Soil organic carbon sequestration potential for Canadian agricultural ecoregions calculated using the Introductory Carbon Balance Model

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[1]Agrégats Waterloo Inc., 2131, route 112, C.P. 60/Stukeley-Sud, Quebec, Canada J0E 2J0 (e-mail: martin-anders.bolinder.1@ulaval.ca); [2]Department of Soil Sciences, SLU, P.O. Box 7014, SE-750 07 Uppsala, Sweden; and [3]Department of Soil Science and Agrifood Engineering, Laval University, Pavillon Paul-Comtois, Quebec, Quebec, Canada G1K 7P4. Received 4 October 2007, accepted 24 April 2008.

Bolinder, M. A., Andrén, O., Kätterer, T. and 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. The potential for storage of atmospheric CO_2-C as soil organic C (SOC) in agroecosystems depends largely on soil biological activity and the quantity and quality of annual C inputs to soil. In this study we used the Introductory Carbon Balance Model (ICBM) approach driven by daily standard weather station data, specific soil properties and crop characteristics at the scale of Canadian agricultural ecoregions. The objectives were to calculate a climate-dependent soil biological activity parameter representative for annual agricultural crop production systems (r_{e_crop}) and to estimate the effect of fallow (r_{e_fallow}). These parameters are based on the daily product of soil temperature and stored water that influence biological activity in the arable layer, and are used to adjust the decomposition rates of the ICBM SOC pools. We also tested r_{e_crop} and r_{e_fallow} on SOC stock change data for different site and treatment combinations from long-term field experiments located in some of the ecoregions. An r_{e_crop} value of 0.95 for western ecoregions was on average 0.23 units lower than that of the eastern ecoregions, indicating a lower decomposition rate of SOC. Although the estimated annual C inputs to soil for small-grain cereals were on average $\approx$7.5% higher in the eastern ecoregions (305 vs. 285 g C m^{-2} yr^{-1}), the overall results suggest that the western ecoregions would have a greater potential to maintain high SOC levels in the long term. However, these parameters varied between ecoregions and, consequently, the SOC sequestration potential was not always higher for the western ecoregions. The effect of fallow was on average $\approx$0.04, i.e., SOC decomposed slightly faster under fallow. Predictions for 24 out of 33 site and treatment combinations across Canada were significantly improved ($P = 0.003$), compared with a previous application with the ICBM that did not differentiate between crops and fallow. The methodology used here enabled us to examine regional differences in the potential for SOC sequestration as a balance between annual C inputs to soil and soil biological activity.

Key words: Annual C inputs, climate, fallow, soil biological activity, agroecosystems

Bolinder, M. A., Andrén, O., Kätterer, T. et Parent, L.-E. 2008. **Calcul du potentiel de séquestration du carbone organique du sol dans les écorégions agricoles du Canada grâce au Modèle d'introduction du bilan du carbone**. Can. J. Soil Sci. **88**: 451–460. La possibilité que les écosystèmes agricoles stockent le C-CO_2 atmosphérique sous forme de C organique dans le sol (COS) dépend dans une large mesure de l'activité biologique du sol ainsi que de la quantité et de la qualité des apports annuels de C. Pour leur étude, les auteurs ont recouru au Modèle d'introduction du bilan du carbone (ICBM) auquel ils ont appliqué les relevés quotidiens des stations météorologiques, les propriétés du sol et les caractéristiques des cultures dans les écorégions agricoles du Canada. L'étude avait deux objectifs : établir un paramètre de l'activité biologique du sol associé au climat représentatif des systèmes de production annuels ($r_{e\_culture}$) et estimer l'incidence de la jachère ($r_{e\_jachère}$). Ces paramètres reposent sur le produit quotidien entre la température du sol et l'eau emmagasinée par celui-ci, qui influe sur l'activité biologique dans la couche arable. On s'en est servi pour ajuster le taux de décomposition des réserves de COS de l'ICBM. Les auteurs ont aussi testé les variables $r_{e\_culture}$ et $r_{e\_jachère}$ avec les données reflétant l'évolution des stocks de COS à différents endroits et pour diverses combinaisons de traitement grâce aux essais de longue durée effectués sur le terrain dans quelques écorégions. La valeur 0,95 pour $r_{e\_culture}$ dans les écorégions de l'Ouest se situe en moyenne 0,23 unité inférieure à celle obtenue pour les écorégions de l'Est, signe que le COS s'y décompose plus lentement. Bien que les apports annuels estimé de C soient, en moyenne plus élevés d'environ 7,5 % dans l'Est que dans l'Ouest (305 contre 285 g de C par m^2 et par année), les résultats globaux laissent croire que les écorégions de lesécoregions de l'Ouest pourraient retenir plus de COS à long terme. Les paramètres varient néanmoins entre les écorégions, de sorte que le potentiel de séquestration du COS n'est pas toujours plus élevé dans les écoregions de l'Ouest. En moyenne, l'incidence de la jachère se situe à $\approx$0,04, indiquant que le COS se décompose un peu plus rapidement sous la jachère. Les prévisions pour 24 des 33 sites et combinaisons de traitement examinés au Canada étaient significativement meilleures ($P = 0,003$) que celles obtenues avec

Abbreviations: **GAI**, green area index; **ICBM**, Introductory Carbon Balance Model; **NPP**, net primary productivity; **SOC**, soil organic carbon

une application antérieure de l'ICBM où l'on ne faisait pas de distinction entre les sols sous culture et les sols sous jachère. La méthodologie employée ici a permis aux auteurs d'examiner les variations régionales du potentiel de séquestration du COS, exprimé sous forme de bilan entre les apports de C annuels et l'activité biologique du sol.

Mots clés: Apports annuels de C, climat, jachère, activité biologique du sol, écosystèmes agricoles

The potential for sequestration and long-term storage of atmospheric CO_2-C as soil organic C (SOC) for different agroecosystems depends largely on soil biological activity and reliable estimates of net primary productivity (NPP) and its proportion returned to the soil as annual C inputs (Paustian et al. 1997; Campbell et al. 2000; Bolinder et al. 2007a, b). The net exchange of CO_2 for a specific soil–plant ecosystem with the atmosphere thus depends on the balance between the amount of photosynthetically fixed C resulting from NPP that remains as SOC, and the release of CO_2 from the decomposition of SOC through soil biological activity.

This potential for SOC storage should be defined within specific climatic regions (Carter 1996), and estimations of SOC contents need to account for large-scale variations in climate and soil properties (e.g., Post et al. 1982; Eswaran et al. 1993). Indeed, although SOC tends to increase almost linearly with increasing annual crop residue C inputs to soil, particularly for situations where the initial status of SOC content is low, this rate of increase depends also on climate, soil properties and management practices (Parton et al. 1996). In most applied soil biological models, the conditions for soil biological activity are mainly driven by the direct influence of climate such as air temperature, precipitation and evaporation on soil water content and temperature, and typically varies with soil properties and plant cover (Andrén et al. 2007).

Management practices such as tillage may disrupt soil structure through its mechanical action and enhance the decomposition of physically protected SOC (Roberts and Chan 1990). Moreover, tillage intensity, which is often determined by the type of crop grown (e.g., annual versus perennial crops) as well as summer fallow have an impact on the soil conditions and decomposer activity (Follett 2001). For example, one of the effects of summer fallow, which is still commonly used to store soil moisture in semi-arid regions by reducing crop transpiration, is the relatively higher rate of SOC decomposition in the warmer and moister surface soil (Boehm et al. 2004). Consequently, it is generally considered that for soils on the Canadian prairies the SOC decomposition rates increase with the frequency of summer fallow in a given rotation, e.g., in the order: continuous wheat < fallow-wheat-wheat < fallow-wheat (Campbell et al. 2000). For eastern Canadian soil and climatic conditions, fallow (practiced to control weed populations) is no longer used as a management practice. However, there are some common crop production systems that result in conditions similar to those of fallow for a significant proportion of a normal growing season, i.e., potato cultivars harvested mid-summer and not followed by a catch- or cover-crop. Fallowing can also significantly contribute to a decline in SOC content (but not necessarily increased CO_2 emission) because of increased soil erosion in the absence of plant cover and a much lower annual plant C input to soil (McGill et al. 1988; Boehm et al. 2004).

The effects of annual C inputs to soil as well as the influence of climate (including effects of management practices on decomposition rates) on agroecosystem SOC dynamics can be examined using models, e.g., the two-compartment Introductory Carbon Balance Model (ICBM) developed by Andrén and Kätterer (1997) for Scandinavian conditions. It provides equations that can be used to estimate long-term trends in SOC dynamics as a function of climate, soil properties and management (r_e parameter) and annual C inputs (i parameter) to soil. Model predictions have been compared with results from Northern European long-term field experiments (Kätterer and Andrén 1999) and are currently used to calculate regional and national soil C balances for Swedish agricultural soils and production regions (Andrén et al. 2008).

Within the ICBM concept, a daily decomposer activity factor, r_e, is calculated from relative water content and soil temperature (Andrén et al. 2004). This factor is the product (calculated on a daily basis) of r_T, r_Θ and r_C, which represent soil temperature, water content and degree of cultivation, respectively. When excluding r_C and using a clay loam soil from the calibration site (i.e., a reference site in Central Sweden), and assuming no crop/plant cover, the climatic influence on decomposition is condensed into one parameter, r_{e_clim}. Its value allows comparisons of climate-induced decomposition rates between sites and regions (Andrén et al. 2007).

The ICBM has been applied to long-term experimental data in North America (Bolinder et al. 2006). It was found that its performance was similar to other commonly used models for Canadian agroecosystems, such as the Century model (Metherell et al. 1993) and modified Woodruff model (Campbell et al. 2000). The regional extension, ICBMregion (Andrén et al. 2004), has also enabled us to characterize the influence of climate on SOC dynamics in Canadian agricultural ecoregions (Bolinder et al. 2007a), by integrating long-term daily standard weather station data into the r_{e_clim} parameter, which affects the decomposition of the young and old SOC pools. Bolinder et al. (2007b) also developed a methodology to estimate annual C inputs to soil as a function of NPP for Canadian agroecosystems which can be used to estimate the ICBM *i* parameter.

In this study we use a more complete ICBM approach by including specific soil properties and crop characteristics at the scale of Canadian agricultural ecoregions. Our objectives were to calculate a parameter representative for annual crop production systems (r_{e_crop}), estimate the effect of fallow (r_{e_fallow}), and to test these ICBM r_{e_crop} and r_{e_fallow} parameters for Canadian conditions. This latter aspect was assessed using measured SOC stock changes for different site and treatment combinations in long-term field experiments located in some of the agricultural ecoregions. The potential for SOC sequestration of agroecosystems in different agricultural ecoregions is discussed based on differences in both annual C inputs to soil and SOC decomposition rates.

THEORETICAL BACKGROUND

Definitions of r_{e_crop} and r_{e_fallow}

The ICBM concept calculates daily soil temperature (r_{e_temp}) and water stored (r_{e_wat}) in the arable layer (0–25 cm) using pedotransfer, soil water balance and biological activity functions. The product of r_{e_temp} times r_{e_wat} summarizes the soil climate and its influence on soil biological activity into one parameter, r_{e_clim} (Andrén et al. 2007). The calculations of r_{e_crop} and r_{e_fallow} used crop and soil data following the flow chart presented by Andrén et al. (2007; Fig. 1). Both parameters were scaled to the initial Swedish calibration site using the same calibration factor as that used for African (Andrén et al. 2007) and Canadian (Bolinder et al. 2007a) applications.

In an earlier application, Canadian daily climate data (air-temperature, total precipitation, potential evapotranspiration) for each agricultural ecoregion were used together with soil properties from the Swedish reference site for the calculations of r_{e_clim} [for details see Bolinder et al. (2007a)]. For r_{e_crop}, Canadian-specific crop characteristics and soil properties are used for each of the Agricultural Ecoregions. The r_{e_fallow} parameter is calculated by excluding the crop (i.e., no crop transpiration), and is used to estimate the effect of fallow as the difference from r_{e_crop}, i.e., fallow effect $= r_{e\_fallow} - r_{e\_crop}$. The types of input data used in the calculations of r_{e_clim}, r_{e_crop} and r_{e_fallow} are summarized in Table 1.

In a previous study, Bolinder et al. (2006) assessed the performance of ICBM using long-term data for various agricultural cropping systems that were conventionally managed at different sites in eastern and western Canada. At that time, the rate-modifying parameter, r_e, was set to the value used by Andrén and Kätterer (1997) for the "most normal practice" (i.e., $r_e = 1.0$) for all the sites, because no regional estimations were available. The ICBM predicted final SOC stocks for several site and treatment combinations, and the deviation from measured final SOC stocks was assessed.

Crop Characteristics and Soil Properties, and Calculation of Annual C Inputs

The crop characteristic information needed for r_{e_crop} are date of emergence, date of ripening and agronomic yield. The specific soil properties needed for each

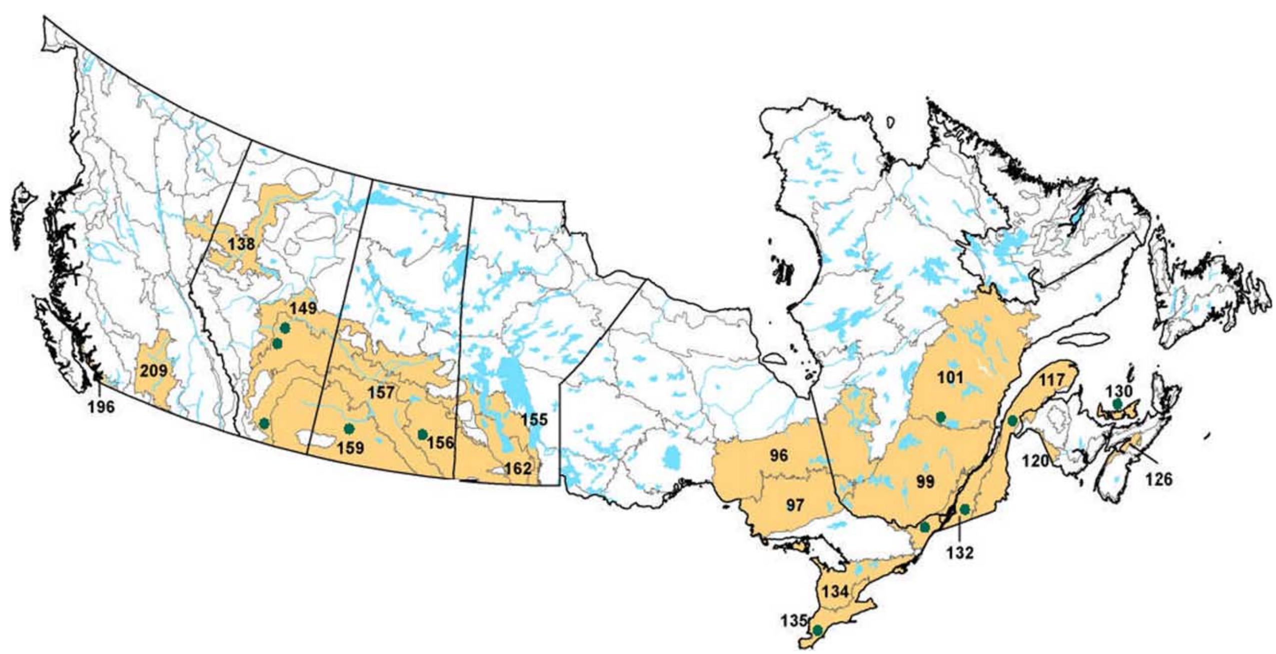

Fig. 1. Location of Canadian long-term field experiments (●) with measured soil organic carbon stock change data used to test the r_{e_crop} and r_{e_fallow} parameters (see Table 2 for more details).

Table 1. Types of input data used to calculate the different r_e parameters for Canadian agricultural ecoregions with the Introductory Carbon Balance Model approach. "Constant" and "Variable" indicate if the parameter is changed between sites

Type of r_e	Daily climatic data	Soil properties	Crop characteristics
r_{e_clim}	Variable[z]	Constant[y]	Constant[w]
r_{e_fallow}	Variable[z]	Variable[x]	Constant[w]
r_{e_crop}	Variable[z]	Variable[x]	Variable[v]

[z]Specific for each Canadian agricultural ecoregion using standard weather station data from Bolinder et al. (2007a).
[y]Soil properties were those of the Uppsala reference site (23% sand, 40% silt, 37% clay and 1.14% soil organic carbon).
[x]Specific for each Canadian agricultural ecoregion (see the text).
[w]Corresponds to that of the Uppsala reference site for a bare-fallow treatment.
[v]Specific for small-grain cereal crop production systems in each Canadian Agricultural Ecoregion (see the text).

Agricultural Ecoregion are sand, clay and SOC contents. The climatic data were described by Bolinder et al. (2007a) for each Canadian Agricultural Ecoregion.

In order to calculate r_{e_crop} values we used crop data provided by de Jong et al. (2000) for the same Canadian agricultural ecoregions and a similar time span as in Bolinder et al. (2007a). The data set includes planting dates, growing season length and crop yields for small-grain cereals estimated using the Erosion Productivity Index Calculator (EPIC) (Williams 1995). That study provided the baseline data with average estimated crop yields for barley and spring wheat. The estimated planting dates generally matched those obtained by expert opinion and observations (Huffman 2000). In our calculations, emergence was set to 14 d after seeding and ripening was to set to 21 d before harvest.

The annual C inputs to soil from crop residues for each agricultural ecoregion were calculated from the grain yields using the approach presented by Bolinder et al. (2007b). Mean annual C inputs to soil were estimated using the allometric coefficients for small-grain cereals and Eq. 14 in Bolinder et al. (2007b) considering that all the straw was retained in the field.

Parameters and Assumptions Used to Estimate r_{e_crop} and r_{e_fallow}

The assumptions used for the calculations of r_{e_crop} *and* r_{e_fallow} for each Canadian agricultural ecoregion were the same as those used to calculate the Canadian r_{e_clim} parameter (Bolinder et al. 2007a), except for some modifications in step 2 and 3, as described below.

Instead of using the soil characteristics of the Swedish reference site in step 2 for volumetric water content at field capacity, Θ_{fc}, and wilting point, Θ_{wp}, these parameters were estimated from sand, clay and organic carbon content data specific to each of the soil series using the pedotransfer function developed by Rawls et al. (2003). Instead of assuming no plant cover in step 3, the water balance was estimated from the small-grain cereal yields using a functional relationship between yield and green area index (GAI) derived from a Scandinavian data set applied to the FAO concept proposed by Allen et al. (1998). The GAI is here defined as the area of all plant parts that are visibly green where only one side of, for example, leaves is counted.

Briefly, for this calculation, inputs are daily mean air temperature, precipitation and potential evapotranspiration, soil water characteristics from step 2 and GAI of the crop, where GAI dynamics are described as a bell-shaped function that is used to calculate transpiration influence on the soil water balance:

$$GAI = GAI_{\max}\exp\left\{-\frac{(t-\mu^2)}{2\sigma^2}\right\}$$

where t is day of year, μ is the day at which $GAI = GAI_{max}$ (maximum GAI) and σ determines the width of this distribution function, which is crop specific. Values for σ have been estimated for Swedish data sets for winter wheat and spring barley (Flink et al. 1995). The empirical relationship between the amplitude of this function (GAI_{max}) and grain yield (Mg dry matter ha^{-1}) was established from experimental results ($n=28$) for barley and winter wheat compiled from Swedish and Danish field experiments (Flink et al. 1995; Olesen et al. 2002; Pettersson 1989). The resulting regression equation:

$$GAI_{\max} = 0.073 \times Yield^2 + 0.408 \times Yield$$

explained 89% of the variation in GAI_{max}. The harvest index (i.e., ratio of [grain]/[grain + straw]) used in these data sets ($\approx$0.45) to estimate total above-ground biomass was similar to that of Canadian wheat and barley cultivars (Bolinder et al. 2007b).

MATERIALS AND METHODS

The calculations for each agricultural ecoregion required a number of weather station data sets (i.e., 1 to 3) and representative soil series (i.e., 1 to 2 per region). Therefore, for example, considering an agricultural ecoregion with standard weather data from three stations and with two representative soil series: we conducted six (i.e., 2×3) series of calculations of r_{e_crop} and r_{e_fallow}, and the results were thereafter averaged to obtain a unique r_{e_crop} and r_{e_fallow} value for each agricultural ecoregion. The calculations were performed using SAS (SAS Institute, Inc. 2004); the programs are available for download from www-mv.slu.se/vaxtnaring/olle/

Soil properties used in the calculations are those of the Ap horizon of one to two representative soil series for each Canadian agricultural ecoregion (see Acknowledgements for sources). The following soil series (Canada Soil Survey Committee 1978) for each ecoregion number were: Hanbury was used for Ecoregions

96, 97 and 99, Hebertville for 101, Du Creux for 117, Caribou and Holmesville for 120, Queens and Cornwallis for 126, Charlottetown for 130, Sainte Rosalie and Grenville for 132, Hariston and Huron for 134, Brookston and Lincoln for 135, Hubalta and Fahler for 138, Whitewood and Waitville for 149, Pelan and Peguis for 155, Oxbow and Yorkton for 156, Weyburn and Regina for 157, Ardill and Haverhill for 159, Red River and Osborne for 162, Whatcom and Nicholson for 196 and 209.

Based on the study by Bolinder et al. (2006), some of the site and treatment combinations from long-term field experiments ($n = 33$) representative for regional climatic and edaphic conditions can be associated with different Agricultural ecoregions (Table 2 and Fig. 1). We retained only the site and treatment combinations that involved mainly annual crops, mostly wheat for the western Canadian ecoregions. Only the western Canadian sites had treatments including fallow, generally classic fallow-wheat and fallow-wheat-wheat rotations [for more details see Bolinder et al. (2006)]. Site and treatment combinations from eastern Canadian ecoregions also included barley, corn, potatoes and soybeans. On very few occasions, when forage crops were grown they only spanned over 1, or at the most 2 yr. We re-ran ICBM for all of these site and treatment combinations with the regional estimations of r_{e_crop} and r_{e_fallow} from the current study presented in Table 3, keeping all other parameters unchanged.

To determine the degree of improvement with the new ICBM predictions made for each of the site and treatment combinations, we used a statistic that takes into account only the direction of the expected trend, where the expected trend was that the new predictions came closer to the measured final SOC stocks. For that purpose we considered a randomization model for paired comparisons, an approach that is described in detail by Siegel (1956) and Lehmann (1975). Briefly, the statistic of the test is equal to the number of positive or negative differences, e.g., a positive difference indicates an improved prediction for a given site and treatment combination. The null hypothesis tested by the sign test is that

$$P(X_A > X_B) = P(X_A < X_B) = 1/2$$

where X_A and X_B are the responses within a related pair (or H_0: the median difference is zero, and H_1: the median of the difference, is positive). The associated probability of occurrence of values as small as x is given by the binomial distribution for $P = Q = 1/2$. Since H_1 predicts the direction of the differences, the expected trend, the region of rejection is one-tailed. It consists of all values of x, where x = the number of minuses, whose one-tailed associated probability of occurrence under H_0 is equal to or less than $\alpha = 0.05$. If a matched pair shows no difference (i.e., the difference, being zero, has no sign) it is excluded from the analysis and n is thereby reduced. For large samples (i.e., $n > 25$) the normal approximation to the binomial distribution was used.

RESULTS AND DISCUSSION

r_{e_crop} and r_{e_fallow} for Canadian Agricultural Ecoregions

The mean r_{e_crop} values were lower for the western Canadian agricultural ecoregions (0.95) compared with the eastern ecoregions (1.18) (Table 3). The highest values in eastern Canada were those obtained for Ecoregions 99 (Southern Laurentians) and 135 (Lake Erie lowland) with r_{e_crop} values > 1.40. Only the Abitibi Plain, Lake Timiskaming Lowland and Central Laurentians Ecoregions had values equal to 1.0 or < 1.0, and the other Ecoregions were characterized by r_{e_crop} values ranging from 1.1 to 1.3. The western Canadian ecoregions showed less difference in r_{e_crop} values, which typically were all less than 1.0, i.e., between 0.75 and 0.99. An exception was Ecoregion 196, the Lower Mainland on the Canadian west coast with a particularly warm and humid climate, for which the calculated r_{e_crop} was 1.49.

The different r_{e_crop} values imply that an ecoregion with a higher annual r_{e_crop} would require a higher annual C input to soil in order to maintain similar SOC contents, and, in particular, to reach the same mass of carbon at steady-state. In fact, the total steady-state carbon mass (T_{SS}) is linear in response to r_{e_crop} and i parameters (Andrén and Kätterer 1997), something that is also the case for most other SOC models. This means that, compared with western ecoregions, the eastern Canadian agricultural ecoregions with an average r_{e_crop} of 1.18 would necessitate an annual C input to soil 24% higher to reach the same T_{SS} (i.e., because the annual r_{e_crop} for western ecoregions were on average 0.95). Although reaching T_{SS} usually takes a long time it remains a reasonable indication of the potential of SOC sequestration for a given "status" of an agroecosystem (Andrén et al. 2008).

Mean annual C inputs to soil for small-grain cereals, estimated as a function of NPP and calculated according to the methodology proposed by Bolinder et al. (2006b), was slightly higher for the eastern ecoregions, due to a higher grain yield (Table 3). Mean annual C inputs to soil for eastern ecoregions was 305 g C m^{-2} yr^{-1} (range of 230 to 391 g C m^{-2} yr^{-1}), and for western Canada the average value was 284 g C m^{-2} yr^{-1} (range of 177 to 243 g C m^{-2} yr^{-1}). In the current data set and at this scale of application the mean annual C input to soil was therefore ≈7.5% higher for the eastern Canadian ecoregions, which would compensate, at least partly for the higher SOC decomposition rates.

Furthermore, both r_{e_crop} and i are linearly related to T_{SS} with predictable and directly opposite effects on T_{SS}, and also generally opposite and predictable effects on the SOC evolution over shorter time-frames. For example, in eastern Canada, although Ecoregion 117

Table 2. Long-term field experiments located in different Canadian ecoregions used for testing projections made with the r_{e_crop} and r_{e_fallow} parameters in ICBM

Eastern Ecoregions, site and treatment combinations	% deviation from measured SOC stocks[z]		Improved trend	Western Ecoregions, site and treatment combinations	% deviation from measured SOC stocks[z]		Improved trend
	With old r_e	With new r_e			With old r_e	With new r_e	
130 Ch'town. − 11 yr P/B	+12.1	+11.4	Yes	156 IH − 10 yr F/W(N+P)	–7.7	– 7.2	Yes
130 Ch'town. − 11 yr P/RC	+6.8	+6.1	Yes	156 IH − 10 yr F/W/W (N+P)	–10.8	–10.1	Yes
130 Ch'town. − 11 yr P/IRG	+9.2	+8.2	Yes	156 IH − 10 yr F/W/W (N+P − straw)	– 18.6	–18.2	Yes
130 Harr. − 9 yr W/B/B/SY	+2.6	+1.6	Yes	156 IH − 10 yr Cont. W (N+P)	–2.7	–1.7	Yes
130 Harr − 11 yr P/B	+8.3	+7.5	Yes	156 EL − 11 yr Cont. B (Fert.)	–6.2	–5.6	Yes
130 Harr. − 11 yr P/B/RC	+1.3	+0.5	Yes	156 BR − 52 yr W/F (Fert.)	–8.7	–7.1	Yes
130 Harr. − 11 yr Cont. P	+11.0	+10.3	Yes	156 BR − 52 yr W/O/B/H/H	–35.1	–33.6	Yes
130 Ch'town. − 9 yr W/B/B/SY	+24.6	+23.2	Yes				
				159 SC − 30 yr F/W (N+P)	–13.1	–10.7	Yes
117 LaPoc − 6 yr Cont. B	−7.9	−9.6	No	159 SC − 30 yr F/W/W	–10.5	–7.6	Yes
				159 SC − 30 yr F/R/W (N+P)	–18.4	–15.9	Yes
101 Norm.-6 yr Cont. B	+5.6	+5.6	No change	159 SC − 30 yr Cont. W (N+P)	–20.0	–17.3	Yes
101 Norm. − 3 yr Cont. B	+7.7	+7.7	No change	159 SC − 30 yr Cont. W (+P)	–12.7	–9.9	Yes
				159 SC − 30 yr W/Lent. (N+P)	–18.8	–16.1	Yes
132 Chic. − 10 yr Cont. C	+24.1	+21.2	Yes				
132 Ottw. − 6 yr Cont. C	+8.3	+7	Yes	157 LB − 39 yr Cont. W	+0.9	+5.5	No
132 Ottw. − 6 yr Cont. W	+1.3	+0.6	Yes	157 LB − 39 yr F/W	+8.3	+12.6	No
				157 LB − 39 yr F/W/W	±0.0	+4.1	No
135 Harw. − 12 yr Cont. C	−0.7	−6.4	No				
135 Harw. − 35 yr C/O/A/A	−18.2	−26.5	No				
135 Harw. − 35 yr Cont. C	+2.1	−8.3	No				

Ecoregions: 130 = Prince Edward Island. 117 = Appalachians. 101 = Central Laurentians. 132 = St. Lawrence Lowlands. 135 = Lake Erie Lowland. 156 = Aspen Parkland. 159 = Mixed Grassland. 157 = Moist Mixed Grassland. Sites: Ch'town = Charlottetown. Harr = Harrington. LaPoc = La Pocatiere. Norm = Normandin. Chic = Chicot. Ottw = Ottawa. Harw = Harrow. IH = Indian Head. EL = Ellerslie. BR = Breton. SC = Swift Current. LB = Lethbridge. Treatments: P = potato. B = barley. RC = red clover. IRG = Italian ryegrass. W = wheat. SY = soybeans. C = corn. O = oats. A = alfalfa. F = fallow. H = hay. R = rye. Lent = lentil. Cont. = continuous.

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

Table 3. Estimated annual r_e parameters, agronomic yields and annual C inputs to soil for each of the Agricultural Ecoregions across Canada

Agricultural ecoregion[z]		Annual r_e parameters (unitless)		Grain Yield (g C m^{-2})	Mean annual C input to soil (g m^{-2})[x]
Name	Number[y]	r_{e_crop}	r_{e_fallow}		
Eastern Canada					
Abitibi Plain	96	0.92	0.97	171	340
Lake Timiskaming Lowland	97	0.99	1.04	171	340
Southern Laurentians	99	1.41	1.46	171	340
Central Laurentians	101	1.00	1.04	197	391
Appalachians	117	1.26	1.30	161	319
Saint John River Valley	120	1.22	1.26	158	314
Annapolis-Minas Lowlands	126	1.17	1.20	130	258
Prince Edward Island	130	1.07	1.10	147	292
St. Lawrence Lowlands	132	1.12	1.14	116	230
Manitoulin-Lake Simcoe	134	1.32	1.35	136	270
Lake Erie Lowland	135	1.49	1.54	132	262
Mean		1.18	1.22	154	305
Western Canada					
Peace Lowland	138	0.75	0.79	154	306
Boreal Transition	149	0.90	0.94	154	306
Interlake Plain	155	0.91	0.95	155	308
Aspen Parkland	156	0.93	0.97	166	330
Moist Mixed Grassland	157	0.82	0.85	113	224
Mixed Grassland	159	0.85	0.88	89	177
Lake Manitoba Plain	162	0.93	0.99	173	343
Lower Mainland	196	1.49	1.51	141	280
Thompson-Okanagan Plateau	209	0.99	1.03	141	280
Mean		0.95	0.99	143	284

[z]These agricultural ecoregions cover approximately 80 to 90% of Canadian agriculture.
[y]For the geographical distribution see the corresponding numbers on the map in Fig. 1.
[x]Calculated with equations from Bolinder et al. (2007b); using C_i for the mean annual C input to soil (see the text).

had a r_{e_crop} value 0.14 units higher than Ecoregion 132, the former ecoregion had an annual C input to soil 39% higher resulting in a greater SOC sequestration potential. Similar considerations apply to Ecoregion 155 versus Ecoregion 157 for western Canada. There were also some ecoregions in eastern Canada that had a combination of r_{e_crop} and i values indicating that they would have a greater potential to sequester SOC compared with some of the western Canadian ecoregions, e.g., eastern Canadian Ecoregions 97 and 101 versus western Ecoregion 209.

In this application of r_{e_crop}, the characteristics used were those for small-grain cereals, although it is possible to make this value more ‘‘crop-specific’’ using other specific GAI indexes than those for small-grain cereals. The same crop characteristics can also be used in ICBM as a reasonable first approximation for agricultural production systems that involve other annual crops than small-grain cereals. The methodology to estimate annual C inputs to soil as a function of NPP for Canadian agroecosystems (Bolinder et al. 2007b), used here to calculate i for small-grain cereals, can also be applied to other annual crop types, and therefore allows an expansion of the analysis of interactions between i and r_{e_crop}.

For example, the annual average C input to soil for the eastern ecoregions from crop residues for small-grain cereal production systems when the straw is retained in the field (i.e., 305 g C m^{-2}) can be considered as a ‘‘medium-input’’ category. A higher C input category typical for eastern Canadian farms (Bolinder et al. 2007b) can result from soybeans or grain-corn, i.e., in the order of 500 to 600 g C m^{-2} yr^{-1}, while a lower range of C inputs can occur for root crops such as potato ($<$ 100 g C m^{-2} yr^{-1}).

The r_{e_crop} values for the eastern Canadian ecoregions varied by a factor of $\approx$1.7, i.e., between about 0.9 to 1.5 (Table 3). When expanding the analysis to involve different types of annual crops illustrates the relative importance of crop types on the potential for SOC sequestration, both within and between eastern ecoregions. A crop within a high input category would increase the i values by a factor of as much as $\approx$2.0 (i.e., grain-corn versus small-grain cereals) to $\approx$0.3 (i.e., a potato crop versus a small-grain cereal crop), hence a much larger variation than the difference in r_{e_crop} values. Therefore, as illustrated in Fig. 2, typical variations in annual C inputs to soil would have a greater impact on the potential of SOC sequestration than differences in soil biological activity.

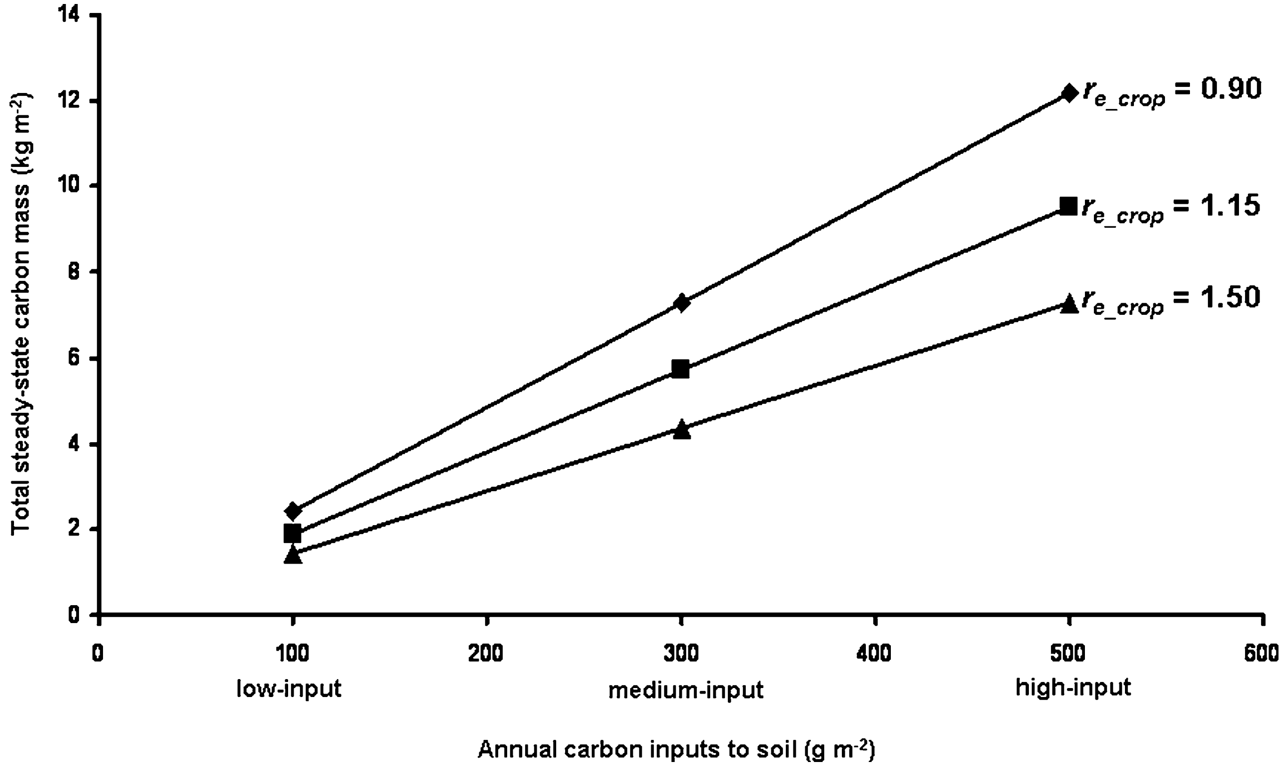

Fig. 2. The effects of different annual carbon inputs (i) to soil on total steady-state carbon mass calculated with ICBM using i values representative for eastern Canadian conditions. These effects are shown for three different soil biological activity parameters (r_{e_crop}), namely 0.90, 1.15 and 1.50, respectively (the lowest value is typical for the Abitibi Plain, intermediate for St. Lawrence Lowlands and the highest for Lake Erie Lowland).

The r_{e_fallow} values followed the same general trend as the r_{e_crop} values, both for the eastern and western Canadian ecoregions (Table 3). The effect of fallow calculated as $r_{e\_fallow} - r_{e\_crop}$ was lowest in Ecoregions 132, 159 and 196 ($\approx$0.02), and highest in Ecoregions 97 and 162 ($\approx$0.06). On average, however, they were the same for both the eastern and western ecoregions ($\approx$0.04). For modeling different management scenarios the average r_{e_crop} would be adjusted. For example, with a fallow-wheat rotation, the effect of fallow would represent in average 0.02 (i.e., 0.04/2) on an annual basis, and 0.013 (i.e., 0.04/3) for a fallow-wheat-wheat rotation.

The effect of fallow is also considered in many other SOC models by various modifications of the SOC decay rates. For example, in the RothC model version 26.3 (Coleman and Jenkinson 1996), decomposition rates under crops are 40% lower than under fallow. Since the refractory C pool is usually set to 40–55% of total SOC (Falloon and Smith 2000), this implies that decomposition in respect to total SOC proceeds about 20% faster in fallows than under crops. Another model, developed for western Canadian semi-arid conditions by Campbell et al. (2000), the two-compartment Modified Woodruff Model (MWM), uses different annual first-order decay rates based on the years of fallow in the cropping sequence, but only for the more active pool of SOC. The decay rate for a continuous cropping system without fallow is set to 0.001 yr^{-1}, to 0.02 yr^{-1} for a fallow–wheat system and to 0.01 yr^{-1} for a fallow–wheat–wheat system. The ICBM and MWM are not directly comparable because of differences in their structure, in particular the fact that r_{e_fallow} (and r_{e_crop}) affects the decomposition rates of both the young (i.e., considered be more active) and old SOC pools (Andrén and Kätterer 1997). However, the way the relative effect of fallow is included according to its proportion within a rotation is similar.

For eastern Canada, early-maturing potato cultivars are commonly planted mid-May and harvested end of July, and vine killing usually takes place mid-July (Mosley and Chase 1993). Therefore, compared with other annual crops, there is plant cover present approximately only half of the growing season, considering scenarios when there is no catch- or cover-crop seeded after harvest. Such production systems are common in eastern Ecoregions, and a combination of r_{e_crop} and r_{e_fallow} values could be used to model the effect of this management practice (i.e., $r_{e\_crop}+r_{e\_fallow}/2$). We will examine such considerations and production systems in more detail in a following paper.

Testing r_{e_crop} and r_{e_fallow} on Data from Long-term Field Experiments

The results for testing if the new predictions including $r_{e\_\_crop}$ and r_{e_fallow} parameters calculated for the different Ecoregions, came closer to measured final SOC content for a given site and treatment combination than those made by Bolinder et al. (2006) are summarized in Table 2. Overall, 24 of the 31 site and treatment combinations across Canada were significantly improved ($P = 0.003$). For Ecoregion 101 (two treatments at the Normandin site) the new $r_{e\_crop} = 1.0$ and predictions therefore remained unchanged. For eastern Canadian Agricultural Ecoregions the trends were improved for 11 out of 15 predictions ($P = 0.059$), and for western Canada 13 out of 16 predictions were improved ($P = 0.011$). A total of eight Ecoregions had available data from long-term field experiments (Table 2 and Fig. 1). Among those, improvements occurred for two Ecoregions in eastern Canada (130 and 132) and two in western Canada (156 and 159).

In the study by Bolinder et al. (2006), it was found that for most site and treatment combinations in eastern Canada ICBM tended to overestimate the final SOC stocks. Therefore, in order to improve the predictions r_e should be increased (i.e., $r_{e\_crop} > 1.0$), thus increasing the decay rates of young and old SOC. This was the case for the sites located in Ecoregions 130 (Charlottetown and Harrington) and 132 (Chicot). But, for Ecoregions 117 (La Pocatiere site) and 135 (Harrow site), where the previous predictions had underestimated the final SOC stocks, r_{e_crop} was also > 1.0 and, consequently, the predictions were not improved. Similarly, for western Canada, previous predictions using $r_e = 1.0$ had underestimated the final SOC content at the Indian Head, Breton and Ellerslie sites located in Ecoregion 156, as well as the Swift Current site (Ecoregion 159). Our estimations of both r_{e_crop} and r_{e_fallow} were < 1.0 and predictions improved for these two ecoregions. However, for the Lethbridge site in Ecoregion 157 previous predictions had overestimated the final SOC content, but our estimations of both r_{e_crop} and r_{e_fallow} were < 1.0 so the predictions did not improve.

The sensitivity of a given site and treatment combination in the different Agricultural ecoregions to the predictions made with the new r_e values (i.e., either r_{e_crop} or r_{e_fallow}) was fairly small. The highest improvement was found for Ecoregion 134 in eastern Canada and for Ecoregion 159 in the western part of the country. For those site and treatment combinations, compared with the old predictions, the new predictions came 27 and 18% closer, respectively, to measured final SOC content. This was calculated as: (the absolute estimated deviation from predicted final SOC stocks with the new r_e values)/(absolute deviation from predicted final SOC stocks using $r_e = 1.0$).

It is recognized that this testing of r_{e_crop} and r_{e_fallow} is incomplete because not all ecoregions for which we calculated these two parameters had long-term experimental data for SOC evolution. Furthermore, for those that had, considering the range of r_{e_crop} and r_{e_fallow} values (Table 3), other factors could be examined in order to improve the predictions. As discussed in Bolinder et al. (2006) for these sites, unrealistic predicted values are not necessarily attributable to deficiencies in a model. For example, precisely measuring a SOC change and initial SOC data is not easy, and estimates of annual C inputs to soil can be improved. The scale of application for which the calculations of the r_{e_crop} and r_{e_fallow} parameters were done can also be refined but these issues were beyond the scope of this study.

CONCLUSIONS

The ICBM approach enabled us to examine regional differences in the potential for SOC sequestration as a function of parameters that integrate climate, soil properties (r_{e_crop}) and NPP (i), as well as the effect of fallow (r_{e_fallow}). Testing the r_{e_crop} and r_{e_fallow} parameters using ICBM on data from long-term Canadian field experiments showed that in most cases they improved predictions of final SOC stocks. The same concept can be applied with other sources of climatic data, crop characteristics and soil properties at a higher level of resolution, such as for example at the field level for a given farm and region. Using more detailed data sets at a higher level of resolution will help us to improve and refine the approach for Canada-specific applications. The relationships discussed between the ICBM r_{e_crop}, r_{e_fallow} and i parameters versus the potential for SOC sequestration in this paper apply to Canadian Agricultural Ecoregions; at other scales of spatial resolution results will presumably be different.

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