Holos will allow a more dynamic output of management and climate induced soil carbon stock change than allowed by the carbon change factors derived from Century model scenario simulations. This flexibility will make carbon change estimates more spatially and farm-system specific, and allow potential users to create their own simulation scenarios that go beyond the previously provided management change options.

There may be some conflict with more traditional carbon simulation approaches with respect to the carbon starting value and the land use prior to the simulation, both of which are circumvented in our proposed approach. Because the purpose of the Holos model is to inform producers about the effects of their management decisions (exploratory focus), it would be unsuitable to require a measured carbon stock starting value as input. In fact, in many cases the results of the model would be misleading, as the effect of the management decision would be confounded by the adjustments of the carbon stock due to previous land use. As demonstrated for the Swift Current fallow-wheat-wheat system, the ICBM-Holos assemblage allows flexible and multi-faceted analysis of competing opportunities for mitigating GHG emissions, looking at either single-year estimates or longer-term, multi-decadal time periods.

Moreover, the model will allow projection 70 years into the future, thus (with the 30 yrs historical simulation) allowing a 100 yr time horizon for assessing system performance regarding carbon stock change. Alternatively, the user will have the opportunity to evaluate alternative

Table 4
Soil C (1) a potato rotation in Prince Edward Island (2) a wheat rotation in Alberta and (3) a corn rotation in Ontario (all provinces in Canada), where all rotations were started in equilibrium state based on the first 6 year-average carbon input, thus representing the carbon change due to rotation management.

	Data for Fig. 4 (1)		Data for Fig. 4 (2)		Data for Fig. 4 (3)			
Year	Crop	Soil C (kg C ha^{-1})	Crop	Soil C (kg C ha^{-1})	Crop ('C' part)	Crop ('D' part)	Soil C (kg C ha^{-1}) in 'C'	'D'
1	Barley	15,240	fallow	54,720	Grain-corn residue returned		96,589	
2	Potato	15,240	wheat	54,720	Grain-corn residue returned		96,589	
3	Potato	15,240	wheat	54,720	Grain-corn residue returned		96,589	
4	Barley	15,240	fallow	54,720	Grain-corn residue returned		96,589	
5	Potato	15,240	wheat	54,720	Grain-corn residue returned		96,589	
6	Potato	15,240	wheat	54,720	Grain-corn residue returned		96,589	
7	Undersown barley	15,793	Undersown wheat	54,305	Grain-corn residue returned		96,896	
8	Potato	15,498	alfalfa	54,136	Soybeans		96,411	
9	Potato	15,278	alfalfa	54,175	Grain-corn residue returned		95,365	
10	Undersown barley	15,960	alfalfa	54,346	Soybeans		96,282	
11	Potato	15,545	Undersown wheat	55,993	Grain-corn residue returned		94,814	
12	Potato	15,400	alfalfa	54,955	Soybeans		95,723	
13	Undersown barley	15,890	alfalfa	54,703	Grain-corn residue returned		94,639	
14	Potato	15,568	alfalfa	54,428	Soybeans		95,619	
15	Potato	15,447	Undersown wheat	56,355	Grain-corn residue returned		94,386	
16	Undersown barley	16,159	alfalfa	55,191	Soybeans		95,281	
17	Potato	15,805	alfalfa	55,013	Grain-corn residue returned		94,081	
18	Potato	15,569	alfalfa	54,859	Soybeans		94,358	
19	Undersown barley	16,123	Wheat (tilled) residue returned	56,150	Grain-corn residue removed	Grain-corn residue returned	93,768	93,768
20	Potato	15,760	Wheat (tilled) residue returned	55,960	Grain-corn residue removed	Grain-corn residue returned	93,340	94,002
21	Undersown barley	16,335	Wheat (tilled) residue returned	56,029	Grain-corn residue removed	Grain-corn residue returned	92,738	93,721
22	Potato	15,967	Wheat (tilled) residue returned	56,074	Grain-corn residue removed	Grain-corn residue returned	92,759	94,125
23	Undersown barley	16,544	Wheat (tilled) residue returned	56,070	Grain-corn residue removed	Grain-corn residue returned	92,892	94,632
24	Potato	16,083	Wheat (tilled) residue returned	56,547	Grain-corn residue removed	Grain-corn residue returned	92,367	94,202
25	Undersown barley	16,593	Wheat (tilled) residue returned	55,896	Grain-corn residue removed	Grain-corn residue returned	92,077	94,089
26	Potato	16,238	Wheat (tilled) residue returned	56,514	Grain-corn residue removed	Grain-corn residue returned	91,521	93,613
27	Undersown barley	16,818	Wheat (tilled) residue returned	56,497	Grain-corn residue removed	Grain-corn residue returned	91,245	93,552
28	Potato	16,294	Wheat (tilled) residue returned	56,749	Grain-corn residue removed	Grain-corn residue returned	91,367	94,013
29	Undersown barley	16,677	Wheat (tilled) residue returned	56,562	Grain-corn residue removed	Grain-corn residue returned	90,777	93,508
30	Potato	16,366	Wheat (tilled) residue returned	56,812	Grain-corn residue removed	Grain-corn residue returned	90,314	93,175

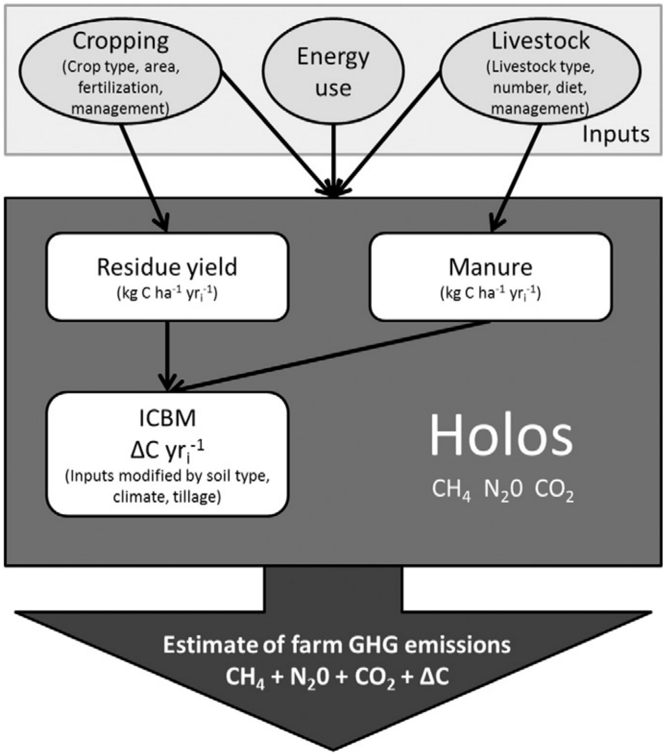

Fig. 3. Conceptual representation of the Introductory Carbon Balance Model (ICBM) in the whole-farm model Holos (where 'i' denotes the current number of year of a multi-year model simulation run).

crop rotations to reverse or emphasize ongoing carbon stock change processes, for example, by retaining more residues or including perennial crops in the rotation (Fig. 4). Our results show clearly the short-term reversibility of soil carbon gains and emphasize the need for a more long-term accounting of carbon change on the farm-level than has been conducted to date.

Carbon stock gains in agricultural systems can be understood as emission offset greenhouse gas emissions, at least for some years or decades. For this purpose, added emissions of CO_2, N_2O and CH_4 are equalized into CO_2-equivalents, and the transfer of CO_2 into the soil (e.g., via the growing biomass) is subtracted. For example, emissions of CH_4 and N_2O from beef and dairy productions systems can, thus, sometimes be partly offset by soil carbon gains (atmospheric CO_2 removal) in associated pastures and perennial forages (Beauchemin et al., 2011; Beauchemin and Mc Geough, 2012). Basarab et al. (2012) showed that carbon gains on pastures and haylands (based on the old Holos approach) were able to reduce the beef production carbon footprint by 11–16%, and pasture management/improvement scenarios for the Lac du Bois grasslands (British Columbia) yielded net carbon gains of 0.4–5.9 Mg CO_2 equivalents on the 757 ha land base of the experiment (Church et al., 2015).

In annual crop production systems, practices that sometimes enhance carbon storage include: reducing tillage, increasing cropping frequency (reducing fallow), and including legumes in rotations (West and Post, 2002; Halvorson et al., 2002). However, carbon gains in agroecosystems are driven by the balance between net primary productivity and respiration, so carbon gains on such lands are often limited because these systems are often designed to remove as much carbon as possible in harvested yields (Janzen, 2004). The higher root fraction and continuous presence of perennials, therefore, strengthens the C addition even if they only are a temporary addition to an otherwise annual crop rotation, and the corresponding carbon gains can be accounted for against the GHG emissions of crop production systems (e.g., N_2O and CO_2). For any 1 Mg carbon stored, 3.67 Mg CO_2-equivalents are offset. Comparing this with estimated carbon footprints of 0.28–1.6 Mg CO_2-equivalents ha^{-1} yr^{-1} for different crops in different ecozones of Canada (Gan et al., 2011a,b,c), carbon stock gains through perennial crop rotation (or cover crops — see Poeplau et al., 2015a) components could turn crop production systems into net carbon importers for several years.

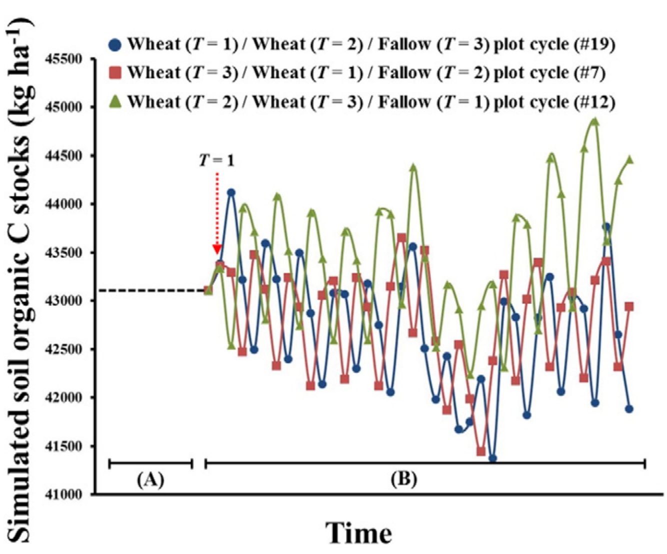

Fig. 4. Total soil organic carbon stocks simulated with ICBM for a fallow-wheat-wheat rotation based on yield data from three long-term plots at Swift Current (SASK). The rotation is grown in a continuous sequence for each plot. Where (A) refers to the historical period (used to initialize the model, T = 0) (B) is the management period for each of the three plots from 1967 to 2003 starting in different phases of the rotation (T = 1). The fallow year is always taking place when the carbon stock curve is lowest.

5. Conclusions

Our findings demonstrate that the inclusion of a site specific carbon balance model will enhance the responsiveness and flexibility of farm-level soil carbon change estimates in the greenhouse-gas model Holos. This will help users to explore a wider, more diverse range of agronomic options for storing additional carbon in soils, and thereby reducing net GHG emissions. For example, it will allow Holos to more definitively estimate the potential benefits of including perennial forages in crop rotations under various configurations. A common constraint in simulating soil carbon change is the difficulty in establishing the starting level. We partially circumvent this difficulty by using, as baseline, an equilibrium value derived for the management and environmental conditions for the preceding thirty-year period. Our approach, further, allows users to project soil carbon change either for individual fields, or for the cropping system as a whole, depending on user requirements. We expect that the more detailed assessment of soil carbon change will be applicable to a wide range of policy-related questions (e.g., carbon credit programs) as well as to unfolding scientific questions.

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References

Andrén, O., Kätterer, T., 1997. ICBM — the introductory carbon balance model for exploration of soil carbon balances. Ecol. Appl. 7, 1226–1236.

Andrén, O., Kätterer, T., Karlsson, T., Eriksson, J., 2008. Soil C balances in Swedish agricultural soils 1990–2004, with preliminary projections. Nutr. Cycl. Agroecosyst. 81, 129–144. http://dx.doi.org/10.1007/s10705-008-9177-z.

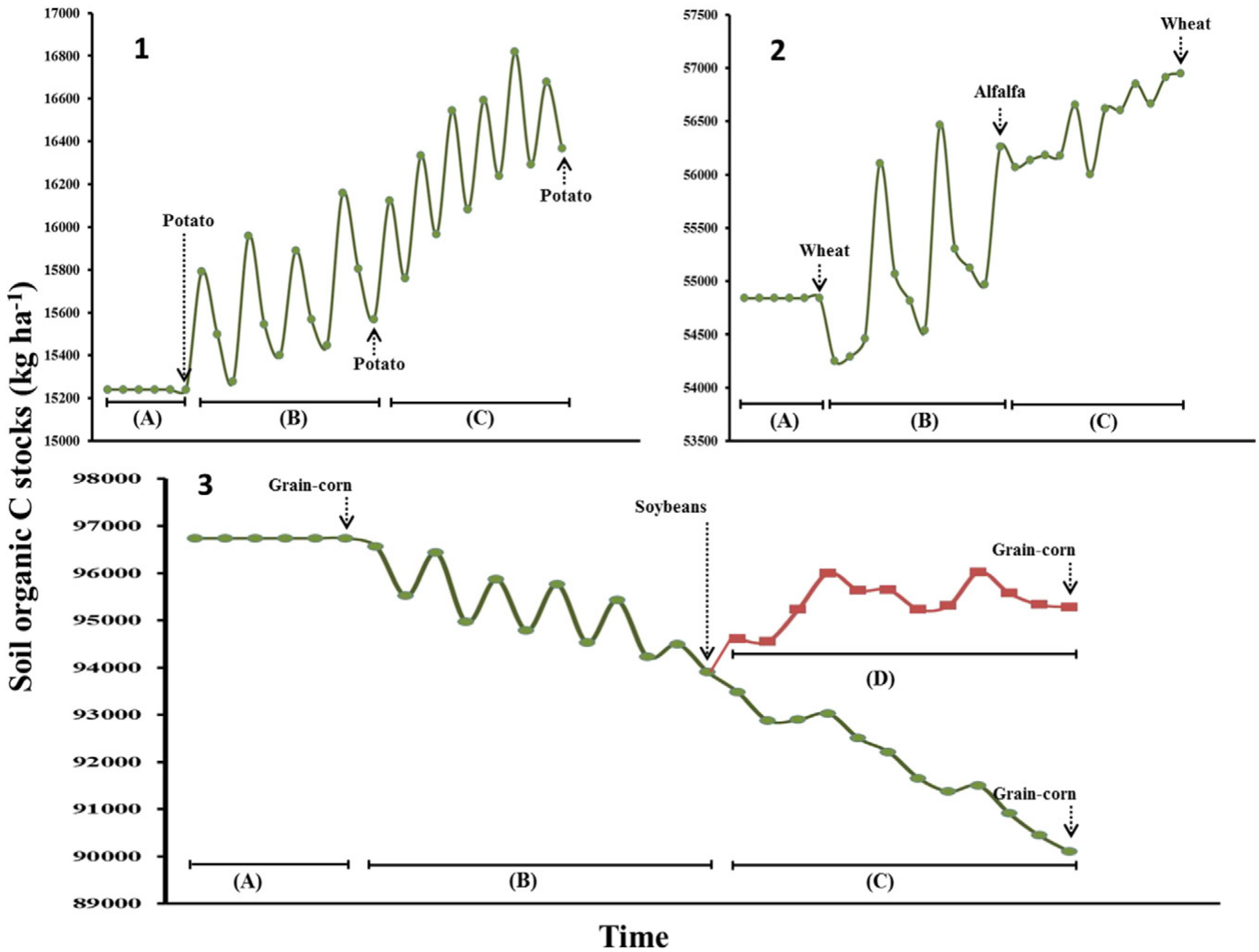

Fig. 5. Soil carbon stocks simulated with ICBM for (1) a potato rotation in PEI starting with 6-yrs of a 3-yr barley/potato/potato rotation, followed by 12-yrs of a 3-yr undersown barley/potato/potato rotation and 12-yrs of a 2-yr undersown barley/potato rotation; (2) a rotation in AB starting with 6-yrs of a 3-yr fallow/wheat/wheat rotation, followed by 12-yrs of a 4-yr undersown wheat/alfalfa/alfalfa/alfalfa rotation and 12-yrs of a continuous wheat rotation; (3) a corn rotation in ON starting with 6-yrs of a continuous grain-corn rotation, followed by 12-yrs of a 2-yr grain-corn/soybean rotation and 12-yrs of continuous grain-corn with and without removal of corn residues (i.e., 70% of corn stover removed). Where (A) refers to the historical period, (B) is the 1st management change and starts at T = 0, (C) and (D) is the 2nd management change. Arrows indicate the last year (and crop) of each rotation.

Antle, J., Capalbo, S., Mooney, S., Elliott, E., Paustian, K., 2002. Sensitivity of carbon sequestration costs to soil carbon rates. Environ. Pollut. 116, 413–422.

Antle, J., Capalbo, S., Mooney, S., Elliott, E., Paustian, K., 2003. Spatial heterogeneity, contract design, and the efficiency of carbon sequestration policies for agriculture. J. Environ. Econ. Manag. 46, 231–250.

Basarab, J., Baron, V., Lopez-Campos, O., Aalhus, J., Haugen-Kozyra, K., Okine, E., 2012. Greenhouse gas emissions from calf- and yearling-fed beef production systems, with and without the use of growth promotants. Animals 2, 195–220.

Beauchemin, K.A., Mc Geough, E., 2012. Life cycle assessment — a holistic approach to assessing greenhouse gas emissions from beef and dairy production. Rev. Argent. Prod. Anim. 32 (1), 69–76.

Beauchemin, K.A., Janzen, H.H., Little, S.M., Allister, T.A., McGinn, S.M., 2010. Life cycle assessment of greenhouse gas emissions from beef production in western Canada: a case study. Agric. Syst. 103, 371–379.

Beauchemin, K.A., Janzen, H.H., Little, S.M., Allister, T.A., McGinn, S.M., 2011. Mitigation of greenhouse gas emissions from beef production in western Canada — evaluation using farm-based life cycle assessment. Anim. Feed Sci. Technol. 166–167, 663–677.

Bolinder, M.A., VandenBygaart, A.J., Gregorich, E.G., Angers, D.A., Janzen, H.H., 2006. Modeling soil organic carbon stock change for estimating whole-farm greenhouse gas emissions. Can. J. Soil Sci. 86, 419–429.

Bolinder, M.A., Andrén, O., Kätterer, T., de Jong, R., VandenBygaart, A.J., Angers, D.A., Parent, L.E., Gregorich, E.G., 2007a. Soil carbon dynamics in canadian agricultural ecoregions: quantifying climatic influence on soil biological activity. Agric. Ecosyst. Environ. 122, 461–470.

Bolinder, M.A., Janzen, H.H., Gregorich, E.G., Angers, D.A., VandenBygaart, A.J., 2007b. An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. Agric. Ecosyst. Environ. 118, 29–42.

Bolinder, M.A., Andrén, O., Kätterer, T., Parent, L.E., 2008. Soil organic carbon sequestration potential for Canadian Agricultural Ecoregions calculated using the Introductory Carbon Balance Model. Can. J. Soil Sci. 88, 451–460.

Bolinder, M.A., Kätterer, T., Andrén, O., Ericson, L., Parent, L.-E., Kirchmann, H., 2010. Long-term soil organic carbon and nitrogen dynamics in forage-based crop rotations in Northern Sweden (63–64 °N). Agric. Ecosyst. Environ. 138, 335–342.

Bolinder, M.A., Fortin, J.G., Anctil, F., Andrén, O., Kätterer, T., de Jong, R., Parent, L.E., 2013. Spatial and temporal variability of soil biological activity in the Province of Québec, Canada (45–58 °N, 1960–2009) — calculations based on climate records. Clim. Chang. 117, 739–755. http://dx.doi.org/10.1007/s10584-012-0602-6.

Bolinder, M.A., Kätterer, T., Poeplau, C., Börjesson, G., Parent, L.E., 2015. Net primary productivity and below-ground crop residue inputs for root crops: potato (*Solanum tuberosum* L.) and sugar beet (*Beta vulgaris* L.). Can. J. Soil Sci. 95, 1–7.

Bolinder, M.A., Kätterer, T., Poeplau, C., Börjesson, G., Parent, L.E., 2015. Net primary productivity and below-ground crop residue inputs for root crops: Potato (Solanum tuberosum L.) and Sugar beet (Beta vulgaris L.). Can. J. Soil Sci. 95 (2), 87–93. http://dx.doi.org/10.4141/cjss-2014-091.

Bontkes, T.S., van Keulen, H., 2003. Modelling the dynamics of agricultural development at farm and regional level. Agric. Syst. 76, 379–396.

Borgen, S.K., Grønlund, A., Andrén, O., Kätterer, T., Tveito, O.E., Bakken, L., Paustian, K., 2012. CO2 emissions from cropland in Norway estimated by IPCC default and Tier 2 methods. Greenh Gas Meas. Manag. 1, 1–17. http://dx.doi.org/10.1080/20430779.2012.672306.

Breland, T.A., Eltun, R., 1999. Soil microbial biomass and mineralization of carbon and nitrogen in ecological, integrated and conventional forage and arable cropping systems. Biol. Fertil. Soils 30, 193–201.

Campbell, C.A., Read, D.W.L., Zentner, R.P., Leyshon, A.J., Ferguson, W.S., 1983. First 12 years of a long-term crop rotation study in southwestern Sasksatchewan — yields and quality of grain. Can. J. Plant Sci. 63, 91–108.

Campbell, C.A., Zenter, R.P., Selles, F., Jefferson, P.G., McConkey, B.G., Lemke, R., Blomert, B.G., 2005. Long-term effects of cropping systems and nitrogen and phosphorus on production and nitrogen economy of grain crops in a Brown Chernozem. Can. J. Plant Sci. 85, 81–93.

Church, J.S., Raymond, A.F., Moote, P.E., Van Hamme, J.D., Thompson, D.J., 2015. Investigating the carbon footprint of cattle grazing the Lac du Bois Grasslands of British Columbia. J. Econ. Manag. Strateg. 15 (1), 1–14.
Congreves, K.A., Grant, B.B., Campbell, C.A., Smith, W.N., VandenBygaart, A.J., Kröbel, R., Lemke, R.L., Desjardins, R.L., 2015. Measuring and modelling the long-term impact of crop management on soil C sequestration in the semiarid Canadian prairies. Agron. J. 107 (3), 1141–1154. http://dx.doi.org/10.2134/agronj15.0009.
Ellert, B.H., Janzen, H.H., 2006. Long-term biogeochemical cycling in agroecosystems inferred from 13C, 14C and 15 N. J. Geochem. Explor. 88, 198–201.
Fortin, J.G., Bolinder, M.A., Anctil, F., Kätterer, T., Andrén, O., Parent, L.E., 2011. Effects of climatic data low-pass filtering on the ICBM temperature- and moisture-based soil biological activity factors in a cool and humid climate. Ecol. Model. 222, 3050–3060.
Gan, Y.T., Campbell, C.A., Janzen, H.H., Lemke, R.L., Basnyat, P., McDonald, C.L., 2009. Carbon input to soil from oilseed and pulse crops on the Canadian prairies. Agric. Ecosyst. Environ. 132, 290–297.
Gan, Y.T., Liang, C., Hamel, C., Cutforth, H., Wang, H., 2011a. Strategies for reducing the carbon footprint of field crops for semiarid areas. A review. Agron. Sustain. Dev. 31, 643–656.
Gan, Y.T., Liang, C., Hamel, C., Cutforth, H., Wang, H., 2011b. Strategies for reducing the carbon footprint of field crops for semiarid areas. A review. Agron. Sustain. Dev. 31, 643–656.
Gan, Y.T., Liang, C., Wang, X.Y., McConkey, B., 2011c. Lowering carbon footprint of durum wheat by diversifying cropping systems. Field Crop Res. 122, 199–206.
Gan, Y.T., Liang, C., Campbell, C.A., Zentner, R.P., Lemke, R.L., Wang, H., Yang, C., 2012. Carbon footprint of spring wheat in response to fallow frequency and soil carbon changes over 25 years on the semiarid Canadian prairie. Eur. J. Agron. 43, 175–184.
Gibbons, J.M., Ramsden, S.J., Blake, A., 2006. Modelling uncertainty in greenhouse gas emissions from UK agriculture at the farm level. Agric. Ecosyst. Environ. 112, 347–355.
Halvorson, A.D., Wienhold, B.J., Black, A.L., 2002. Tillage, nitrogen, and cropping system effects on soil carbon sequestration. Soil Sci. Soc. Am. J. 66, 906–912.
Hénin, S., Dupuis, N., 1945. Essai de bilan de la matière organique du sol. Ann. Agron. 15, 17–29 (In French).
Janssen, S., van Ittersum, M.K., 2007. Assessing farm innovations and responses to policies: a review of bio-economic farm models. Agric. Syst. 94, 622–636.
Janzen, H.H., 2004. Carbon cycling in earth systems—a soil science perspective. Agric. Ecosyst. Environ. 104, 399–417.
Janzen, H.H., Angers, D.A., Boehm, M., Bolinder, M., Desjardins, R.L., Dyer, J.A., Ellert, B.H., Gibb, D.J., Gregorich, E.G., Helgason, B.L., Lemke, R., Masse', D., McGinn, S.M., McAllister, T.A., Newlands, N., Pattey, E., Rochette, P., Smith, W., VandenBygaart, A.J., Wang, H., 2006. A proposed approach to estimate and reduce net greenhouse gas emissions from whole farms. Can. J. Soil Sci. 86, 401–418.
Kätterer, T., Andrén, O., 2001. The ICBM family of analytically solved models of soil carbon, nitrogen and microbial biomass dynamics — descriptions and application examples. Ecol. Model. 136, 191–207.
Kätterer, T., Andersson, L., Andrén, O., Persson, J., 2008. Long-term impact of chronosequential land use change on soil carbon stocks on a Swedish farm. Nutr. Cycl. Agroecosyst. 81, 145–155. http://dx.doi.org/10.1007/s10705-007-9156-9.
Kätterer, T., Bolinder, M.A., Andén, O., Kirchmann, H., Menichetti, M.A.L., 2011. Roots contribute more to refractory soil organic matter than aboveground crop residues, as revealed by a long-term field experiment. Agric. Ecosyst. Environ. 141, 184–192.
Kätterer, T., Bolinder, M.A., Berglund, K., Kirchmann, H., 2013. Strategies for carbon sequestration in agricultural soils in northern Europe. Acta Agric. Scand. Sect. A 62 (4), 1–18.
Kröbel, R., Janzen, H.H., Beauchemin, K.A., Bonesmo, H., Little, S.M., McAllister, T.A., 2013. A proposed approach to estimate and reduce the environmental impact from whole farms. Acta Agric. Scand. Sect. A 62 (4), 225–232.
Kruseman, G., Ruben, R., Hengsdijk, H., van Ittersum, M.K., 1995. Farm household modelling for estimating the effectiveness of price instruments in land use policy. Neth. J. Agric. Sci. 43, 111–123.
Lemke, R.L., VandenBygaart, A.J., Campbell, C.A., Lafond, G.P., Grant, B., 2010. Crop residue removal and fertilizer N: effects on soil organic carbon in a long-term crop rotation experiment on a Udic Boroll. Agric. Ecosyst. Environ. 135, 42–51. http://dx.doi.org/10.1016/j.agee.2009.08.010.
Liebig, M.A., Gross, J.R., Kronberg, S.L., Phillips, R.L., 2010. Grazing management contributions to net global warming potential: a long-term evaluation in the Northern Great Plains. J. Environ. Qual. 39, 799–809.
Little, S., Linderman, J., Maclean, K., Janzen, H.H., 2008. HOLOS — a tool to estimate and reduce greenhouse gases from farms. Methodology and Algorithms for Versions 1.1.x. Agriculture and Agri-Food Canada (Cat. No. A52-136/2008E-PDF, 158 pp.).
Lokupitiya, E., Paustian, K., Easter, M., Williams, S., Andrén, O., Kätterer, T., 2010. Carbon balances in US croplands during the last two decades of the twentieth century. Biogeochemistry http://dx.doi.org/10.1007/s10533-010-9546-y.
Marshall, I.B., P Schut and M. Ballard (compilers). 1999. A National Ecological Framework for Canada: Attribute Data. Environmental Quality Branch, Ecosystems Science Directorate, Environment Canada and Research Branch, Agriculture and Agri-Food Canada, Ottawa/Hull, Canada.
McConkey, B.G., Angers, D.A., Bentham, M., Boehm, M., Brierley, T., Cerkowniak, D., Liang, C., Collas, P., de Gooijer, H., Desjardins, R., Gameda, S., Grant, B., Huffman, E., Hutchinson, J., Hill, L., Krug, P., Martin, T., Patterson, G., Rochette, P., Smith, W., VandenBygaart, B., Vergé, X., Worth, D., 2007. Canadian Agricultural Greenhouse Gas Monitoring Accounting and Reporting System: Methodology and Greenhouse Gas Estimates for Agricultural Land in the LULUCF Sector for NIR 2006. Agriculture and Agri-Food Canada, Ottawa, Canada (Available: http://sis.agr.gc.ca/cansis/nsdb/ecostrat/index.html).
Newlands, N.K., Davidson, A., Howard, A., Hill, H., 2011. Validation and inter-comparison of three methodologies for interpolating daily precipitation and temperature across Canada. Environmetrics 22 (2), 205–223.
O'Brien, D., Capper, J.L., Garnsworthy, P.C., Grainger, C., Shalloo, L., 2014. A case study of the carbon footprint of milk from high-performing confinement and grass-based dairy farms. J. Dairy Sci. 97, 1–17.
Olesen, J.E., Schelde, K., Weiske, A., Weisbjerg, M.R., Asman, W.A.H., Djurhuus, J., 2007. Modelling greenhouse gas emissions from European conventional and organic dairy farms. Agric. Ecosyst. Environ. 112, 207–220.
Pacini, C., Wossink, A., Giesne, G., Huirne, R., 2004. Ecological-economic modelling to support multi-objective policy making: a farming systems approach implemented for Tuscany. Agric. Ecosyst. Environ. 102, 349–364.
Pannell, D.J., 1996. Lessons from a decade of whole-farm modelling in Western Australia. Rev. Agric. Econ. 18, 373–383.
Pannell, D.J., Malcolm, B., Kingwell, R.S., 2000. Are we risking too much? Perspectives on risk in farm modelling. Agric. Econ. 23, 69–78.
Poeplau, C., Aronsson, H., Myrbeck, Å., Kätterer, T., 2015a. Effect of perennial ryegrass cover crop on soil organic carbon stocks in southern Sweden. Geoderm. Reg. 4, 126–133.
Poeplau, C., Kätterer, T., Bolinder, M.A., Börjesson, G., Berti, A., Lugato, E., 2015b. Low stabilization of aboveground crop residue carbon in sandy soils of Swedish long-term experiments. Geoderma 237-238, 246–255.
Rotz, C.A., Montes, F., Chianese, D.S., 2010. The carbon footprint of dairy production systems through partial life cycle assessment. J. Dairy Sci. 93, 1266–1282.
Schils, R.L.M., Olesen, J.E., del Prado, A., Soussana, J.F., 2007. A review of farm level modelling approaches for mitigating greenhouse gas emissions from ruminant livestock systems. Livest. Sci. 112, 240–251.
Smith, P., 2014. Do grasslands act as a perpetual sink for carbon? Glob. Chang. Biol. 20 (9), 2708–2711.
Soil Landscapes of Canada Working Group, 2010. Soil Landscapes of Canada Version 3.2. Agriculture and Agri-Food Canada (digital map and database 1:1 million scale).
Sterk, B., van Ittersum, M.K., Leeuwis, C., Wijnands, F.G., 2007. Prototyping and farm system modelling—partners on the road towards more sustainable farm systems? Eur. J. Agron. 26, 401–409.
Ten Berge, H.F.M., van Ittersum, M.K., Rossing, W.A.H., van den Ven, G.W.J., Schans, J., van den Sanden, P.A.C.M., 2000. Farming options for The Netherlands explored by multi-objective modelling. Eur. J. Agron. 13, 263–277.
VandenBygaart, A.J., Gregorich, E.G., Angers, D.A., 2003. Influence of agricultural management on soil organic carbon: a compendium and assessment of Canadian studies. Can. J. Soil Sci. 83, 362–380.
VandenBygaart, A.J., Gregorich, E.G., Angers, D.A., Bolinder, M.A., Janzen, H.H., Campbell, C.A., 2009. Modeling soil organic carbon change in Canadian agroecosystems: testing the Iintroductory Carbon Balance Model. In: Lal, R. (Ed.), Soil Carbon Sequestration and the Greenhouse Effect, second ed. SSSA Special Publication Number 57, pp. 13–28.
Vanin C., Howlet, D., Schut, P., Kröbel, R., and Huffman, T., Agricultural Land Use in Canada: Data and Methodology to Define the Extent. (in preparation for Agriculture, Ecosystems and Environment).
West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Sci. Soc. Am. J. 66, 1930–1946.
Zimmermann, A., Heckelei, T., Perez Dominguez, I., 2009. Modelling farm structural change for integrated ex-ante assessment: review of methods and determinants. Environ. Sci. Pol. 12, 601–618.