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Modelling soil organic carbon stock change for estimating whole-farm greenhouse gas emissions

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[1]*Soils and Crops Research and Development Centre, Agriculture and Agri-Food Canada, 2560 Hochelaga Blvd, Sainte-Foy, Quebec, Canada G1V 2J3;* [2]*Eastern Cereal and Oilseed Research Centre, Agriculture and Agri-Food Canada, KW Neatby Building, 960 Carling Avenue, Ottawa, Ontario, Canada K1A 0C6;* [3]*Lethbridge Research Centre, Agriculture and Agri-Food Canada, 5403 – 1st Avenue South, Lethbridge, Alberta, Canada T1J 4B1.* *Received 15 November 2004, accepted 29 June 2005.*

Bolinder, M. A., VandenBygaart, A. J., Gregorich, E. G., Angers, D. A. and Janzen, H. H. 2006. **Modelling soil organic carbon stock change for estimating whole-farm greenhouse gas emissions**. Can. J. Soil Sci. **86**: 419–429. Modelling soil organic carbon (SOC) stock changes in agroecosystems can be performed with different approaches depending on objectives and available data. Our objective in this paper is to describe a scheme for developing a dynamic SOC algorithm for calculating net greenhouse gas emissions from Canadian farms as a function of management and local conditions. Our approach is flexible and emphasizes ease of use and the integration of available knowledge. Using this approach, we assessed the performance of several SOC models having two or more compartments for some common agroecosystems in Canada. Analysis of long-term data for conventional management practices at different sites (n = 36) in Canada, including recent model applications in the literature on some of those data, indicated that the results obtained with two-compartment models, such as the Introductory Carbon Balance Model (ICBM) and Modified Woodruff Model (MWM), yielded results comparable to those of a multi-compartment model (CENTURY). The analysis also showed that a model such as ICBM needs tuning to be applied to management and conditions across Canada. Two-compartment models programmable in a simple spreadsheet format, though they may not supplant more complex models in all applications, offer advantages of simplicity and transparency in whole-farm analyses of greenhouse gas emissions.

Key words: Virtual Farm, soil organic carbon, soil disturbance, C inputs, Introductory Carbon Balance Model (ICBM), CENTURY, Modified Woodruff Model (MWM).

Bolinder, M. A., VandenBygaart, A. J., Gregorich, E. G., Angers, D. A. et Janzen, H. H. 2006. **Modélisation de l'évolution des stocks de carbone organique du sol en vue d'une estimation des emissions de gaz à effet de serre des exploitations agricoles**. Can. J. Soil Sci. **86**: 419–429. On peut modéliser l'évolution des stocks de carbone organique du sol (COS) dans les écosystèmes agricoles de diverses manières, selon l'objectif visé et les données disponibles. Les auteurs décrivent une méthode permettant d'élaborer un algorithme dynamique pour le COS à partir duquel on calculera les émissions nettes de gaz à effet de serre des exploitations agricoles canadiennes en fonction des pratiques culturales et des conditions locales. Il s'agit d'une approche adaptable qui insiste sur la convivialité et l'intégration des connaissances actuelles. Grâce à cette approche, les auteurs ont évalué l'efficacité de plusieurs modèles sur le COS à deux ou plusieurs compartiments avec quelques écosystèmes agricoles communs au Canada. L'analyse des données à long terme sur les pratiques agricoles traditionnelles à divers endroits (n = 36) au Canada, dont l'application de modèles à certaines données récemment rapportées dans la documentation, indique que les résultats issus des modèles à deux compartiments comme l'Introductory Carbon Balance Model (ICBM) et le Modified Woodruff Model (MWM) sont comparables à ceux d'un modèle à compartiments multiples (CENTURY). L'analyse révèle aussi qu'un modèle tel l'ICBM doit être ajusté avant qu'on puisse l'appliquer aux pratiques et aux conditions particulières au Canada. Même s'il est peu probable qu'ils supplantent les modèles plus complexes dans toutes les applications, les modèles à deux compartiments programmables à l'aide d'un simple chiffrier ont pour atouts leur simplicité et leur transparence dans l'analyse des émissions de gaz à effet de serre des exploitations agricoles.

Mots clés: Ferme virtuelle, carbone organique du sol, perturbation du sol, apports de C, Introductory Carbon Balance Model (ICBM), CENTURY, Modified Woodruff Model (MWM)

The dynamics of soil organic carbon (SOC) in agricultural land are governed by the balance between input of organic materials and outputs from the decomposition of SOC. This net balance is influenced by inherent soil properties and climate, and by management practices that influence carbon inputs or decomposition.

Estimating and modelling a change in SOC stocks in agricultural land is not easy, partly because:

- SOC stocks vary in time and space in response to many physical, chemical and biological processes and their interactions;
- SOC change occurs very slowly, usually over decades, and thus detection is difficult at shorter time scales (i.e., several years);
- Changes in SOC stocks, typically about 0.3 Mg C ha^{-1} yr^{-1} are small compared with total SOC stocks, sometimes as high as 100 Mg C ha^{-1} or more, making them hard to detect; and,

Abbreviations: **GHG**, greenhouse gas; **ICBM**, Introductory Carbon Balance Model; **MWM**, Modified Woodruff Model; **SOC**, soil organic carbon

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- Soil sampling and SOC analysis are time consuming and relatively costly.

Data from long-term agronomic experiments and process-based studies, and the understanding of C dynamics derived from them, can be integrated into simulation models and used to predict changes in SOC stocks that occur as a result of management practices. Numerous SOC models have been developed, each containing different driving variables and with varying levels of complexity. McGill (1996) reviewed and classified 10 commonly used SOC models, and showed that they shared basic characteristics such as temporal scale, and soil organic matter compartmentalization and control. Smith et al. (1997), after comparing predictions from nine of these models to long-term data from seven sites in Europe, North America and Australia, concluded that no one model performed consistently better than others across all data sets. Model calibration (e.g., by adjusting initial SOC content and distribution in the different model pools, adjusting estimates for crop residue C inputs) was almost always required because the models were used in situations (i.e., land-uses, treatments, crop types and climatic conditions) not considered in their development. Campbell et al. (2000), for example, concluded that neither EPIC nor CENTURY was able to predict accurately SOC stock changes due to management practices in long-term studies in Saskatchewan.

Ecologists often attempt to simplify the complexity, and reduce the spatial and temporal heterogeneity of ecological systems by averaging over scales of time and space. Strayer et al. (2003) suggest that simple models can work well in ecological systems because (1) the heterogeneity may occur at smaller scales of space and time than those at the resolution of the study (2) model imprecision may often be acceptable, particularly if the bias is relatively small; and (3) the models incorporate empirical (or semi-empirical) approaches that use empirically determined constants or functions. Recently, there has been a trend toward developing models that are easy to understand and use, and that describe SOC dynamics in agroecosystems as a function of a few basic plant and soil processes (e.g., Andrén and Kätterer 1997; Campbell et al. 2000; Izaurralde et al. 2001).

Such simplified models may be especially useful as subroutines in estimating net whole-farm emissions of greenhouse gases. The net effect of a proposed mitigation practice depends not only on changes in SOC storage, but also on concurrent effects on emissions of N_2O and CH_4 (Robertson et al. 2000; Flessa et al. 2002). Simplified algorithms may allow all greenhouse gas (GHG) sources and removals to be considered without the overall assembled model becoming too complex and unmanageable.

One example of an effort to simulate whole-farm GHG emissions is the "Model Farm" program of Agriculture and Agri-Food Canada. It was established to study processes of GHG emission and removal, and build a "Virtual Farm" that would simulate GHG budgets at the farm scale as a function of possible management scenarios using a series of interconnected algorithms (Janzen et al. 2006). An algorithm for quantifying net SOC stock change is a critical component of such a model.

Our objective is to describe an approach, to select, develop, and continually update a Canadian-specific SOC algorithm to be used in calculating net whole-farm GHG emissions as a function of current or proposed management options. We tested the applicability of a dynamic two compartment model, the Introductory Carbon Balance Model (ICBM) across the country. For that purpose we used published data from long-term research plots in eastern and western Canada, and we also reviewed other recently published evaluations of similar models in Canada and included them in the analysis.

Common Approaches for Modelling SOC Stock Changes

The various SOC models we examined can be categorized into three types (Fig. 1), following a scheme similar to that of Jenkinson (1990), based principally on the number of SOC compartments or pools. With the first type of model, total SOC stock (i.e., one SOC compartment) changes are assessed using relative comparisons, or simply by calculating the net balance between input and outputs with linear humification coefficients and mineralization rates on an annual basis. For instance, methods used by the Intergovernmental Panel on Climate Change (IPCC 2004) determine changes in carbon stocks in soils based on soil geographic databases and land-use and management for a given country (IPCC 2004). This approach includes three tiers of methodologies, of which Tier 1 calculates SOC responses to a management change using default parameters and reference carbon stocks, and Tier 2 replaces the default values with country-specific estimates, based on representative measurements or models. VandenBygaart et al. (2003) conducted a search in the literature for measured changes in SOC stocks and used the IPCC Tier 2 approach to analyse SOC stock changes for major soil and crop management practices across Canada. The Tier 3 approach of IPCC utilizes estimates of SOC change derived from dynamic, multi-compartment models.

Models using two or more SOC pools, are non-linear and more dynamic based upon first order kinetics, and are usually parameterized with long-term data on net SOC changes. Parameterization can also be accomplished using isotopic measurements (e.g., ^{13}C, ^{14}C) to provide decay rates for the individual SOC pools. Information from process-based studies, either from long-term field data or controlled studies (e.g., incubation), as well as climatic variables, is also more thoroughly integrated in these models.

A dominant factor in assessing changes in C stocks is C input from organic amendments and above- and below-ground crop residues (Fig. 1). Differences in residence time of C added in organic amendments are accounted for in many models, but the quality of crop residues is not well defined in most models.

The C input is quantified to varying degrees in each type of model. With the Intergovernmental Panel on Climate Change Tier 1 approach, the annual crop residue C and C inputs from organic amendments are merely described as categories (i.e., low, medium and high), determined in a semi-quantitative manner relative to a reference or baseline (e.g., VandenBygaart et al. 2003).

Two-compartment models usually estimate crop residue C inputs with sub-models using simple physiological rela-

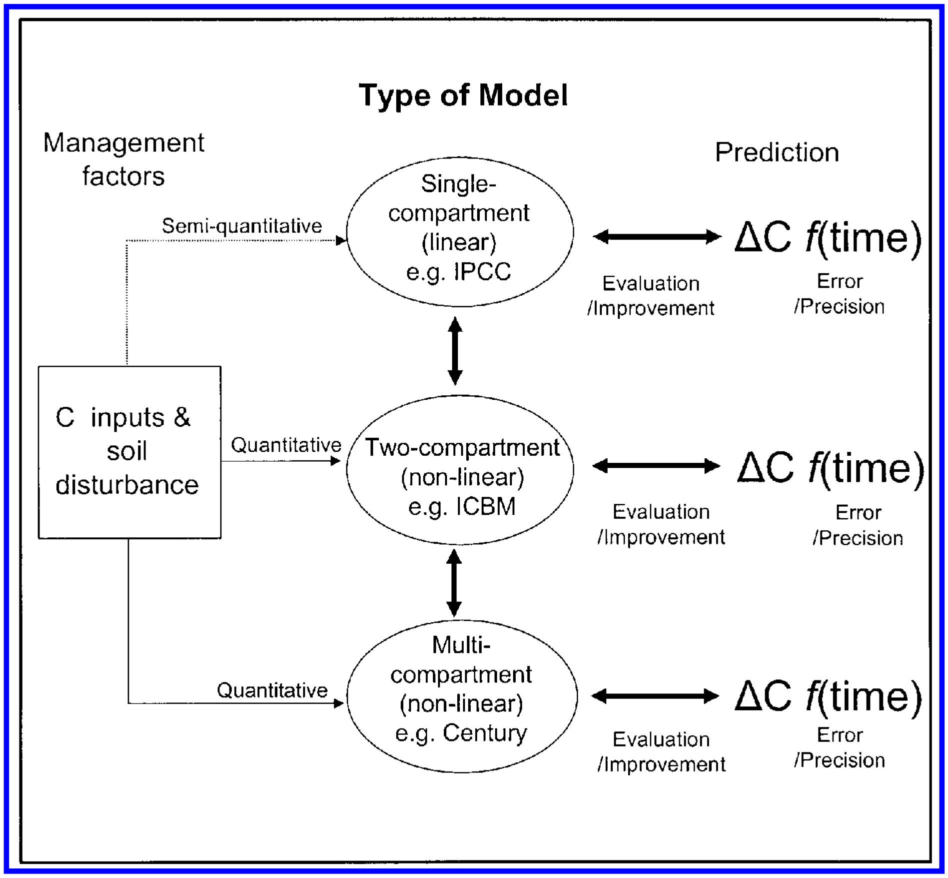

Fig. 1. An approach for modelling SOC stock change for whole-farm estimates of net greenhouse gas emissions.

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tionships and parameters. In these sub-models, above-ground crop residues for cereals are calculated from harvest index data (Bolinder 2004; Izaurralde et al. 2001) or related regression relationships (Campbell et al. 2000). The below-ground crop residue C inputs (i.e., roots) are calculated using locally selected estimates of shoot- (i.e., straw + grain for cereals) to-root ratios at the approximate time of peak above-ground biomass (i.e., close to harvest). Bolinder (2004) and Campbell et al. (2000) also included assumptions to estimate C inputs from exudates, whereas no such specific assumptions were made by Izaurralde et al. (2001).

With multi-compartmental SOC models, estimates of crop residue C inputs are often obtained from dynamic process-based crop production sub-models, where crop production is driven by climatic variables. For example, CENTURY has a crop production sub-model that can be calibrated with a number of crop-specific parameters for different environments (Metherell et al. 1993). This sub-model is not always easy to calibrate, particularly for rotations involving two or more crops (Green Plan 1993).

In two- and multi-compartment models, unlike the single compartment model, C inputs are used in a quantitative manner, and the sub-models that estimate crop residue C inputs need to be calibrated to reflect different kinds of crops grown within a given soil and climatic region.

Physical disturbance such as tillage is another factor affecting SOC dynamics (Paustian et al. 1997; Six et al. 2004), and most models generally account for this (Fig. 1). For instance, under Canadian conditions, VandenBygaart et al. (2003), using the IPCC approach, found that the effect of tillage on SOC stock change varies both with soil and climatic conditions across Canada. For eastern Canada, tillage-induced effects on SOC dynamics also appeared to be related to interactions between soil management (i.e., type and depth of tillage), quantity and quality of residue inputs, soil fauna, and soil climatic conditions (Gregorich et al. 2005).

Two- and multi-compartment models usually include parameters that accelerate the first-order decay rates when soils are tilled. For example, the ICBM and CENTURY models have a cultivation factor that affects the decomposition rates of each SOC pool (Andrén et al. 2004; Metherell et al. 1993). This factor can be modified and should be calibrated for specific environments. Physical disturbance of soil also affects soil erosion, which is considered in some but not all SOC models. The effect of erosion on SOC stocks depends largely on scale and modelling objectives. For our purposes, we assume that eroded material is redistributed within a farm and does not affect net CO_2 emissions.

Models are usually evaluated against measured data from long-term field experiments (Fig. 1). Modelling is a progressive, incremental process, based on accumulated knowledge; as new information emerges, improvements are incorporated. The model predictions have varying degrees of error and precision. A reasonable expectation and criterion to use for the performance of a model is that prediction should have precision (i.e., differences in final SOC stocks or SOC rate changes per unit of time) not exceeding that of measurements.

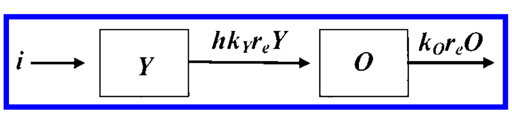
Evaluation and Comparison of Two- and Multi-compartmental Models

The initial premise of the "Virtual Farm" is to begin with a rudimentary prototype based largely on basic IPCC algorithms (Janzen et al. 2006, this issue). Thereafter, as understanding expands, these basic algorithms can be replaced by models of higher complexity; but only if these advanced models demonstrably enhance reliability or flexibility and do not place excessive demands on new variables or data inputs.

Ideally, these models could integrate Canadian-specific knowledge on SOC dynamics and related driving variables, but should be improved continuously as new knowledge is acquired. Compared with an IPCC-based approach, such a model would better reflect the dynamics of SOC stocks because the output would be non-linear and more than one SOC compartment is considered. But perhaps more importantly, such a model would also use quantitative (rather than semi-quantitative) estimates of C input. This latter consideration is particularly important for crop residue C inputs influenced by management (i.e., they are a function of yield and type of crops).

Based on simplicity, transparency and ease of adaptability, we selected the Introductory Carbon Balance Model (ICBM), a two-compartment first-order kinetic model driven by annual C inputs, which is programmed and run in Microsoft Excel format. It was developed to calculate SOC stock changes in a 30-yr time frame and tested for Northern Europe (Andrén and Kätterer 1997; Kätterer and Andrén 1999). The ICBM uses a reasonable number of parameters for which information is available for Canadian agroecosystems.

The ICBM, described by Andrén and Kätterer (1997), uses an approach similar to that developed earlier by Hénin and Dupuis (1945). Briefly, the ICBM has five parameters:



where (Y) and (O) are the "Young" and "Old" SOC pools (ca: 7 and 93% of total SOC, respectively), and (k_Y) and (k_O) represent the first order decay rates for these two SOC pools; $[(1 - h)k_Y r_e Y]$ equals the outflow as CO_2 from (Y). The "humification" coefficient (h) determines the fraction that enters (O), and (i) is the annual C inputs from organic amendments and crop residue C inputs. An external rate-modifying parameter (r) is included in order to account for effects such as climate, texture and soil disturbance. Components from other process-based models can also be incorporated into the ICBM approach. For example, Kätterer and Andrén (1999) included a log-linear function to modify the humification coefficient as a function of clay content (h_{clay}), like that used in RothC (Coleman and Jenkinson 1996) and other multi-compartment process-based models (e.g., CENTURY).

To assess its application to Canadian conditions, we evaluated the performance of the ICBM by selecting data from field experiments (i.e., representative site and treatment combinations) from a literature search compiled by VandenBygaart et al. (2003) (Tables 1 and 2). We considered only conventionally managed sites (conventionally tilled, mineral fertilized, without added manure) and treatment combinations that had bulk density values, allowing SOC to be expressed on a mass basis. Another criterion was that field experiments had detailed yield and residue management data to quantitatively estimate the mean annual crop residue C inputs.

Eastern Canada

The data set for eastern Canada included 18 site and treatment combinations, most of which have been described by Carter et al. (1997, 2003a) and Bolinder et al. (1999). We compared the performance of ICBM with that of CENTURY version 4.0 (Parton et al. 1987), which had earlier been evaluated against long-term field measurements in eastern Canada (Voroney and Angers 1995; Liang et al. 1996; Carter et al. 2003b).

The basic parameter values used for CENTURY were the same as those described by Metherell et al. (1993). For all simulations, the initial SOC content was allocated to CENTURY's three SOC turnover pools (i.e., active, slow and passive) in the proportions presented in the version 4.0 of the model, and the model was run with a monthly time step. For weather data, we used mean monthly means with no variability (i.e., option M), from Canadian Climate Normals data at the nearest weather station. For ICBM, the parameters were those presented by Andrén and Kätterer (1997). The CENTURY crop production sub-model was calibrated to reflect the measured (Carter et al. 2003b) and estimated (Green Plan 1997; Bolinder 2004) crop residue C inputs for each site and treatment combination, and the ICBM mean annual C input parameter (i) was set at the same value (Table 1).

When estimated, the below- and above-ground residue C inputs were calculated from yield data for corn, wheat, barley and forages using the sub-model of Bolinder (2004), based on measurements and assumptions for these crops in eastern Canada. Briefly, the annual average above- and below-ground residue C inputs were estimated from the annual average grain yield for corn and small-grain cereals, based on harvest index (50% for corn, 48% for soybeans, 41% for wheat, 55% for barley and 53% for oats) and shoot-to-root ratios (5.0 for corn, 6.0 for wheat, 2.0 for barley and soybeans, and 2.5 for oats). We assumed that extra-root C from these crops was equivalent to root biomass C. For forage crops, the root biomass was estimated assuming a shoot to root ratio of 1.0 and annual extra-root C release equivalent to 50% of the root biomass C. For potato, we used a

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Table 1. Site and treatment description, data used to simulate SOC for conventionally managed eastern Canadian sites, and comparisons between measured and predicted final SOC stocks with the ICBM and Century models (SOC in g C m^{-2}).

Site location, duration and treatments	[Clay, silt, sand]	Estimated annual average C inputs used in simulations (g C m^{-2})	Initial SOC estimate used in simulations	ICBM predicted final SOC and (% deviation from measured final SOC[z])	Century predicted final SOC and (% deviation from measured final SOC[z])	Reference for data sources and Century predictions
Maritime sites						
Ch'town. – 11 yr P/B	[17, 28, 55]	110	4180	3939 (+12.1)	3600 (+2.4)	Carter et al. (2003)
Ch'town. – 11 yr P/RC	[17, 28, 55]	175	4180	4097 (+6.8)	3750 (–2.3)	Carter et al. (2003)
Ch'town. – 11 yr P/IRG	[17, 28, 55]	300	4180	4401 (+9.2)	4000 (–0.8)	Carter et al. (2003)
Harr. – 9 yr W/B/B/SY	[8, 30, 62]	482	5000	5504 (+2.6)	4937 (–8.0)	Green Plan (1997)
Harr. – 11 yr P/B	[8, 30, 62]	192	5162	5002 (+8.3)	4400 (–4.8)	Green Plan (1997)
Harr. – 11 yr P/B/RC	[8, 30, 62]	236	5162	5109 (+1.3)	4550 (–9.8)	Green Plan (1997)
Harr. – 11 yr Cont.P	[8, 30, 62]	105	5162	4790 (+11.0)	4200 (–2.7)	Green Plan (1997)
Ch'town. – 9 yr W/B/B/SY	[10, 36, 54]	270	3000	3260 (+24.6)	3018 (+15.3)	Green Plan (1997)
Napp. – 67 yr Cont.For	[18, 60, 22]	176	4000	3917 (+0.2)	3850 (–1.5)	Green Plan (1997)
Quebec sites						
LaPoc – 6 yr Cont.B	[58, 30, 12]	218	5000	4927 (–7.9)	4936 (–7.7)	Green Plan (1997)
Norm. – 6 yr Cont. B	[47, 39, 14]	273	4598	4663 (+5.6)	4750 (+7.6)	Bolinder (2004)
Norm. – 3 yr Cont.B	[45, 45, 10]	429	7000	7079 (+7.7)	7162 (+8.9)	Green Plan (1997)
Chic. – 10 yr Cont.C	[28, 22, 50]	612	3000	4068 (+24.1)	3625 (+10.6)	Green Plan (1997)
Ontario sites						
Ottw. – 6 yr Cont.C	[10, 25, 65]	403	5000	5265 (+8.3)	4780 (–1.7)	Green Plan (1997)
Ottw. – 6 yr Cont.W	[10, 25, 65]	133	5000	4772 (+1.3)	4315 (–8.4)	Green Plan (1997)
Harw. – 12 yr Cont.C	[36, 35, 29]	410	5000	5411 (–0.7)	4972 (–8.8)	Green Plan (1997)
Harw. – 35 yr C/O/A/A	[36, 35, 29]	303	5000	5333 (–18.2)	4800 (–26.4)	Green Plan (1997)
Harw. – 35 yr Cont.C	[36, 35, 29]	378	5000	5713 (+2.1)	5487 (–2.0)	Green Plan (1997)
Absolute deviation from measured final SOC (%) Mean				8.4	7.2	
Range				0.2 to 24.6	0.8 to 26.4	
SD				7.5	6.3	

Sites: Ch'town = Charlottetown, Harr = Harrington, Napp = Nappan, LaPoc = La Pocatiere, Norm = Normandin, = Chic = Chicot, Ottw = Ottawa, Harw = Harrow. Treatments: P = potato, B = barley, RC = red clover, IRG = Italian ryegrass, W = wheat, SY = soybeans, For = forage, C = corn, O = oats, A = alfalfa, Cont. = continuous.

[z][(Predicted final SOC) – (Measured final SOC)/(Measured final SOC)] × 100.

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Table 2. Site and treatment description, data used to simulate SOC for conventionally managed western Canadian and US sites, and comparisons between measured and predicted final SOC stocks with the ICBM and MWM models (SOC in g C m^{-2})

Site location, duration and treatments	[Clay, silt, sand]	Estimated annual average C inputs used in simulations (g C m^{-2})	Initial SOC estimate used in simulations	ICBM predicted final SOC and (% deviation from measured final SOC[v])	MWM predicted final SOC and (% deviation from measured final SOC[v])	Reference for data sources
West Canada sites						
IH – 10 yr F/W (N+P)[z]	[63, 21, 16]	142	3006	2985 (–7.7)	3159 (–2.3)	Campbell et al. (1998)
IH – 10 yr F/W/W (N+P)	[63, 21, 16]	175	3192	3223 (–10.8)	3456 (–4.4)	
IH – 10 yr F/W/W (N+P – straw)	[63, 21, 16]	103	3037	2926 (–18.6)	3164 (–11.9)	
IH – 10 yr Cont. W (N+P)	[63, 21, 16]	222	3791	3858 (–2.7)	4197 (+5.8)	
SC – 30 yr F/W (N+P)	[25, 50, 30]	123	3047	2945 (–13.1)	3227 (–4.7)	Campbell et al. (2000)[w]
SC – 30 yr F/W/W[y]	[25, 50, 30]	130	3047	2977 (–10.5)	3357 (+0.9)	
SC – 30 yr F/R/W (N+P)	[25, 50, 30]	146	3047	3050 (–18.4)	3537 (–5.4)	
SC – 30 yr Cont. W (N+P)	[25, 50, 30]	178	3047	3196 (–20.0)	3697 (–7.5)	
SC – 30 yr Cont. W (+P)	[25, 50, 30]	129	3047	2973 (–12.7)	3457 (+1.5)	
SC – 30 yr W/Lent. (N+P)	[25, 50, 30]	171	3047	3164 (–18.8)	3707 (–4.9)	
EL – 11 yr Cont. B (Fert.)[x]	NR	210	15000	13687 (–6.2)	15317 (+5.0)	Monreal et al. (1997)
LB – 39 yr Cont. W	[25, 30, 45]	126	3404	3216 (+0.9)	3737 (+17.2)	Janzen et al. (1997)
LB – 39 yr F/W	[25, 30, 45]	111	3458	3176 (+8.3)	3391 (+15.6)	
LB – 39 yr F/W/W	[25, 30, 45]	79	3471	3013 (±0)	3445 (+14.3)	
BR – 52 yr W/F (Fert.)	[18, 39, 43]	21	2640	1947 (–8.7)	2301 (+7.9)	Izaurralde et al. (2001)
BR – 52 yr W/O/B/H/H	[18, 39, 43]	57	2640	2189 (–35.1)	2741 (- 18.7)	
US site						
PND – 56 yr F/W (nb–45)	[18, 70, 12]	122	4990	4211 (+1.8)	4602 (+11.3)	Rasmussen and Parton (1994)
PND – 56 yr F/W (nb–90)	[18, 70, 12]	123	4875	4141 (–1.2)	4509 (+7.6)	
Absolute deviation from measured final SOC (%) Mean				10.9	8.2	
Range				0 to 35.1	0.9 to 18.7	
SD				9.0	5.4	

Sites: IH = Indian Head (SK), SC = Swift Current (SK), EL = Ellerslie (AB), LB = Lethbridge (AB), BR = Breton (AB), PND = Pendleton (OR). Treatments: F = fallow, W = wheat, Lent. = lentil, B = barley, O = oats, H = hay, Fert. = fertilized, Cont. = continuous, NR = not reported.

[z]This site (1987–1996) was conventionally tilled between 1987 and 1990 and thereafter no-tilled.

[y]Average for N + P, + P, + N.

[x]This site was zero-tilled.

[w]MWM predictions for this site as presented by Campbell et al. (2000); considering the “Mean annual SOC change based on measured data” (i.e., not including the eroded C). [v][(Predicted final SOC) – (Measured final SOC)/(Measured final SOC)] × 100.

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constant estimate for annual crop residue C inputs (Carter et al. 2003b).

The ICBM was originally developed and parameterized with data from a long-term (35-yr) field experiment, under a cold temperate and semi-humid climate in Central Sweden, with soil types and conditions comparable to those in eastern Canada. The eastern Canadian site and treatment combinations we examined were all conventionally managed, and the rate-modifying parameter (*r*) was set to the value used by Andrén and Kätterer (1997) for the "most normal practice" (i.e., 1.0). The simulations were conducted for the total SOC stocks in the 0- to 20-cm layer (Table 1).

Except for a few site and treatment combinations, the ICBM model predicted final SOC stocks within 10% of measured values (Table 1) though, in most cases, the model tended to overestimate the final SOC stocks. With CENTURY, deviations from measured values were generally similar in magnitude to those obtained with the simpler ICBM approach, but CENTURY, unlike ICBM, tended to underestimate final SOC stocks. Both models yielded similar results for the long-term Harrow (35 yr) and Nappan (67 yr) sites. CENTURY was initially developed and tested for natural grasslands (Parton et al. 1987). In this case, the ICBM also predicted accurately the net SOC change for the continuous forage treatment at Nappan (+ 0.2% deviation), similar to what was predicted with the CENTURY model (– 1.5%). However, the CENTURY predictions for the six long-term potato rotations at Charlottetown and Harrington were better (average of 3.8% absolute deviation) than those made by ICBM (average of 8.1% absolute deviation).

Overall, the mean absolute deviation of predicted final SOC stocks from measured values for the 18 different site and treatment combinations was 8.4% for ICBM and 7.2% for CENTURY (Table 1). The variability in this absolute deviation from measured values was high but similar for both models (CV = 89% and 88%, for ICBM and CENTURY, respectively). According to a paired *t*-test, the predicted absolute deviation from measured final SOC stocks was not significantly different ($P = 0.233$) between the models.

Western Canada (and US Great Plains)

Several empirical equations have been developed recently for the semi-arid Canadian prairies. Campbell et al. (2000) evaluated a two-compartment model developed by Woodruff (1949) using long-term data (~ 30 yr) from Swift Current, and Izaurralde et al. (2001) developed a model using long-term data (~ 50 yr) from Breton (Table 2). Both of these are similar to the ICBM approach, especially the Woodruff model (1949) used by Campbell et al. (2000), which also included coefficients and decomposition rate constants determined from a study by Voroney et al. (1989). This model, also programmable in Microsoft Excel, has the equation:

$$SOC_t = C_0\left(q_1 e^{-k1t} + q_2 e^{-k2t}\right) + \sum_{n=0}^{t}\left[A_n\left(p_1 e^{-r1(t-n)} + p_2 e^{-r2(t-n)}\right)\right]$$

where SOC_t is the total amount of SOC remaining after a given number of years (*t*). The first part of the equation describes the dynamics of pre-existing SOC (C_O), where (*k*) represents the annual rate of decomposition. The second part of the equation determines the decomposition (*r*) of annual crop residue C inputs (A_n). Whereas (*q*) and (*p*) refer to the proportions of pre-existing SOC and annual crop residue C inputs each of which have different first order kinetics, the subscripts 1 and 2 denotes the "active" and "slower" decomposing pools of these two components. The active (q_1) and slower (q_2) decomposing SOC pools represent ca. 20 and 80% of total SOC, respectively.

We conducted simulations for 16 conventionally managed long-term treatments in western Canada, and two treatments in one US site (Table 2), using ICBM as described for the eastern Canadian sites. Because ICBM was not designed for semi-arid regions, we also applied the Modified Woodruff Model (MWM) for Indian Head, Ellerslie, Lethbridge, Breton and Pendleton, to have a comparison with a model developed for these conditions. A detailed description of the MWM and its application using data from Swift Current was presented by Campbell et al. (2000).

For each site, the mean annual crop residue C inputs for the ICBM *i* parameter and the mean annual C addition as plant residue for the MWM A_n parameter were set to identical values (Table 2). For Indian Head, Swift Current and Breton, we used estimates of above- and below-ground C provided by the authors. For continuous barley at Ellerslie, we assumed straw yield = grain yield × 1.5. Only straw C input was considered in the estimates for the Pendleton site. For the Lethbridge site, we considered the equations used by Campbell et al. (2000) for Indian Head and Swift Current to estimate above-ground C input (straw yield = 58 + 1.64 × grain yield) and below-ground C input (root input = straw yield × 0.59) from yield data in Janzen et al. (1997). In all sites and treatments, the cereal straw was left on plots, except at Breton and for the "minus straw" treatment at Indian Head. The simulations considered SOC stocks for the 0- to 15-cm layer at Indian Head, Lethbridge and Breton, and the 0- to 30-cm layer at other sites.

For most sites and treatments, ICBM tended to underestimate the final SOC stocks, in contrast to the eastern Canadian studies, and the deviations from measured values were higher for the western Canadian sites (Table 2). The MWM model predictions were better than those made by ICBM for the Indian Head and Swift Current sites, but the deviations from measured values for Lethbridge and Pendleton were higher than those obtained with ICBM. MWM tended to underestimate final measured values for Indian Head and Swift Current, and generally overestimated measured values for other sites.

Overall, the mean absolute deviation for the 18 different combinations was 10.9% for ICBM and 8.2% with MWM (Table 2). The variability in absolute deviation from measured values was higher for ICBM (CV = 83%) than for MWM (CV = 66%). According to a paired *t*-test, the predicted absolute deviation from measured final SOC stocks was not significantly different ($P = 0.259$) between the models.

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The CENTURY model has also previously been evaluated and tested on most of the site and treatment combinations we considered in western Canada and at Pendleton. For example, CENTURY predictions for the two treatments we considered at Pendleton were within ± 5% of observed values (Parton and Rasmussen 1994), slightly overestimating final SOC stocks. The Ellerslie site and some of the site and treatment combinations from Swift Current and Breton were considered for CENTURY simulations by Monreal et al. (1997). The predicted final SOC stocks were slightly underestimated and fell within ± 10% of measured data. A detailed discussion of CENTURY simulations and predictions using data from Swift Current was presented by Campbell et al. (2000).

Model Improvement and Development

ICBM was able to predict final SOC stocks within ± 10% of measured data for 22 (13 in eastern and 9 in western Canada) out of the 36 conventionally managed site and treatment combinations we examined across Canada, and within ± 5% for 11 (6 in eastern and 5 in western Canada) of 36 comparisons (Fig. 2; Table 1 and 2). This performance of ICBM was comparable to that of another two-compartment model (MWM) for the western Canadian sites, and to that of a multi-compartment model (CENTURY) commonly used across the country (particularly for the eastern Canadian sites).

When considering soils as carbon sinks, what matters most is not the *actual* C stock, but the *change* in C stock. Removal or accrual of atmospheric CO_2 depends not on SOC stocks, but on the change in SOC stocks. In the 22 site and treatment combinations, the average deviation from the estimated net *change* in SOC stock was 220 g C m^{-2}. For 7 out of these 22 comparisons, the deviation exceeded 250 g C m^{-2}. In the 11 site and treatment combinations where final SOC stocks were predicted within ± 5%, the deviation from the estimated net change in SOC stock was less than 140 g C m^{-2} (range of 0 to 138 g C m^{-2}, average of 58 g C m^{-2}) (Fig. 3). Expressed on an annual basis (i.e., g C m^{-2} yr^{-1}) the rate changes for these 11 site and treatment combinations were also well matched (data not shown). Only the ICBM-predicted SOC stock changes are shown, but results from CENTURY for the eastern sites and MWM for the western sites were similar to those presented. Rate changes obtained with the MWM for Swift Current, and with CENTURY for Swift Current, Ellerslie and Breton were discussed in Campbell et al. (2000) and Monreal et al. (1997).

The challenge in accurately predicting changes in C stock could be related to a number of factors. Deviations between measured and predicted values are not necessarily attributable entirely to deficiencies in the model, given the difficulty of precisely measuring soil C change. For example, a 5% uncertainty in SOC analysis (150 g m^{-2} on an initial SOC stock of 3000 g m^{-2}) could affect the apparent accuracy of predicted values. Also, an accurate estimate of the initial SOC level is crucial because SOC stock change (and related rate changes) is calculated from the difference between final and starting SOC levels. In some studies, the initial soil C was estimated from later samples or from soils outside the experimental plots (e.g., fencerow, grassed roadway). Finally, some inaccuracy may enter the predicted values because of uncertainty in the measurements and assumptions used to estimate C inputs, and unknown, persistent influences of historical land management practices at the experimental sites.

The models still need improvement to predict reliably the changes in C stocks for dominant agroecosystems and management practices across the country. One challenge may be to quantitatively estimate the annual crop residue C inputs for various regions and management practices. One approach is to estimate residue C input as a function of net primary productivity (NPP). This has the advantage of providing a common unit and ecological basis across ecosystems. In the sub-models now used to calculate residue C inputs (e.g., Campbell et al. 2000; Izzauralde et al. 2001; Bolinder 2004), fixed estimates are used as input to SOC models. The different sub-models also use divergent assumptions, especially about root and extra-root C. We are developing a more uniform sub-model for commonly grown crops in Canada, based on a compilation of Canadian-specific measurements of shoot- to root-ratios and harvest index data. These will quantify variability associated with the estimates, to better account for the effects of this variability on the predicted SOC stocks or rate changes.

The most recent version of the ICBM model (Andrén et al. 2004) now includes an "annual soil climate parameter" (r_e) that indirectly modifies the first-order decay rates. Briefly, the r_e parameter involves three components, reflecting the effects on decomposition of soil water content (r_W), soil temperature (r_T) and tillage (r_C). The r_W and r_T components are calculated from daily mean air temperature, precipitation and potential evapotranspiration data, while r_C is based on comparisons between tillage treatments (e.g., no-till versus conventionally tilled soils). To obtain annual r_e values for a given crop and region, $r_W \times r_T \times r_C$ are multiplied for each day, and an annual mean value is calculated. We intend to estimate and test the applicability of a Canadian-specific annual soil climate parameter with the ICBM-Region concept (Andrén et al. 2004) using daily weather station data for different regions across the country. The cultivation component (r_C), will be based on relative tillage coefficients developed from studies compiled for soil Great Groups across Canada by VandenBygaart et al. (2003). Since those coefficients had an uncertainty estimate, this cultivation factor will also allow us to include a variability assessment related to soil disturbance. For the MWM, Campbell et al. (2000) suggested that the usefulness and feasibility of the model would be enhanced by including the effects of weather and cultivation on the decay rates.

This ICBM-based approach will not likely supplant the more elaborate SOC models such as Century in all applications. While simplified algorithms have some advantages for direct use in whole-farm GHG models, the multi-compartment models still play a key role in improving our understanding of pertinent processes and, perhaps, in generating coefficients that can be used as an alternative way of calculating SOC change on farms.

CONCLUSIONS

The approach outlined here for modelling net SOC stock and rate changes within the Virtual Farm is flexible and

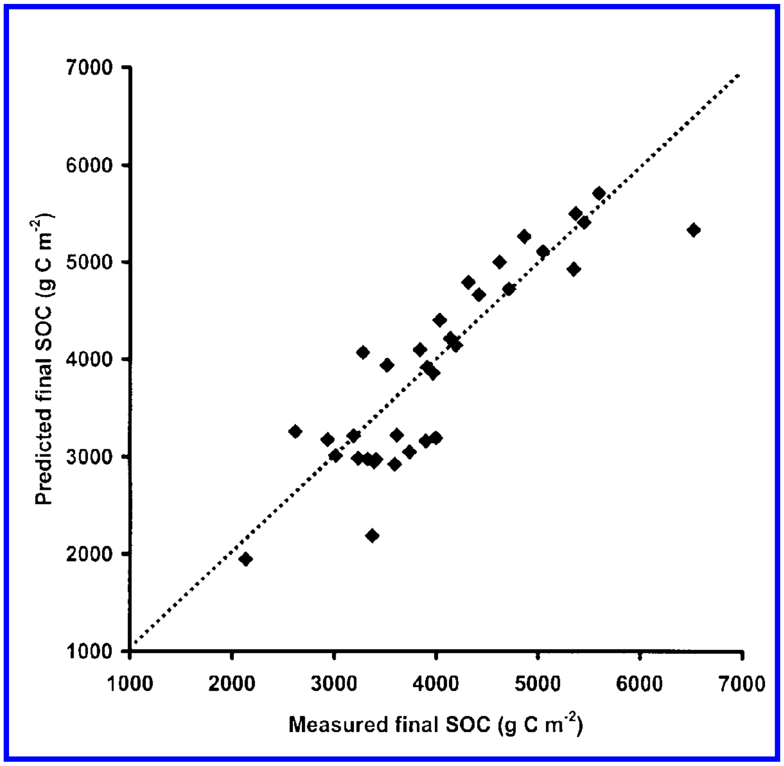

Fig. 2. ICBM predicted vs. measured final SOC stocks at the end of the 36 conventionally managed long-term site and treatment combinations in eastern and western Canada including data from one US site; dashed line is 1:1 (The Ellerslie site and treatment data were excluded because of scale.)

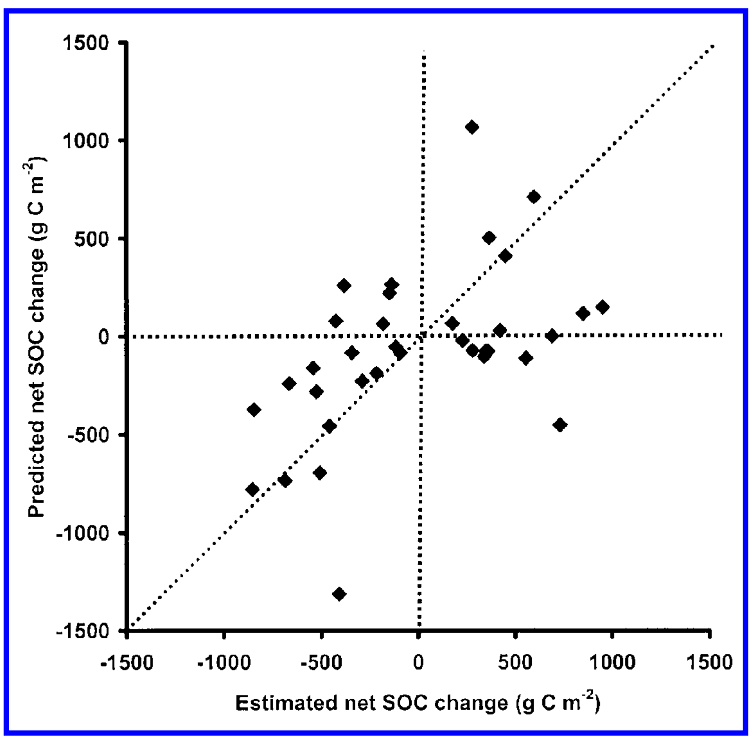

Fig. 3. ICBM predicted vs. estimated net change in SOC stock for the 36 conventionally managed long-term site and treatment combinations in eastern and western Canada including data from one US site; The dashed lines are 0:0 and 1:1.

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emphasizes compilation and integration of current knowledge, ease of use, and transparency. Our analysis suggests that, for whole-farm analyses such the Virtual Farm, the performance of two-compartment models is similar to that of more complex multi-compartment models. Whereas two-compartment models are more tractable than multi-compartment models, this assessment showed that the ICBM model will require further refinement for Canadian conditions in order to reliably predict changes in SOC stocks. With such a model, it appears that we can make relatively simple and transparent improvements in order to build a robust algorithm that will adequately reflect the wide range of Canadian soil and climatic conditions. For that purpose, our emphasis will focus on more consistent estimates for crop residue C inputs, as well as on including climatic and tillage effects into the ICBM model. More site and treatment combinations will also be added to our SOC databases, including new measurements, and this will aid in testing and modifying models for agroecosystems across Canada.

ACKNOWLEDGMENTS

The Model Farm Program of Agriculture and Agri-Food Canada provided funding for this work.

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