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ICBM: THE INTRODUCTORY CARBON BALANCE MODEL FOR EXPLORATION OF SOIL CARBON BALANCES

OLOF ANDRÉN AND THOMAS KÄTTERER

Department of Soil Sciences, P.O. Box 7014, SLU, S-750 07 Uppsala, Sweden

Abstract. A two-component model was devised, comprising young and old soil C, two decay constants, and parameters for litter input, ''humification,'' and external influences. Due to the model's simplicity, the differential equations were solved analytically, and parameter optimizations can be made using generally available nonlinear regression programs. The calibration parameter values were derived from a 35-yr experiment with arable crops on a clay soil in central Sweden. We show how the model can be used for medium-term (30 yr) predictions of the effects of changed inputs, climate, initial pools, litter quality, etc., on soil carbon pools. Equations are provided for calculating steady-state pool sizes as well as model parameters from litter bag or ^{14}C-labeled litter decomposition data. Strategies for model parameterization to different inputs, climatic regions, and soils, as well as the model's relations to other model families, are briefly discussed.

Key words: carbon budgets; global change; mathematical model; soil carbon.

INTRODUCTION

Serious concerns about increasing CO_2 levels in the atmosphere and the need for strategies to reverse the trend have triggered a vast amount of research worldwide. One of the obvious, but sometimes overlooked, C sources sinks is soil carbon (Schimel et al. 1994, Lal et al. 1995, Paustian et al. 1995).

To be able to calculate the carbon source/sink relations between soil and atmosphere we need data concerning soil carbon dynamics for various experimental conditions as well as a method to interpret them—and to make predictions as to what will happen if the experimental conditions (including climate) change.

Soil carbon dynamics can be described using a number of approaches. The most common method is to divide the soil organic matter into a number of pools with different, usually measurable, properties (see reviews by Ågren et al. 1991, Paustian 1994, Paustian et al. 1997). The number of pools varies with the model objectives, but in general, as the numbers of pools and parameters increase, so does the versatility of the model.

In this paper we present a minimum model that can be applied using a 30-yr time perspective, with 1-yr time steps. Our aim was to only include processes that are absolutely necessary and comparatively well known. On the other hand, the generation of parameter values for the model can be as complex as warranted and possible. For example, the annual input of carbon to the soil could be based on thorough research of annual surface and root litter input, including root exudates—or simply be the best available guestimate, based on data on regional crop production, etc.

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We also wanted the model structured so that it could be understood by laymen but still remain reasonably versatile. Selecting a simple model structure also made complex simulation techniques unnecessary—the model is analytically solved, and predictions can even be made using a pocket calculator. Parameter optimizations can be performed with generally available statistical packages such as SAS (Proc NLIN; SAS 1985). The model equations, SAS program code, MS Excel code, and a stand-alone IBM PC program can be obtained from the World Wide Web.[1]

ICBM, the Introductory Carbon Balance Model, is to be used to help us answer questions such as: Is a particular system losing or sequestering soil carbon? What will happen to soil carbon if the mean annual soil temperature increases by 5°C? How much will the soil carbon pool increase if we double the annual carbon input? Why is the soil carbon content lower in some regions than in others?

In this paper we describe the model and suggest some basic principles for parameterization. In a second paper we intend to validate the model using data sets from Northern European agricultural field trials, as well as develop stricter, possibly partly automatic, procedures for parameterization.

As a test application, ICBM will be used as an instrument for predicting soil carbon balances in Swedish agricultural land. The country is divided into regions according to climate, soil, and cropping system, and a strategy for parameterization for different regions is under development. It is our hope that the model will also be used for other estimates of soil carbon dynamics; for example, the Swedish regions could be replaced with any number of regions anywhere in the world.

[1] http://jordek10.eom.slu.se/olle/ICBM.html

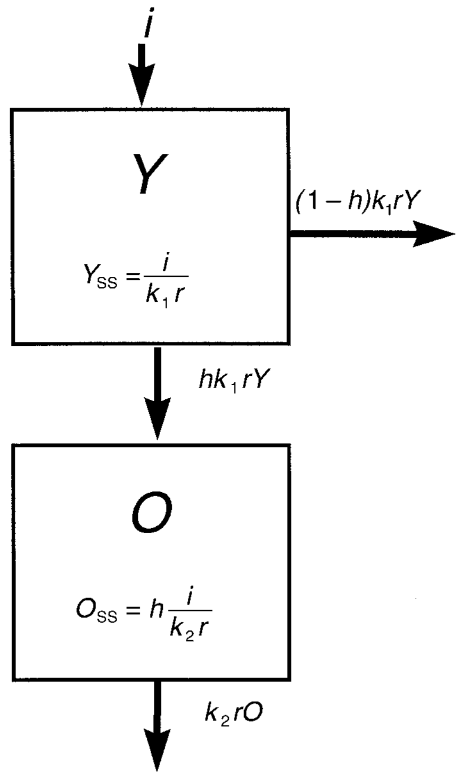

FIG. 1. Structure of ICBM (Introductory Carbon Balance Model). Flux equations are positioned close to their respective arrows, and equations describing steady-state conditions are inside the boxes. See *Model structure and properties* for explanation of variables.

MODEL STRUCTURE AND PROPERTIES

The first assumption is that two pools (young, Y, and old, O) of soil carbon are sufficient (Fig. 1). Second, outflows from the pools follow first-order kinetics (k_1, k_2). Third, external (mainly climatic, but also edaphic) factors can be condensed into one parameter, r, which affects the decomposition rates of Y and O equally. The parameter r does not affect the ''humification coefficient'' (h), i.e., the fraction of the annual outflux from Y that enters O. Note, however, that h can be set differently depending on variation not only in litter quality but also in external factors. For instance, for a given litter the value assigned to h in sandy soil could be different from that in a clayey soil. Fourth, mean annual carbon input to the soil can be described by one parameter, i.

The differential equations describing the state variable dynamics are:

$$\frac{dY}{dt} = i - k_1rY \tag{1}$$

$$\frac{dO}{dt} = hk_1rY - k_2rO. \tag{2}$$

The differential equations can be integrated and then become:

$$Y = \frac{i}{k_1r} + \left(Y_0 - \frac{i}{k_1r}\right)e^{-k_1rt} \tag{3}$$

$$O = h\frac{i}{k_2r} + \left(O_0 - h\frac{i}{k_2r} - h\frac{k_1rY_0 - i}{r(k_2 - k_1)}\right)e^{-k_2rt} + \left(h\frac{k_1rY_0 - i}{r(k_2 - k_1)}\right)e^{-k_1rt} \tag{4}$$

where Y_0 and O_0 are initial values for Y and O.

From Eqs. 1–4 some model properties can be derived. First, the steady-state equation for Y is

$$Y_{ss} = \frac{i}{rk_1}. \tag{5}$$

For O, the corresponding equation (when Y is in steady state) becomes

$$O_{ss} = \frac{hk_1Y_{ss}}{k_2} \tag{6a}$$

or

$$O_{ss} = \frac{hi}{rk_2}. \tag{6b}$$

The total soil C at steady state can thus be written as

$$T_{ss} = \frac{i(1/k_1 + h/k_2)}{r}. \tag{7}$$

At steady state, the Y fraction of T_{ss} is

$$\frac{Y_{ss}}{T_{ss}} = \frac{k_2}{k_2 + hk_1}, \tag{8}$$

and the relative proportions of Y_{SS} and O_{SS} can thus be expressed as

$$\frac{Y_{ss}}{O_{ss}} = \frac{k_2}{hk_1}. \tag{9}$$

Second, the relation between the present model's parameters and the single-exponential k value usually calculated from litter-bag and ^{14}C-labeled litter data can be described as follows. The fraction remaining after one year (M_1) from an initial mass M_0 is usually expressed as

$$\frac{M_1}{M_0} = e^{-k}. \tag{10}$$

The remaining mass in the ICBM model, applied to litter-bag data, is

$$\frac{M_1}{M_0} = e^{-k_1r} + h(1 - e^{k_1r}) \tag{11}$$

because $i = 0$, the fraction of Y entering O stays in the litter bag, and $O_0 = 0$ (cf. Fig. 1). Decomposition of O is negligible during early decomposition since $k_2O \ll k_1Y$. Combining Eqs. 10 and 11 results in

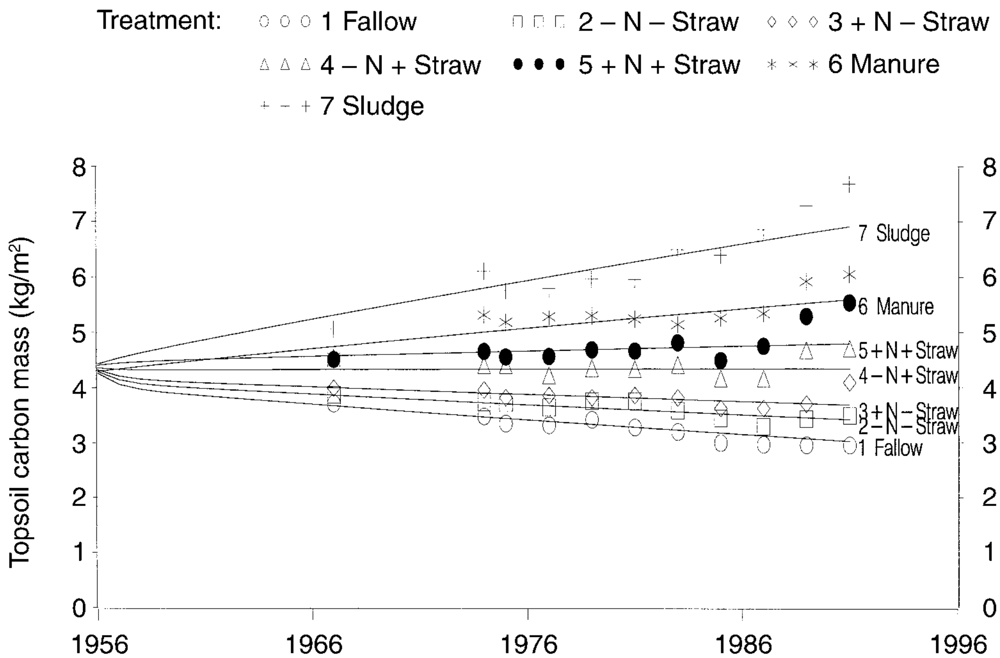

FIG. 2. Model fit to topsoil carbon data from Kirchmann et al. (1994) for seven treatments. The lines are model predictions, and the symbols indicate data.

$$k_1 = -\frac{1}{r}\ln\frac{e^{-k} - h}{1 - h} \tag{12}$$

and

$$k = -\ln[(1 - h)e^{-k_1 r} + h]. \tag{13}$$

For example, assume that we have estimated $k = 0.6$ yr^{-1} in a litter-bag experiment. Assume further that we have estimated $h = 0.13$ for this substrate and that the climate factor (r) is unity. Then, $k_1 = -\ln[\exp(-0.6) - 0.13]/(1 - 0.13)$, i.e., $k_1 = 0.73$. It can also be seen from Eq. 12 that when $r = 1$ and $h = 0$, k_1 and k become identical, i.e., ICBM reverts into a single-exponential decomposition model.

In differential form, the state-variable equations are quite transparent and easily grasped (Eqs. 1, 2, Fig. 1). However, the integrated forms (Eqs. 3, 4) are more opaque for the average reader, and a walk-through may be in order.

The steady-state equations (Fig. 1 [*in boxes*], Eqs. 5–9) show that Y_{SS} and O_{SS} are linear or inversely linear in i, r, and k_1, and h, i, r, and k_2, respectively. Thus, the effect of changing a parameter is calculated by multiplication. However, T_{SS}, the total steady-state carbon mass (Eq. 7), is linear only in i and r.

The parameters i and r, therefore, have directly predictable but opposite effects on T_{SS}. For instance, doubling both r and i simultaneously will have no effect on T_{SS}. As pointed out by Cole et al. (1993), the linear response to i has positive implications for sequestering atmospheric carbon into the soil, e.g., if we double the annual input we will end up with twice the amount of C in the soil (assuming steady states). However, to reach the new T_{SS} after doubling i usually takes a long time (see example below, in *Model dynamics and parameter sensitivity*).

The parameters k_1, k_2, and h have a more complex influence on T_{SS} (Eq. 7), but their effects can be understood by investigating Y_{SS} and O_{SS} separately. Clearly, O_{SS} can be expressed without k_1 (Eq. 6b), so changes in k_1 will only affect Y_{SS}, and O_{SS} will remain constant. Similarly, h and k_2 will not affect Y_{SS} (Eq. 5).

The model structure is related to that of commonly used models for litter decomposition. Assuming $i = 0$ and $h = 1$, ICBM becomes a ''consecutive first-order'' decomposition model (Eqs. 1, 2). If $i = 0$ and $h = 0$, ICBM becomes a ''parallel first-order'' model. The consecutive and parallel models are very similar; in fact, one can be viewed as a reparameterization of the other. (See Andrén and Paustian 1987 and papers cited therein.) Clearly, by setting i, h, O_0, and k_2 to zero, ICBM becomes a single-component, first-order decomposition model, perhaps the most common type (Wieder and Lang 1982).

MODEL PARAMETERIZATION

We used data from a 35-yr field experiment in Sweden (Parton et al. 1983, Paustian et al. 1992, Kirchmann et al. 1994, Persson and Kirchmann 1994, Hyvönen et al. 1996) to initially parameterize the model (Fig. 2). Seven treatments were used here: bare fallow (fallow), four treatments with or without nitrogen fertilization (N) and straw incorporation or removal (−N−straw,

TABLE 1. Parameters used in the ICBM model, set for the results from Persson and Kirchmann (1994). For all treatments, $k_1 = 0.8$, $k_2 = 0.00605\ \mathrm{yr}^{-1}$.

Treatments	O_0	i Straw	i Roots	h	r
Bare fallow	3.96	0.0	0.0	0.13	1.32
+N+straw	4.11	0.19	0.095	0.125	1.00
−N+straw	4.05	0.19	0.058	0.125	1.22
−N−straw	3.99	0.0	0.057	0.125	1.17
+N−straw	4.02	0.0	0.091	0.125	1.07
Farmyard manure	3.99	0.19	0.082	0.25†	1.10
Sewage sludge	4.14	0.19	0.106	0.34†	0.97
Steady state	4.16	0.20	NC	0.125	1.00

Note: Total initial soil carbon content ($Y_0 + O_0$) was measured in 1956, and we assumed that 0.3 kg C/m² was Y_0 in all treatments, except steady state (0.25 kg/m²). O_0 is in kg C/m² in the topsoil; i is in kg C·m^{-2}·yr^{-1}, whereas h and r are dimensionless. ''Straw'' includes carbon added as farmyard manure or sewage sludge, and ''Roots'' includes stem bases. NC = not calculated separately. For pure manure h = 0.31; for sludge h = 0.47.

† Weighted means for crop residues and organic amendments.

+N−straw, −N+straw, +N+straw), one manure-amended (manure), and one sewage-sludge-amended (sludge). Measurements of soil carbon dynamics, carbon inputs, and crop yields (Kirchmann et al. 1994) were used for the parameterization.

The site's climate is cold temperate and semihumid with an annual mean air temperature of +5.4°C and an annual mean precipitation of 520 mm. The coldest month is January (−5.3°C) and the warmest is July (16.7°C). The topsoil (0–25 cm) contains 36.5% clay, 41% silt, and 22.5% sand, and has been classified as a Eutric Cambisol with a pH(H_2O) of 6.6 (Persson and Kirchmann 1994). Arable-field topsoil in the region usually shows little or no biological activity during winter; the topsoil can be partly frozen between mid-November and mid-April (Jansson et al. 1990).

The comprehensive data set together with results from other field experiments in the region (e.g., Andrén et al. 1990, Kätterer et al. 1993) allowed us to use a stepwise parameterization process, based on data or at least guesses based on data. For optimizations and regressions we used the SAS system procedures NLIN and REG (SAS 1985), and the resulting parameter values are listed in Table 1.

Bare fallow: optimization of k_2

We optimized k_2 by fitting the model to the soil carbon data from the bare fallow, assuming that $i = 0$. The climate factor, r, was for convenience set to 1. Parameters k_1 and h were taken from literature, and due to $i = 0$ they only had a minor influence on the result (see Fig 1).

−N−straw, −N+straw, +N−straw, +N+straw: obtaining r and h values

We used measured inputs of straw and roots for i, while k_1 for straw and roots was taken from literature and k_2 was taken from the bare-fallow optimization above. The parameter h was optimized by fitting the model to soil carbon data. For each treatment, we used a set of r values ranging from 0.65 to 1, since the bare fallow would be moister due to less transpiration and thus have a greater r than the plots with vegetation. For each r value this resulted in a set of four r/h pairs, representing the four vegetated treatments not receiving manure or sewage sludge.

We assumed that h would be constant for the straw + roots input in all four treatments. Therefore, we re-sorted the r/h pairs into sets with identical h values. Each set had four r/h pairs, one from each treatment. The r values in each set with identical h values were subjected to linear regression (dependent variable: r, independent variable: mean annual crop yield). Thus we assumed that the yield differences (higher plant biomass gives higher transpiration) induced different r values.

We then selected the r value set that gave the best fit to the yields. This set gave us the r values for each of the four treatments as well as the common h value.

Manure and sewage sludge: r and h

Since the differences in r were assumed to be correlated with differences in yield, we could use the regression between yield and r, calculated above, to obtain r values for the manured and sewage-sludge-amended plots from their measured crop yields.

Then we could optimize the h values for the manure and sludge treatments, respectively. The h values obtained in this way by fitting to soil carbon data are weighted averages over the inputs of both, e.g., manure and crop residues.

Using our knowledge of the added amounts of crop residues and manure or sludge, we could calculate the h value for ''pure'' manure or sewage sludge, knowing that $h_{\mathrm{average}} = (h_1 i_1 + h_2 i_2)/i$.

Normalization of r

We then set $r = 1$ for the +N+straw treatment, since this represents the most normal practice, and changed r for the other treatments correspondingly. The increase in r was counterbalanced by reducing k_2 by the same fraction (Eq. 2). Parameter k_1 was not changed according to Eq. 1, since it had originally been estimated from vegetated plots and, owing to the large difference between k_1 and k_2, the value of parameter k_1 only had a minor effect on total soil C (cf. Eq. 7).

Details on the parameterization procedure

For the optimization of k_2 to measured topsoil (Ap horizon) C dynamics in bare fallow, we used $h = 0.13$ $Y_0 = 0.3$ kg/m², Eqs. 3 and 4, and the SAS procedure NLIN (SAS 1985). Using $r = 1$ means that we initially defined the temperature and moisture conditions in a bare fallow on a clay soil in central Sweden as a climate/soil type reference. The resulting k_2 was 0.0085 yr^{-1}.

We assumed that $k_1 = 0.8$ (half-life 0.87 yr) for all litter inputs, namely straw and roots/stem bases, sewage sludge, and farmyard manure. This corresponds to a single-exponential k of 0.65 yr^{-1} (if $h = 0.13$ and $r = 1$; see Eq. 13), which is a rough average of k for straw and roots obtained in experiments nearby using litter bags as well as ^{14}C-labeling techniques (Andrén 1987, Andrén and Paustian 1987, Andrén et al. 1990, 1992, 1993, Paustian et al. 1990). This corresponds to $\exp(-0.65) = 52\%$ of the initial litter remaining after one year.

Values for the parameter i in the 35-yr field experiment were based on measured straw and other organic amendments (Kirchmann et al. 1994, Persson and Kirchmann 1994), as well as on inputs from stem bases and roots calculated as follows.

Johansson (1992) reported the relative amounts of C translocated to barley roots until the beginning of the reproductive phase, as measured in a climate chamber with ^{14}C atmosphere, to be 27% (high N) or 32% (low N) of the total assimilated C minus respiration from aboveground parts. Total soil ^{14}C respiration was 15% (high N) or 19% (low N) of the net assimilated ^{14}C. Using results from Cheng et al. (1993), we assumed the contribution from root respiration to total soil respiration to be 40%. Consequently, total C input via roots was ~21% $(27 - [0.4 \times 15])$ and 24% $(32 - [0.4 \times 19])$ of the net assimilated C in the high-N and low-N treatment, respectively. If 70% of these inputs reach the topsoil, then ~15% (high N) and 17% (low N) of the total net assimilated ^{14}C will be recovered in the topsoil. This is equivalent to ~25% (low N) or 21% (high N) of the shoot carbon.

In addition, if stem bases account for 5% (Kätterer et al. 1993) of the total aboveground production, 30% (low N) or 26% (high N) of the crop C is delivered to the topsoil. These fractions (26 and 30%, respectively) were used in proportion to the average yearly dry matter yields of the cereals harvested (grains and straw; Kirchmann et al. 1994), i.e., 30% of the treatment with the lowest yield (no N, no straw), 26% of that with the highest yield (sewage sludge) and intermediate fractions for those treatments with intermediate yields. The C content of the yields was assumed to be 50%.

Model fit to soil carbon data

The model fit to data from Persson and Kirchmann (1994) is presented in Fig. 2. In general, the trends in the soil carbon data are well described by the model.

Predicted total soil C in all treatments seems to change fairly linearly after an initial nonlinear phase. This is an effect of the relatively small changes in total carbon during the 30-yr period; when changes are small, relative and absolute mass changes become similar, since the mass base on which the relative change is calculated is only altered slightly.

The low measured values for soil C in 1985 followed by a positive break in the trends (Fig. 2) were clearly not possible for the model to emulate. However, the shift after 1985 led to only a slight change in the optimized parameters. For example, if k_2 is calculated on the basis of bare fallow data only for the 1956–1985 period, excluding the three last data points, k_2 only changes by 3%. If the same operation is performed before optimizing h for farmyard manure, h will decrease by 5%.

Parameter values for steady-state conditions

In our reference, the nitrogen-fertilized plots with annual straw additions, simulated total soil carbon was increasing slightly. Using Eqs. 5 and 6 we can calculate the steady-state values. These become $0.285/0.8 = 0.356$ for the young fraction and $0.125 \times (0.285/0.00605) = 5.89$ kg for the old, giving a total of over 6 kg at steady state. Clearly, the conditions described by the model are far from steady state, even at the end of the 30-yr period.

However, by changing i slightly we can parameterize for steady-state conditions, serving as a baseline from which we can show consequences of parameter changes. Using Eq. 7 we can calculate that $i = 0.201$ will result in steady state at 4.41 kg total soil C (as measured in the +N+straw treatment in 1956; see Table 1). From Eq. 8 we can calculate that $Y_{SS} = 0.25$ and $O_{SS} = 4.16$.

Two special cases, organogenic and "tropical"

We also parameterized the model for two special cases. First, we applied the model to calculated data from organogenic soils, e.g., arable soils that are situated on drained peat bogs. Using a set of reasonable assumptions (McAffee 1985, Berglund 1989), we calculated a topsoil (0–25 cm) carbon mass of 22.5 kg/m^2. These soils under bare fallow would show ~2 cm/yr of subsidence, i.e., the soil surface is sinking. Assuming that 35% of the subsidence is due to C oxidation and the rest is due to compaction/shrinking below the topsoil, we can calculate an annual C input of 0.63 kg from the subsoil due to plowing. Steady-state C mass in Y, calculated from Eq. 5 and the standard parameter set, then becomes $0.63/0.8 = 0.79$ kg. Assuming steady state for total soil C, the old C mass becomes $22.5 - 0.79 = 21.71$ kg. Solving Eq. 6 for h and inserting the standard parameter values, we obtain $h = 0.21$. This value represents the humification quotient of the peat subsoil annually converted to topsoil due to subsidence and thus deeper plowing. Note that this occurs when assuming that $r = 1$; if r is higher than in our reference, the calculated h will be higher (Eq. 6b). Also note that a soil created from a drained peat bog may reduce its rate of subsidence with time, as gradually older layers are exploited. For the ICBM model, this would mean that i decreases and perhaps h increases with time. This can be handled by predicting, e.g., 5 yr and then changing the parameters, running for another 5 yr, etc. Alternatively, ICBM can be run as a simulation model with i and h as gradually changing driving variables (see *Within-year dynamics* below).

Second, we parameterized the model to emulate a low-carbon soil, typically found in hot and humid climates. This illustrates how r, representing external influences on decomposition, can be calculated for a given climate. The climate in central Sweden is cold temperate and has $r = 1$ in our reference treatment.

Using a soil temperature and moisture data set from central Sweden measured during 1989–1990 (Kätterer and Andrén 1995) we calculated a daily temperature factor from $Q_{10} = 2$ and a base temperature of 25°C. For the 0–5°C temperature interval we assumed a linear increase from zero activity at 0°C, to the Q_{10}-based value at 5°C. We assumed that the soil temperature in the hot and humid climate remains constant at 25°C and, consequently, has a temperature factor of 1.

The relation between decomposer activity and soil moisture, or, more precisely, soil water tension, can be expressed as a log-linear relationship (Andrén and Paustian 1987 and papers cited therein). We used the data set mentioned above and a log-linear relationship between daily soil water tension and activity with parameters from Andrén et al. (1992, 1993) to calculate a daily moisture effect. For simplicity, we assumed that moisture is not limiting in the hot and humid climate, i.e., that soil moisture is ideal for decomposition every day.

Then we multiplied the Swedish temperature and moisture factors for each day, and the average climate factor became 0.187. Thus, r for the hot and humid climate becomes $1/0.187 = 5.36$. This value is probably on the low side; the growing season of 1989 was unusually warm. However, a comprehensive discussion on which climatic variables and data sets one should use for applying models to different climatic regions is beyond the scope of this paper (see, e.g., Powlson et al. 1996).

Within-year dynamics

To indicate the within-year dynamics not accounted for by annual time steps, we simulated 10 yr with daily time steps. Since ICBM assumes that input, i, is delivered to Y for every time step, we set $i = 0$ for every day of the year except one, e.g., the day of plowing. At every change between years, we simply set

$$Y_0 = i + Y \tag{14}$$

where Y was the calculated value for the last day of the previous year (see Eqs. 1–4).

Finally, we applied measured temperature and soil moisture data from central Sweden (Kätterer and Andrén 1995) as driving variables for a year's decomposition of the Y pool. ICBM in this form becomes a single-exponential decomposition model with r as the driving variable. For simplicity, we used numerical simulation, i.e., a calculating loop with a daily time step, applying the r value for each day to the difference equation:

$$Y_{\mathrm{day}+1} = Y_{\mathrm{day}} - krY_{\mathrm{day}}. \tag{15}$$

Model Dynamics and Parameter Sensitivity

We ran the model for 30 yr to show the consequences of changes in the state variables and parameters, one at a time (Fig. 3).

A parameter set that results in steady-state soil C was used as a reference for investigations of the 30-yr consequences of changes in state variables and parameters (Fig. 3A).

If k_2 (the parameter controlling decomposition of O) is doubled, O will decrease by ~20% (Fig. 3B). O_{SS} will be halved (Eq. 6), but Y will not be affected (Eq. 5). Due to the still low k_2, O is far from steady state after 30 yr.

Doubling k_1 (the parameter controlling decomposition of Y) halves Y_{SS} (Eq. 5), and Y fairly rapidly approaches steady state (Fig. 3C). O_{SS} is not affected by the change in k_1 (Eq. 6b), but this occurs when Y is in steady state, i.e., when the doubling of k_1 is balanced by the halving of Y (Eq. 6a). Thus, as seen in the figure, there will initially be a slight increase in O owing to the doubled k_1.

Use of a material with twice the ''humification quotient'' will have considerable effects on the O pool (Fig. 3D). O_{SS} will be doubled (Eq. 6), but Y will not be affected. Using Eq. 13 and data from Table 1, the single-exponential model k values become 0.53 if manure is a part of the input (Table 1, $h = 0.25$) and 0.45 if sewage sludge is added ($h = 0.34$). Increasing h in ICBM thus decreases k in the single-exponential model.

If we assume a temperature increase of 10°C and a Q_{10} factor of 2 (r doubled), ~15% of the total soil carbon will be lost during a 30-yr period (Fig. 3E). Both Y_{SS} and O_{SS} and, consequently, T_{SS} will be halved (Eqs. 5–7). As discussed above, i and r counteract each other, so doubling i doubles the steady-state values (Fig. 3F). Soil carbon will increase by ~ 0.9 kg/m^2 over 30 yr. Note, however, that to obtain this increase an additional 6.24 kg had to be added as i, i.e., the soil C increase was only 14% of the increase in input. In other words, 86% was lost as CO_2 to the atmosphere.

Reducing i to zero, as in a bare fallow, has comparatively great consequences (Fig. 3G). Clearly, the steady-state value without input is zero. However, during the 30-yr period not more than 1 kg C is lost from the soil. If there were to be no C input to the soil throughout the period, $30 \times 0.208 = 6.24$ kg would be saved compared with the input needed to maintain steady state. This, and the small gain in soil carbon obtained by doubling the annual input (Fig. 3F), illustrates that it may be better from an atmospheric C balance viewpoint to replace fossil fuels with, e.g., straw instead of trying to sequester C in the soil.

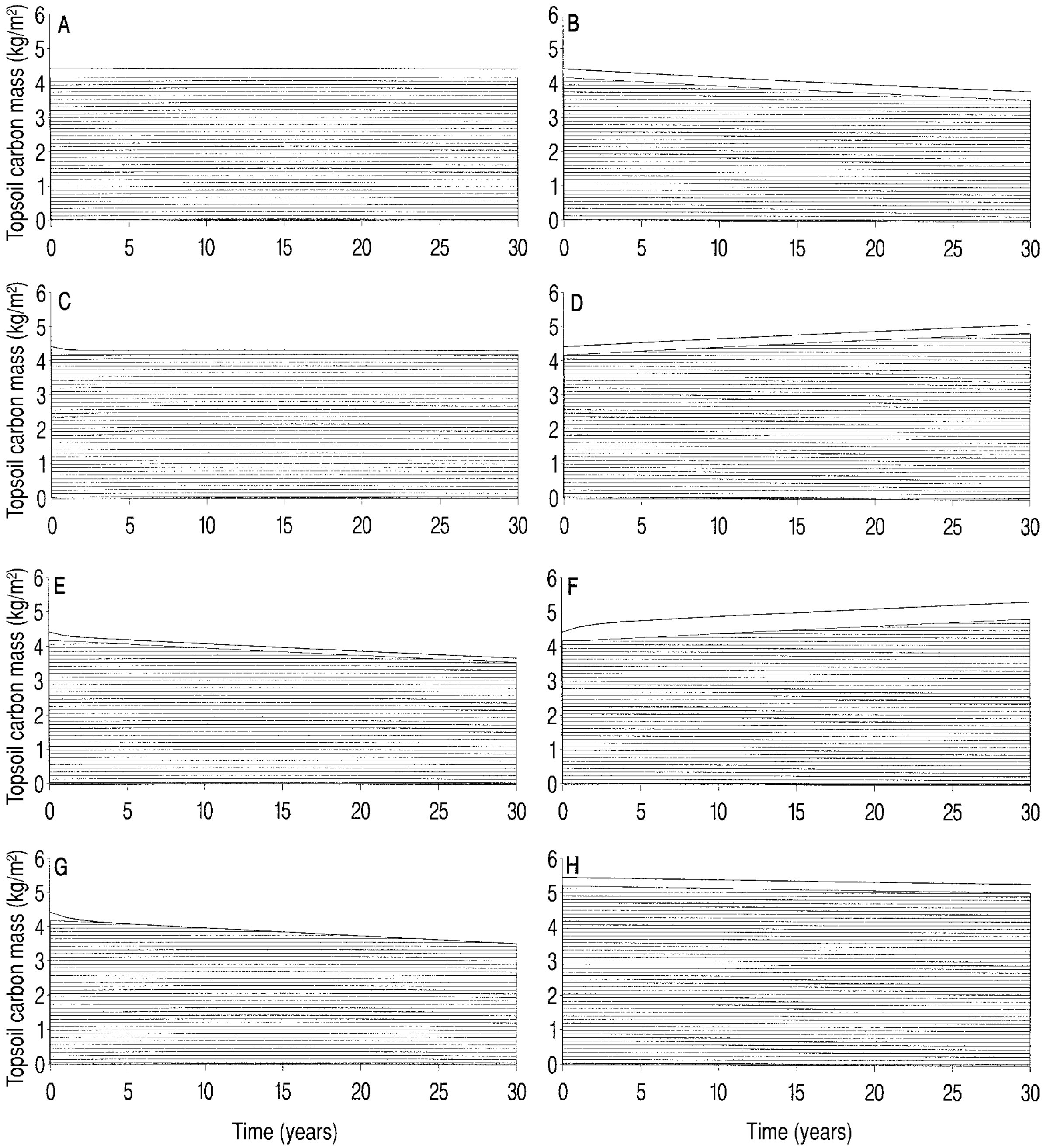

FIG. 3. Results of changes in parameters and pool sizes in ICBM from a 30-yr perspective, parameterized for steady state of the *Y* (young, white) and *O* (old, striped) pools: (A) $Y_0 = 0.25$, $O_0 = 4.16$, $k_1 = 0.8$, $i = 0.20$, $k_2 = 0.00605$, $h = 0.125$, $r = 1$; (B) $k_2 = 0.0121$; (C) $k_1 = 0.16$; (D) $h = 0.25$; (E) $r = 2$; (F) $i = 0.40$; (G) $i = 0$; (H) $O_0 = 5.19$.

The fact that a greater input is needed to maintain a greater C pool is illustrated in the figure where we start with a 25% higher *O* pool (Fig. 3H). This pool decreases towards O_{SS}, although slowly.

When we applied ICBM to an organogenic soil, we were able to calculate a steady-state *h* (Fig. 4A and *Model parameterization*). The value of *h*, 0.23, should be considered fairly reasonable, given the *h* values for farmyard manure and a highly processed sewage sludge (Table 1). The steady-state value of *h* increases to 0.29 (see Eq. 7 if we use the, perhaps more realistic, assumption that *r* is 1.25 in the uncropped organic soil. Eq. 7 also shows that, with the parameter settings used here, T_{SS} is not sensitive to changes in k_1.

The assumption that steady-state conditions can exist in organic soils subjected to high losses is supported by a comprehensive Finnish investigation, in which there was little or no change registered in topsoil carbon

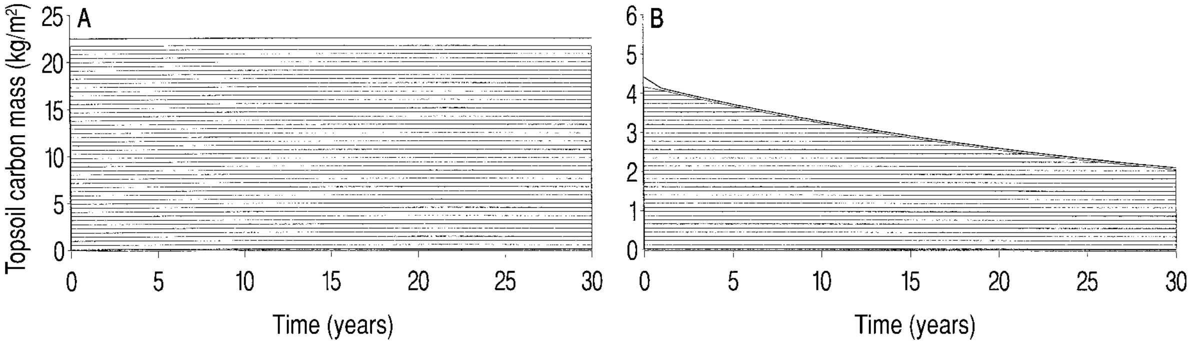

FIG. 4. (A) Example of ICBM outputs when parameterized for an organic soil, $Y_0 = 0.79$, $O_0 = 21.7$, $i = 0.63$, $h = 0.23$; and (B) assuming a hot, humid climate, $r = 5.36$. All other parameters were set as in Fig. 3A.

of organogenic soils between 1974 and 1987 (Erviö et al. 1990). Since i in the present case was 0.63 kg/yr from subsidence, not photosynthesis, the amount of CO_2-C lost during 30 yr would be close to 19 kg/m^2 in spite of the steady-state conditions in terms of topsoil carbon.

Changing the climate in central Sweden to hot and humid ($r = 5.36$, see *Model parameterization*) would have quite dramatic consequences, and thus the ''cold-temperate'' assumption that soil C only changes slowly has to be revised (Fig 4B). Thirty years of hot and humid conditions would reduce total soil C to 2.1 kg. T_{SS} would be 0.82 kg, i.e., 19% of that in Sweden (assuming that all other parameters are unchanged).

It is perhaps fortunate that we have no Swedish experimental field data supporting this, but it is common for soils in hot and humid climates to have low C contents. Although we believe that the ICBM model can easily be parameterized for these soils, we do not think that the prediction in Fig. 4B is fully valid in this extreme case. To deal with changes of this magnitude, two pools probably not are sufficient, and a model using a more detailed approximation of the soil organic matter's continuum of decomposability would be needed, e.g., the multicompartment approach of the Rothamsted model (Jenkinson et al. 1987), the CENTURY model (Parton et al. 1988), or the continuous-quality-change approach of Ågren and Bosatta (1996).

Another approach can be to assume that an undecomposable fraction is also present, at least from a 30-yr perspective. This fraction can be viewed as being outside the model. For example, if we imagine Fig. 4B with an undecomposable ''baseline'' fraction of 2 kg, the reduction would clearly be much less dramatic. However, undecomposable fractions should be used with care and only with clearly limited time constraints, such as those typical for litter-bag experiments (e.g., Berg and Ekbohm 1991). If an undecomposable fraction is used, we can otherwise end up with models with wildly unrealistic properties. An undecomposable fraction that has an input will grow forever, and a model with such a fraction will, when the input is zero, asymptotically approach the level of this fraction but never go below it. Soil organic matter is neither a ''black hole'' nor is its constituent C bound in a diamond crystal lattice.

A 1-yr time step is only a coarse approximation of the amount of Y present—this fraction is fairly dynamic. In Fig. 2, the initial part of the Fallow curve is a sloping straight line, but this is most likely an oversimplification. It is possible to divide k_1 and k_2 by 365 and run the model with daily time steps and only have input on the first day of an arbitrary 365-d period (Fig. 5A). This reveals that Y, assuming C input only at plowing, will follow an exponential decomposition function, in spite of being at a steady state on an annual basis.

A more realistic example, using measured climate data and assuming plowing in early April (Fig. 5B), shows that the decomposition rate of the Y fraction is highly variable during the year. The within-year dynamics can probably be disregarded from the 30-yr perspective, but one, nevertheless, has to take it into account when sampling to obtain estimates of Y, e.g., by soil coring and fractionation through sieving and/or flotation.

CONCLUDING REMARKS

We have shown that the model can be parameterized using a well-managed long-term experiment with a comprehensive set of measurements. However, a crucial question for the general application of the model is how to obtain good parameter values when available data are less complete. We suggest the following strategy.

1) Tentatively, consider k_2 as a global constant with the value 0.006 yr^{-1}.

2) Estimate r based on differences from the climate in central Sweden. This can be done simply by comparing annual mean temperature (+5.4°C) and precipitation (520 mm) in the new site with those of central Sweden, and applying coarse corrections based on the differences. If a more detailed climatic data set is available, more precise corrections based on daily values of soil temperature and moisture and daily calculations of the actual r can be used to cal-

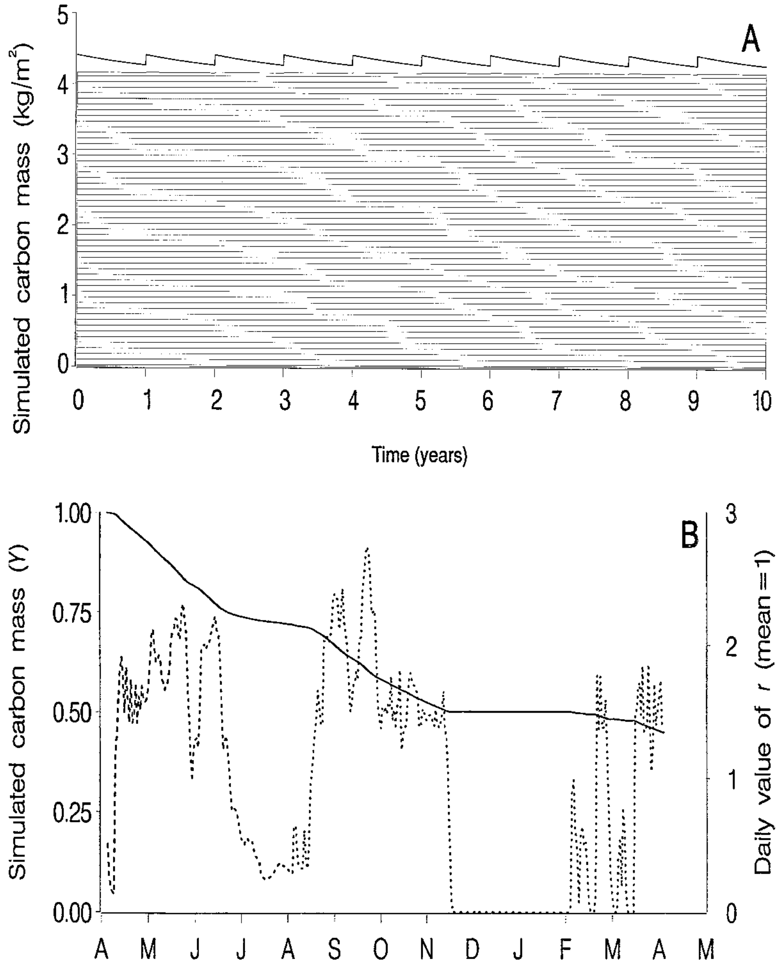

FIG. 5. Within-year carbon dynamics, normally not included in the ICBM model. The dynamics of Y and O during 10 yr, assuming a constant r and steady-state conditions on an annual basis. (B) The dynamics of Y within a year, using climate data measured daily (Kätterer and Andrén 1995) to generate daily r values, are shown as a stippled line.

culate an average, annual r (see *Model parameterization: Two special cases, organogenic and ''tropical''* for more details).

3) Estimate the humification coefficient, h, from available literature data (litter bags, ^{14}C experiments, etc.). It can be approximated as the fraction remaining after 5–10 yr. Alternatively, general literature data can be used. Assume a slightly higher h for biologically active clay soils. Then k_1 can be estimated using Eq. 11. Note that as long as $k_1 \gg k_2$, the total carbon storage is not particularly sensitive to the value of k_1 (see, e.g., Eq. 7).

4) Estimate i. The litter input from aboveground plant parts can usually be easily appreciated. The contribution from belowground parts usually has to be an educated guess, but again, literature data can be of value.

5) Calculate the steady-state values, Y_{SS} and O_{SS} (Eqs. 5–9).

6) If data on the total carbon mass in the soil are available, compare these with the steady-state values. Assume $Y_0 = Y_{SS}$ and O_0 = measured or guessed total soil C mass minus Y_{SS}, apply the model, and see how rapidly steady-state is approached.

7) Based on experience with the model's behavior, adjust parameters and rerun in an iterative process. Then try different scenarios. Note that when a spreadsheet is used on a standard personal computer, the processing time for a 30-yr prediction is usually well below 1 s, i.e., the what-if exploration can be truly interactive.

For general use, parameters can be set more or less automatically. We are just beginning to develop ''front-end models,'' i.e., a set of functions with which a reasonable parameter set can be constructed based on climatic zone data, primary productivity, management practices, etc. In connection with this task, further investigations of the relations between ICBM and other models dealing with climate/plant production/decomposition and soil C/N are important. We have no wish to reinvent the wheel.

Addendum

After submitting the original manuscript, we became aware of the fact that we had to some extent reinvented the wheel—simple models along these lines have, not surprisingly, been suggested before. Hénin and Dupuis (1945) and Hénin et al. (1959) proposed a model approach similar to that of ICBM, but without the r factor. When applicable, we used these papers to check our independently made integrations.

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