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Long-term agricultural field experiments in Northern Europe: analysis of the influence of management on soil carbon stocks using the ICBM model

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Abstract

Land use in general and particularly agricultural practices can significantly influence soil carbon (C) storage. Changes in topsoil C mass measured in long-term agricultural field trials in Sweden and other Northern European countries were compiled and aggregated into seven treatment classes, including manured, fertilized and straw exported. The impact of crop rotations and management practices on C stocks in the topsoil was analyzed using both a static model and a dynamic soil carbon model (introductory C Balance Model; ICBM). ICBM consists of two state variables and four fluxes (governed by four rate-determining parameters), and one parameter, r_e, combining most external factors affecting C mineralization (temperature, precipitation, drainage, etc.). Simple 'front-end models' were used to estimate values for two of the parameters, i (annual C input) and h (humification coefficient) initially based on incomplete records from the field trials, official agricultural statistics and other literature. The r_e parameter was then optimized for each class of treatments, using an algorithm for non-linear least squares. Initial soil C mass, present C inputs and abiotic conditions, such as soil temperature and moisture, were the deciding factors in whether C stocks declined or increased. Steady-state values calculated using the static and dynamic model were similar for both models, but differed greatly between treatment classes. For cereal-dominated cropping systems where the straw was removed, manure application increased steady-state values about three times (from 3 to 9 g C m^{-2}), compared with corresponding treatments. Incorporation of straw resulted in intermediate steady-state values (5–6 g C m^{-2}). C mineralization rates were highest in bare fallow treatments. For one class of soils, C retention in the soil was found to increase significantly with increasing clay content. The hypothesis that the climatic gradients in Northern Europe affect decomposition and primary production rates similarly, leading to the same soil C stocks, could not be rejected.

Keywords: Agricultural management; Carbon balances; Land use; Long-term experiments; Model

1. Introduction

The quantity of carbon (C) present to a depth of 1 m in soil organic material (SOM) globally is about twice the 750 Pg present in the atmosphere as CO_2, namely, around 1576 Pg (Eswaran et al., 1993) or 1394 Pg (Post et al., 1982). The size of the SOM pool indicates that even small changes in the global stock of SOM could cause a significant change in atmospheric CO_2, and, consequently, the global C cycle (see Schimel et al., 1994). Thus, one major piece of the 'global C

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balance' puzzle is the exchange of C between soils and the atmosphere. The balance between the quantity and quality of inputs on the one hand, and the decomposition of SOM as well as weathering of carbonate (naturally occurring or from applied lime) on the other hand, will determine whether the soils are net sources or sinks for CO_2. Climate and inherent soil properties, which in native ecosystems are the primary determinants of soil C balances, are in agricultural ecosystems complemented, and in some cases overshadowed by both present and historical land use and management practices (Paustian, 1994). In long-term agricultural field experiments, the effects of treatments affecting soil C balances are integrated over decades and therefore constitute a valuable database, for example, for the validation of models used for predicting future changes. In other words, to look forward we have to look back.

The interpretation of data from long-term field experiments has to deal with several sources of errors and should be done with care. However, by using a database including many experiments, these errors may at least partly cancel each other out, and the resulting mean value will be more realistic than data from a single experiment.

Several SOM models using different approaches have been successfully applied to data from long-term experiments (e.g. Hyvönen et al., 1996; Powlson et al., 1996; Paul et al., 1997; Smith et al., 1997). Andrén and Kätterer (1997) presented a soil C model to be applied in a 30-year time perspective, with 1-year time steps. This model, the Introductory C Balance Model (ICBM), was parametrized using data from a Swedish long-term experiment. ICBM is simple, analytically solved and predictions can be made using a computer spreadsheet. The model parameters can quite easily be estimated from generally available data, such as climate, soil-type and crop. Thus, it is a model that can also be used by non-experts to make reasonable estimates regarding SOM dynamics as affected by climate and management.

The objectives of this study were: (1) to utilize published data from long-term experiments in Northern Europe (latitude $\geq 52°$), and to classify these experiments into treatment classes and quantify the influences of initial soil C stocks and treatment classes on soil C balances, (2) to use a static model to summarise this information, (3) to develop simple front-end models for ICBM, for the estimation of parameter values representing conditions in Northern Europe, and (4) to discuss the quality of input data as well as model outputs.

2. Methods

2.1. Long-term agricultural experiments in Northern Europe

The selection criteria for inclusion of experiments were: (1) site location in Denmark, Finland, Norway or Sweden (and 'classical' sites from Germany and Great Britain); (2) experimental period of longer than 8 years; and (3) known initial soil C content.

Unfortunately, the third selection criterion resulted in the exclusion of many experiments, and very few of those remaining were primarily designed for investigating C balances. Table 1 gives an overview of the field experiments used in this compilation. The treatments from all sites were aggregated into seven classes, of which five (A–E) consisted of cereals grown in monoculture or as the dominant crop within rotations which included oilseeds, root crops and grass ley. One class (F) had ley (cultivated grassland) dominating the crop rotations, and one (G) included experiments where treatments were more varied with time than in normal crop rotations. Details on treatments can be obtained from: http://www.mv.slu.se/vaxtnaring/olle/icbm.html.

Bulk density values of the soils are needed to convert C concentrations to mass base. Where bulk density was not reported, values found in reports from similar sites (in terms of soil-type and latitude) were used. In class G, which consisted of Finnish soils with moderate-to-high organic matter content and changes in soil C concentrations up to 44%, a regression equation was used (as used by Howard et al., 1995 for soils in England and Wales) to estimate bulk density (bulk density = 1.3 − (0.274 log %C)).

To calculate topsoil C mass on an areal base, for example, g m^{-2}, it is necessary to know the depth of the topsoil. In some cases where both initial and final topsoil depths were reported (e.g. Erviö, 1995), we defined topsoil depth as the mean of initial and final depth reported. Where the depth of the topsoil was not given, we assumed that it was 25 cm. This paper only

Table 1
The Northern European experimental sites included in the database (in Swedish alphabetical order)

Place (abbreviated), Latitude °N	Exp. period	Class[a]	Soil-type	Initial C%	Refs.
Sweden					
Assarsgården (Assarsgd), 59	1966–1986	B, C, D	Clay > 30%	2.3	Mattsson, 1991
Ekebo, 56	1960–1984	B, C, D	Sandy till	2.2–2.3	Bjarnason, 1989[b]
Fjärdingslöv (Fjardingl), 55	1960–1984	B, C, D	15–20% clay	1.6	Bjarnason, 1989[b]
Hvilan, 56	1956–1977	C, D, E	17.2% clay	3.7–3.9	Persson, 1981
Lyckebo, 56	1956–1977	C, D, E	9.5% clay	1.5–1.6	Persson, 1981
Lönstorp (Loenstor), 56	1972–1981	B	22% clay	1.7	Mattsson, 1987
Offer, 64	1969–1982	E	27% clay	2.5	Mattsson, 1987
Orup 56	1960–1984	B, C, D	Sandy till	2.2–2.3	Bjarnason, 1989[b]
Petersborg (Petersbo), 56	1956–1977	B, C, E	13.6% clay	1.1–1.2	Persson, 1981
Röbäcksdalen (Roback), 64	1969–1982	E	10% clay	3.3	Mattsson, 1987
Stenstugu (Stenstug), 58	1972–1981	B	28% clay	1.7	Mattsson, 1987
Ultuna, 60	1963–1990	B, C, D	Clay > 30%	2.3	Mattsson, 1992
Ultuna Frame (F_Ultuna), 60	1956–1991	A, B, C, D, E	36% clay	1.5	Kirchmann et al., 1994
Västraby (Vastraby), 56	1960–1984	B, C, D	30% clay	1.8	Bjarnason, 1989[b]
Ugglarp 56	1960–1984	B, C, D	Sandy till	1.5–1.7	Bjarnason, 1989[b]
Örja (Orja), 56	1960–1984	B, C, D	15–20% clay	1.2	Bjarnason, 1989[b]
Norway					
Ås (As), 60	1953–1984	B, C, D, E, F	Clay loam	3.8	Uhlen, 1991
Finland					
Etelä (ESA)	1960–1991	G	4% clay	4.6	Erviö, 1995
Hämeen (HAM1)	1960–1991	G	3% clay	1.9	Erviö, 1995
Hämeen (HAM2)	1960–1991	G	26% clay	3.2	Erviö, 1995
Jokioinen (Jokioin)	1984–1994	C, D, E, F	Clay	3.2–3.7	Erviö and Talvitie, 1995
Jokioisten (JKA)	1960–1991	G	78% clay	3.5	Erviö, 1995
Karjalan (KAR)	1960–1991	G	4% clay	4.2	Erviö, 1995
Kymenlaakson (KYM1)	1960–1991	G	42% clay	3.6	Erviö, 1995
Kymenlaakson (KYM2)	1960–1991	G	63% clay	3.6	Erviö, 1995
Lounais (LOU1)	1960–1991	G	52% clay	2.9	Erviö, 1995
Lounais (LOU2)	1960–1991	G	45% clay	3.1	Erviö, 1995
Pohjois (PSA1)	1960–1991	G	37% clay	4.0	Erviö, 1995
Pohjois (PSA2)	1960–1991	G	19% clay	10.8	Erviö, 1995
Puutarhantutkimuslaitos (PTL)	1960–1991	G	48% clay	3.8	Erviö, 1995
Satakunnan (SAT1)	1960–1991	G	7% clay	3.0	Erviö, 1995
Satakunnan (SAT2)	1960–1991	G	32% clay	3.5	Erviö, 1995
Satakunta (Satakunt)	1984–1994	C, D, E, F	Silt	3.0–3.2	Erviö and Talvitie, 1995
Denmark					
Askov, grassl. conv. (AskoLeyb), 55	1956–1987	A, C, D	9% clay	3.0–3.1	Christensen and Johnston, 1997
Askov, Lermarken (AskovLer), 55	1956–1985	A, B	12% clay	1.6–1.7	Christensen, 1990
Askov, CS (AskovCS), 55	1912–1984	B, D, E	4% clay	1.0–1.2	Christensen, 1993
Askov, CS subs1 (AskoCSs1), 55	1956–1988	C, D, E	2.5% clay	0.3	Christensen and Johnston, 1997
Askov, CS subs2 (AskoCSs2), 55	1956–1987	C, D	2.5% clay	0.1	Christensen and Johnston, 1997
Askov, SL (AskovSL), 55	1914–1984	B, D, E	12% clay	1.5–1.7	Christensen, 1993
Great Britain					
Rothamsted DG (RothamDG), 52	1852–1976	A	20–25% clay	1.2	Jenkinson and Rayner, 1977
Rothamsted Ho (RothamHo), 52	1870–1970	B, D, E	20–25% clay	1.1	Jenkinson and Johnston, 1977
Rothamsted Ley (RothLey1, 2), 52	1948–1980	F, F	20–25% clay	1.7	Christensen and Johnston, 1997
Woburn, 52	1876–1971	B, D	12% clay	1.5	Christensen and Johnston, 1997
Woburn Ley (WobLey)	1937–1970	F	12% clay	1.0	Christensen and Johnston, 1997
Woburn MG (WoburMG)	1942–1960	E, E	Sandy loam	0.8	Johnston et al., 1989

Table 1 (*Continued*)

Place (abbreviated), Latitude °N	Exp. period	Class[a]	Soil-type	Initial C%	Refs.
Germany					
Halle, 52	1878–1958	B, D, E	Sandy	1.2	Sauerbeck, 1980

[a]Classes: A, bare fallow (no crop, repeated weeding and/or harrowing); B, straw exported or burnt, no or low N fertilization; C, crop residues incorporated, medium to high N fertilization; D, straw exported or burnt, medium to high N fertilization; E, application of different amounts of farm-yard manure; F, permanent grassland or crop rotations with more than 50% ley; G, crop rotations with different frequency of fallow, cereals and ley, with or without manure/slurry application.

[b]All calculations were based on total soil N assuming a constant C/N ratio of 10.

deals with changes in the topsoil (i.e. the top layer down to ploughing depth).

Carbon mass in the topsoil at the start and end of the reported experimental period was then calculated using bulk density and topsoil depth (Fig. 1).

2.2. Static model

Mean annual changes in C stocks (ΔC_{ma}) were calculated for all treatments in all classes at all sites ($N = 99$). Analysis of covariance was used to test

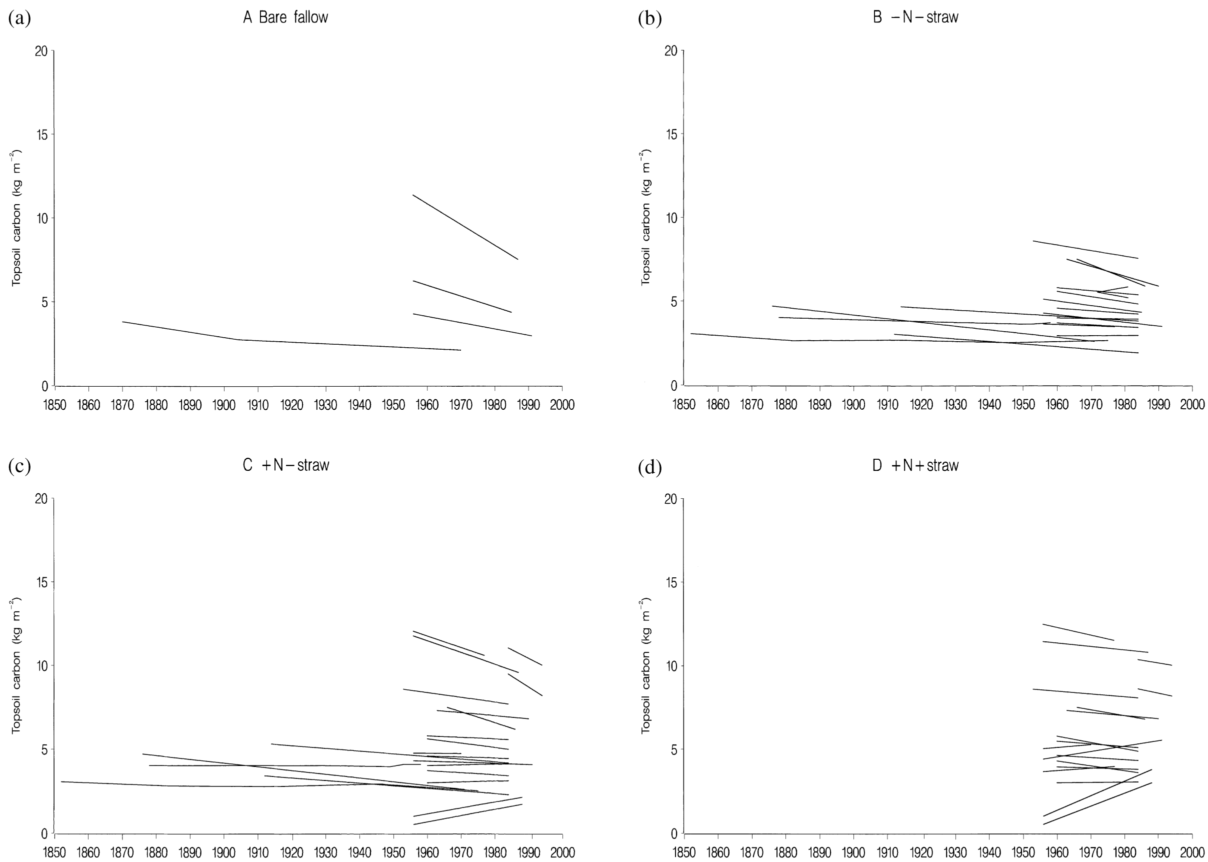

Fig. 1. Carbon in the topsoil (kg m^{-2}) measured in long-term field experiments as affected by management: See Table 1 for site descriptions and references and http://www.mv.slu.se/vaxtnaring/olle/icbm.html for details. Classes: A, bare fallow (no crop, repeated weeding and/or harrowing); B, straw exported or burnt, no or low N fertilization; C, crop residues incorporated, medium-to-high N fertilization; D, straw exported or burnt, medium to high N fertilization; E, application of different amounts of farm-yard manure; F, permanent grassland or crop rotations with more than 50% ley; G, crop rotations with different frequency of fallow, cereals and ley, with or without manure/slurry application.

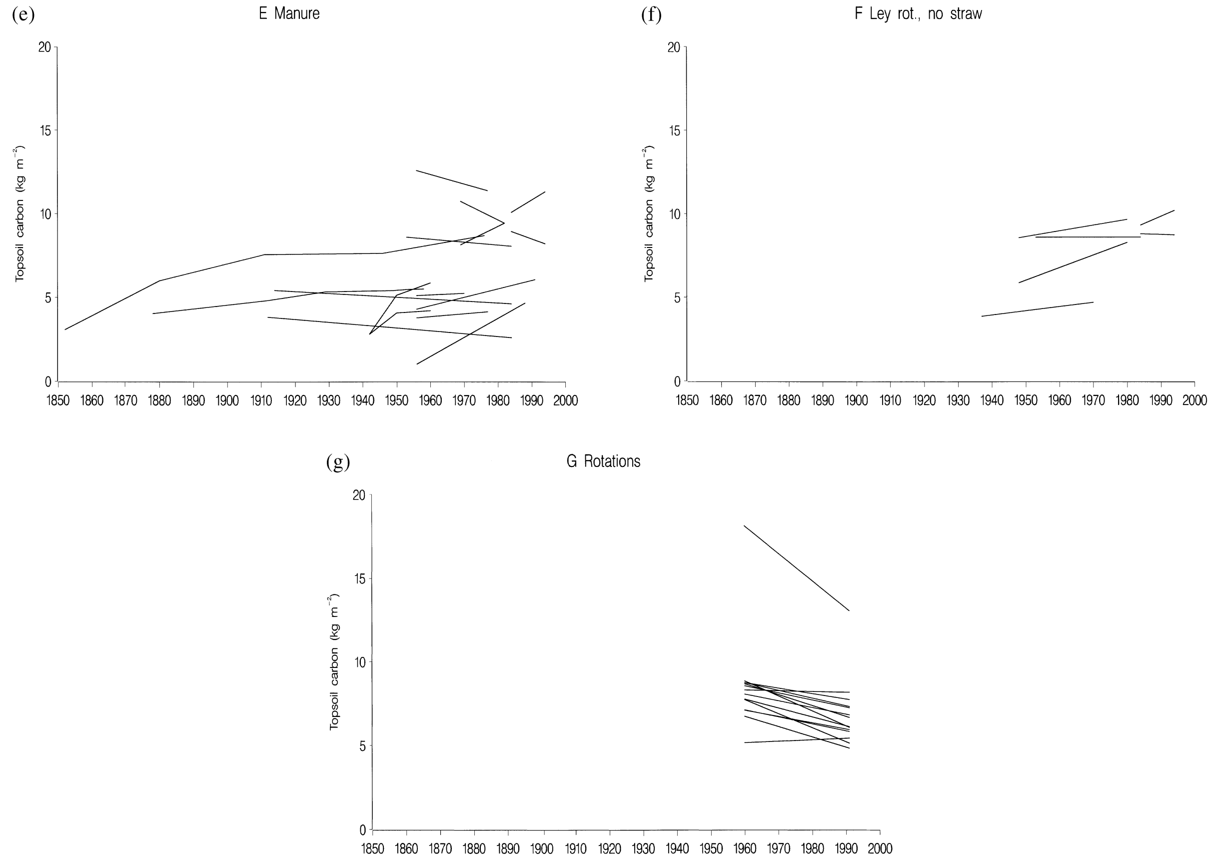

Fig. 1 (*Continued*).

which factors contributed to reduce the computed variance (procedure GLM in SAS; SAS Institute, 1982). Treatment class (A–G) was used as a classifying variable and the initial C stock (C_0), clay content and latitude as numerical covariates. A significance level of 5% was used in all tests.

2.3. Dynamic ICBM model

The ICBM model (Fig. 2; Andrén and Kätterer, 1997) was designed as the minimum soil C balance model to be applicable in a 30-year time perspective. ICBM consists of two state variables, young (Y) and old (O) organic material, whose dynamics are described by the following two differential equations:

$$dY/dt = i - k_Y r_e Y \qquad (1)$$

$$dO/dt = h k_Y r_e Y - k_O r_e O, \qquad (2)$$

where i is the C input to the soil, k_Y and k_O are the rate constants for decomposition, h the humification coefficient (different for different inputs) and r_e is a rate-modifying parameter (Note: In the original paper, parameters k_Y, k_O and r_e were called k_1, and k_2 and r, respectively). External influences, such as climate and soil cultivation, are condensed into r_e, which thus is site- and treatment-specific. External influences on the humification coefficient (e.g., sandy or clayey soil) are taken into account simply by changing h.

For more information about the model, including solutions to the differential equations and general parametrization strategies, see Andrén and Kätterer (1997). Model code and equations can also be downloaded from: http://www.mv.slu.se/vaxtnaring/olle/icbm.html.

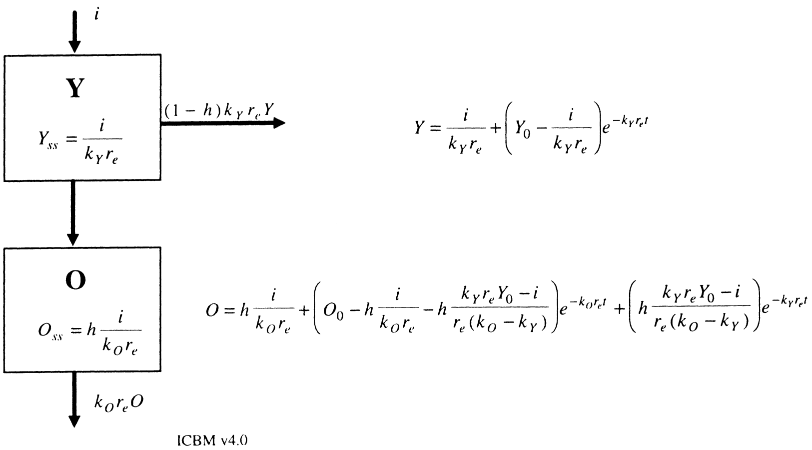

Fig. 2. Structure of ICBM. Flux equations are positioned close to their respective arrows, steady-state equations are given within the boxes, and equations describing state variable dynamics are on the right side (modified after Andrén and Kätterer, 1997). See Section 2.3 for explanation of symbols.

2.4. Model calibration

The model was calibrated for seven treatments in a Swedish long-term experiment (Andrén and Kätterer, 1997), where the above-ground C input was measured with high accuracy (see 'F_Ultuna' in Table 1; Kirchmann et al., 1994; Persson and Kirchmann, 1994). Five of these seven treatments were almost identical to treatment classes A–E, as used in this application. The values of i, r_e and h for those five are listed in Table 2. Total initial soil C content ($Y_0 + O_0$) was measured, and Y_0 was assumed to be 0.3 kg C m^{-2}. Corresponding to Andrén and Kätterer (1997), the rate constants k_Y and k_O were assumed to be the same for all treatments, 0.8 and 0.006 $year^{-1}$, respectively.

2.5. Model application

For each class (A–G), ICBM was used to predict soil C dynamics between the start and the end of the experiments. The parameter values for k_Y and k_O obtained in the calibration were used (see above) and for h, 0.125 for plant-derived C and 0.31 for manure-derived C were used for all classes (Table 2).

2.5.1. Estimation of C input (i)

For those experiments where the inputs to soil via straw, manure or slurry were given as mass but no C concentrations were reported, straw was assumed to contain 0.45 g C g^{-1} dry mass, manure 0.12 g C g^{-1} fresh mass and slurry 0.03 g g^{-1} fresh mass. The latter

Table 2
Parameter values as calibrated for treatments in a Swedish long-term experiment (Andrén and Kätterer, 1997)[a]

Treatment	O_0	i	h	r_e
A (Bare fallow)	3.96	0	0.13	1.32
B (No mineral N, no straw)	3.99	0.057	0.125	1.17
C (Mineral N, no straw)	4.02	0.091	0.125	1.07
D (Mineral N + straw)	4.05	0.285	0.125	1.00
E (Manure added)	3.99	0.082 + 0.19[b]	0.25[c]	1.10

[a] O_0 is in kg C m^{-2} in the topsoil, i is in kg C m^{-2} $year^{-1}$, summed from above- and below-ground C sources and from manure (E), whereas h and r_e are dimensionless. The rate constants k_Y and k_O were the same for all treatments, 0.8 and 0.006 $year^{-1}$, respectively.
[b] From manure.
[c] Weighted mean, i.e. $h = 0.125$ for plant-derived material and 0.31 for manure.

two assumptions were based on average values for dry mass content of organic amendments in Swedish agriculture, that is, about 25% and 6% for manure and slurry, respectively (Steineck et al., 1991). When the quantity of manure added was not given, 70 g C m^{-2} year^{-1} was assumed. This corresponds to typical manure application rates in Sweden of about 30 Mg ha^{-1} of fresh mass every fifth year (Steineck et al., 1991).

When values were not given for the above-ground C inputs deriving from straw and/or stubble in cereals ($i_{a(cer)}$), estimates were based on an overall mean for Sweden, modified for each treatment class (see Eq. (3)). Thus, $i_{a(cer)}$ was estimated based on Swedish official statistics for barley (*Hordeum distichum* L.) straw production, which are 398 g dry mass m^{-2} year^{-1} (overall mean for Sweden; Anon., 1992) corresponding to about 190 g C m^{-2} year^{-1}. This amount was assumed to be valid for classes where N fertilization was moderate (E, F and G), and 20% higher or lower than the Swedish average for the classes receiving relatively high (C and D) or low (B) doses of mineral fertilizer.

Pettersson (1989) measured the C input via stubble and other above-ground harvest residues in two barley cropping systems (with and without N fertilization, both with export of straw) during a 4-year period. In that study, the above-ground residue C input was 35% and 52% of the total straw mass at harvest in the fertilized and unfertilized treatment, respectively. Since small amounts of mineral N or manure were applied at some sites in class B (straw exported, low or no N fertilization), $i_{a(cer)}$ was assumed to be 45% of total straw at harvest. Correspondingly, 40% was assumed for classes (E–G), and 35% for classes C and D. Thus, when no other values were given, $i_{a(cer)}$ was $0.8 \times 190 \times 0.45 = 68$ g m^{-2} year^{-1} in B; $1.2 \times 190 = 228$ g m^{-2} year^{-1} in class C; $1.2 \times 190 \times 0.35 = 80$ g m^{-2} year^{-1} in D; and $190 \times 0.40 = 76$ g m^{-2} year^{-1} in E and when cereals were grown in F and G.

Estimates of C input from below-ground crop sources ($i_{b(cer)}$), that is, stem bases, root tissue and root exudates, were adapted from comprehensive C balance studies in fertilized and unfertilized barley and in grass ley in central Sweden (Andrén et al., 1990; Paustian et al., 1990). The estimated inputs were 110 and 90 g m^{-2} year^{-1} in the fertilized and unfertilized barley, respectively. Thus, the below-ground input was assumed to be 90 in B, 110 in classes C and D, and 100 g C m^{-2} year^{-1} in E and, multiplied by the relative frequency of cereals (f_{cer}), in F and G.

In F and G, where the cropping systems totally or partly consisted of ley in accordance with Paustian et al. (1990), an annual C input of 382 g m^{-2} was assumed, where 97 g ($i_{a(ley)}$) and 285 g ($i_{b(ley)}$) came from above- and below-ground sources, respectively, corresponding to the relative frequency of ley in crop rotation (f_{ley}). For E, F and G, total C input (i) was calculated:

$$i = i_m + \left(i_{a(cer)} + i_{b(cer)}\right) f_{cer} + \left(i_{a(ley)} + i_{b(ley)}\right) f_{ley}, \tag{3}$$

where i_m is the annual C input via manure.

2.5.2. Estimation of the humification quotient (h)

The humification quotient (h) was weighted according to the proportions of C input via manure ($h_m = 0.31$) and crop-derived C sources ($h_c = 0.125$; see Table 2):

$$h = \frac{h_c(i_a + i_b) + h_m i_m}{i} \tag{4}$$

When h was assumed to depend on the clay content (see below), a log-linear function, h_{clay} was used, which changed the value of h corresponding to that in the 'Rothamsted model' (RothC-26.3; Coleman and Jenkinson, 1996) and several others (Powlson et al., 1996):

$$h_{clay} = \alpha e^{\beta clay} \tag{5}$$

where α and β are scaling parameters and clay is the percent clay content in the soil. Normalization for 36.5% clay (the clay content in the calibration dataset) leads to:

$$h_{clay} = e^{\beta(clay - 36.5)} \tag{6}$$

Thus h was modified by introducing clay as an argument:

$$h(clay) = h\, h_{clay} \tag{7}$$

which on insertion into Eq. (4) gives:

$$h(clay) = \left(\frac{h_c(i_a + i_b) + h_m i_m}{i}\right) e^{\beta(clay - 36.5)} \tag{8}$$

2.5.3. Estimation of r_e

The only remaining parameter that was not adapted from the calibration (Table 2) or estimated from literature data, was r_e. If a value of r_e is estimated for each class that results in the best fit between measured and predicted final C stocks for each class, then this r_e value represents the external conditions of the class which are inherent to it, that is, N fertilization, straw and/or manure input, etc. Note that the latitude, which should affect r_e due to higher temperatures at lower latitudes and other precipitation and evapotranspiration conditions, is considered implicitly (see Section 3).

Before estimating r_e for each treatment class, r_e was split into three (r_{e_cer}, r_{e_fallow} and r_{e_ley}) in F and G where crops were rotated:

$$r_e = r_{e\text{-cer}} f_{cer} + r_{e\text{-fallow}} f_{fallow} + r_{e\text{-ley}} f_{ley}; \quad \Sigma f_i = 1 \tag{9}$$

where f_i denotes the frequency within crop rotation, expressed as a fraction of the total number of years.

Thereafter, for each treatment class, the best fit of the ICBM model to data was estimated from all experiments within that class by optimizing r_e (or r_{e_cer}, r_{e_fallow}, r_{e_ley}) using the multivariate secant method (Ralston and Jennrich, 1979), in the SAS procedure NLIN (SAS Institute, 1982).

2.5.4. Calculation of steady-state

For the treatment classes B–E, steady-state values were calculated. According to Eqs. (1),(2),(8) and (9), the total soil C stock at steady-state (C_{ss}) is a function of treatment class and clay content:

$$C_{ss(class,clay)} = \frac{i}{r_{e(class)}}\left(\frac{1}{k_Y} + \frac{h(clay)}{k_O}\right) \tag{10}$$

Class-specific mean values were assumed for i (for classes B–E, respectively: $i_a = 64$, 221, 76, 71; $i_b = 90$, 110, 110, 100; $i_m = 16$, 0, 14, 176). The values for h_c and h_m were taken from the original calibration (Table 2; i.e. 0.125 and 0.310, respectively).

3. Results and discussion

Data from the long-term experiments clearly show that the long-term site history in general decides whether soil C is increasing or decreasing under the prevailing climate and management system (Fig. 1). If the initial soil C pool is high, for example, as a result of waterlogging, frequent manuring and/or cropping with perennials, soil C will decrease when land use is changed to more frequent production of annuals (Fig. 1). In soils where the initial C pool is low, soil C can increase even when only cereals are cropped and the straw is removed (Fig. 1).

For the whole dataset ($N = 99$), inclusion of initial C stock (C_0) and treatment class significantly reduced the variance of measured mean annual changes in soil C (ΔC_{ma}) as analyzed using the static model. Independently estimated contributions of C_0 and treatment class to total model R^2 (=0.55) were 0.33 and 0.23, respectively. The effects of clay content and latitude were not significant. Parameter estimates for the 'treatment class' variate and 'C_0' covariate are presented in Table 3. On average over all C_0, soil C stocks increased in classes C, E and F and decreased in A, B, D and G. Thus, ley-dominated crop rotations, manure application and cereal monocultures where straw is incorporated seem, on average, to increase soil C stocks in Northern Europe. The C stock at which the predicted annual C change would equal zero was calculated. According to this model, up to 11 kg C m^{-2} could be sustainably stored in class F.

Considering the crudeness of the assumptions made, there was a reasonable level of agreement at

Table 3
Estimates of parameter values for the 'treatment class' (α_{class}) variate and 'initial C stock' (C_0) covariate that explained 55% of the variance in mean annual changes in C stock (ΔC_{ma}) according to analysis of covariance ($N = 99$)[a]

Class	α_{class}	LS means	C_0 ($\Delta C_{ma} = 0$)
A	0.00096	0.047[a,b]	0.43
B	0.028	0.021[b]	3.13
C	0.053	−0.005[c]	5.30
D	0.031	0.017[b]	3.10
E	0.085	−0.037[d]	8.50
F	0.109	−0.060[d]	10.9
G	0.0	0.049[a]	0.33

[a] $\Delta C_{ma} = -0.0033 + 0.010\ C_0 - \alpha_{class}$. LS means are the mean changes in ΔC_{ma} at average C_0. LS means with the same superscript letter are not significantly different. C_0 ($\Delta C_{ma} = 0$) is the soil C stock (kg m^{-2}) at 'steady state' where the predicted C changes equal zero, i.e. setting $\Delta C_{ma} = 0$ and solving the model equation for C_0. Definitions for classes are given in the text.

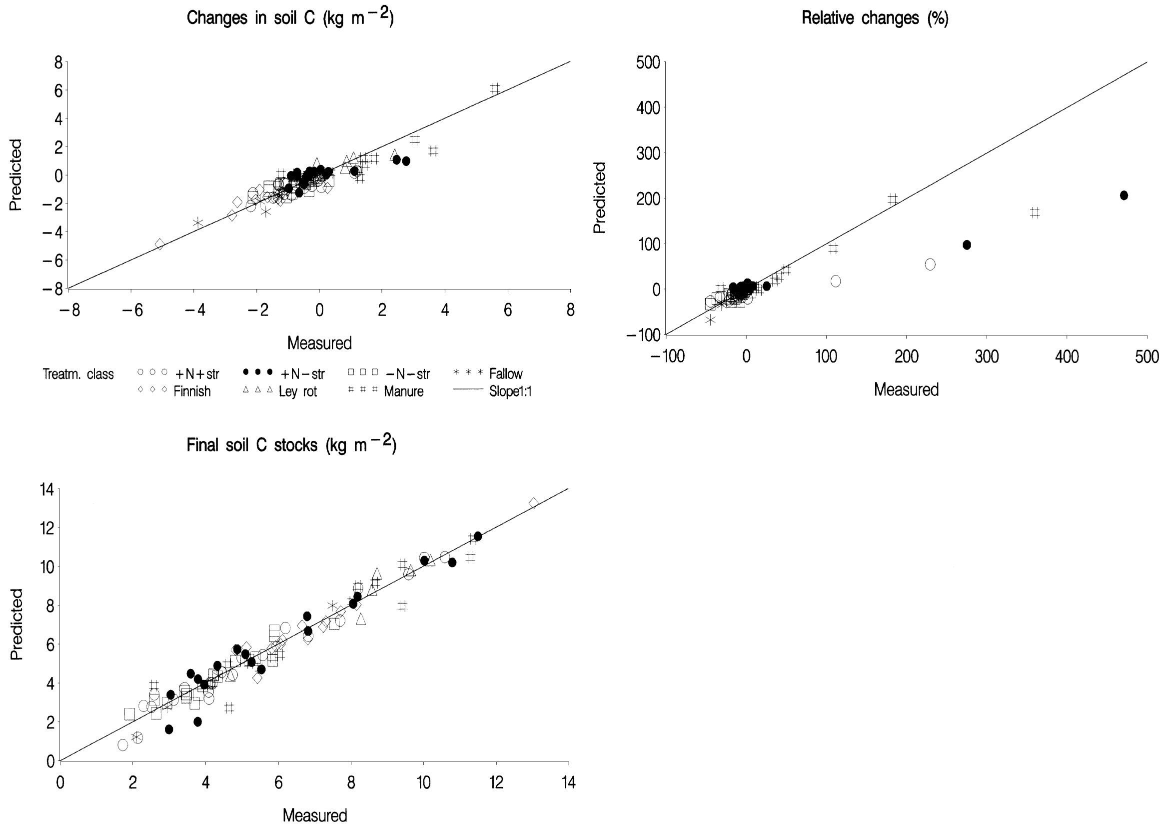

Fig. 3. Predicted vs. measured C stocks (kg m^{-2}) in the topsoil at the end of the 99 experiments and predicted vs. measured absolute (kg m^{-2}) and relative (%) changes in C stocks during the experimental periods. Parameter h was adjusted for clay content (see text). Lines are 1 : 1. Definitions for classes are given Fig. 1.

the end of the experiments between C stocks measured and predicted using the dynamic ICBM model ($R^2 = 0.95$; Fig. 3). Also, the measured absolute and relative changes in C stocks were reasonably well reproduced by the model ($R^2 = 0.83$ and 0.82, respectively; Fig. 3) except for five data points at the two sites 'AskoCSs1' and 'AskoCSs2' (see the five symbols below the line in the graph showing relative changes in C). At these sites, measured soil C concentrations increased during a 31-year period by up to 471%, whereas the model predicted a 207% increase. The five experiments at these sites were actually lysimeter experiments conducted under natural conditions (Christensen and Johnston, 1997). The soil was a subsoil from 50–100 cm depth, which was sieved, mixed and placed in concrete cylinders. Thus, these experiments may not be directly comparable with experiments conducted under more normal field conditions. Nevertheless, these results may indicate that with the present parameter settings, ICBM cannot accurately reproduce soil C dynamics when initial conditions are too far from steady-state, and perhaps even the simple model structure is insufficient (cf. Andrén and Kätterer, 1997).

3.1. Estimation of carbon stocks

Several factors that are not caused by cropping systems per se or by fertilization practice may affect measurements of soil C stocks. A constant soil bulk density, as we used for classes A–F, is perhaps not the best assumption. Agricultural machinery has become heavier and the frequency of its usage has increased since the 1950s. In recent years, however, the situation has improved through the use of such developments as wider, low-pressure tires, etc. If the topsoil's bulk density increases, the ploughing will reach deeper into the subsoil, even if the distance from the surface remains constant. Topsoil C may also be lost vertically as dissolved organic matter (DOC), or horizontally by erosion and the movement of soil between experimental plots, which weakens the assumption that C lost from soil equates to C added to the atmosphere. This dispersion of soil caused by soil cultivation can be considerable, especially when the experimental plots are small (Kofoed, 1960; Sibbesen et al., 1985; Sibbesen, 1986).

Comparative measurements of C concentrations of the same soil C over long periods of time or between two different soils can also be misleading since analytical methods may have differed. For example, soil C concentrations at F_Ultuna were analyzed by wet combustion between 1956 and 1983 and by dry combustion thereafter (Kirchmann et al., 1994). The presence of charcoal leads to an apparent overestimation of the organic matter content when using a combustion method. The chemical oxidation methods (e.g. the methods of Walkey-Black and Kurmies) have the advantage that charcoal is not oxidised, but, on the other hand, the conversion factors are highly empirical and the presence of manganese interferes with the method (Buurman, 1996). The correlation between loss on ignition (LOI; which was also used at some sites) and soil C is also highly empirical and may partly depend on other soil properties such as clay content. Further, soil analyses are usually carried out on the 'fine earth' fraction (<2 mm), and information on the relative amount of coarser fractions is frequently omitted (Buurman, 1996).

Moreover, there has usually been an increase in ploughing depth as measured from the surface, due to more powerful machinery. Both increased density (more soil mass) and increased ploughing depth (diluting C-rich topsoil with usually C-poor subsoil) affect the calculations of C mass from C concentration. Earthworms may also add to the diluting effects, for example, *Lumbricus terrestris*, for example, can lift subsoil to the surface and drag down litter. Surface castings of earthworms may exceed 3 kg soil m^{-2} $year^{-1}$ (Edwards and Lofty, 1977), corresponding to an annual replacement of a 2 mm deep soil layer.

How much can these factors affect the apparent C mass in the topsoil? Assume first that the soil bulk density increases from an initial value 1.2 to 1.4 Mg m^{-3}, second that the topsoil's thickness (ploughing depth) increases from 18 to 25 cm, and third a topsoil with a C content of 1.5% and a subsoil that has 60% of the topsoil's C content and a constant density of 1.4 Mg m^{-3}. Thus, the initial amount of C at 0–18 cm depth is $1.2 \times 1.5 \times 1.8 = 3.24$ kg m^{-2}. When the bulk density of the soil increases from 1.2 to 1.4 Mg m^{-3} the same amount of C is now found at 0–15.4 cm depth. When the depth of the topsoil (ploughing depth) simultaneously increases to 25 cm, the contribution of C from the subsoil is $0.6 \times 1.5 \times 1.4 \times 0.96 = 1.21$ kg m^{-2}. Thus, the amount of C at 0–25 cm depth has increased from 3.24 to 4.45 kg m^{-2}. To a depth of 25 cm, a C% of 1.5 and bulk density of 1.4 Mg m^{-3} corresponds to a C amount of $1.4 \times 1.5 \times 2.5 = 5.25$ kg m^{-2}. Consequently, although the measured C% in the topsoil was constant over time in this hypothetical example, the amount of C in the topsoil has increased by factor $5.25/4.45 = 1.18$. Thus, reduced C concentration does not necessarily indicate reduced C mass.

Not only is the topsoil affected by the treatments, Schjønning et al. (1994) investigated the impact of different treatments on the C content in topsoil and in the upper part of the subsoil (30–35 cm) in a sandy loam soil in Denmark. The long-term application of farmyard manure resulted in higher C concentration and lower bulk density in both the topsoil (0–20 cm) and subsoils (30–35 cm). After 90 years of manure application the amounts of C stored in the respective depth layers (4.15 and 0.48 kg C m^{-2}) were 18% and 32% higher than in the unmanured control. However, the mass increase in subsoil C (30–35 cm) was quite small (about 0.12 kg C m^{-2} per 90 years). In the classical continuous cereal experiment in Halle, Germany, Lenz (1969) investigated the effect of the application of mineral fertilizer and farmyard manure on C% to 1 m depth. While the C content in the Ap-horizon (0–20 cm) had increased considerably after 81 years of manuring (1.70% C) relative to the unmanured (1.20% C) and NPK-fertilized treatment (1.28% C), treatment differences below the Ap-horizon were very small. Compared with the NPK-fertilized treatment, C% in the manured treatment was slightly higher at 20–40 cm depth (0.78% and 0.70% C, respectively), but slightly lower below 40 cm depth (ΔC was about 0.02%). In conclusion, the impact of treatments on subsoil C seems to be of minor importance from a C balance viewpoint.

3.2. Estimation of carbon input (i) and external conditions (r_e)

Spring barley was used as a standard crop for the estimation of both above- and below-ground C inputs. The rationale behind this decision was the dominance of spring cereals over other crops in classes A–E. Expected higher inputs during years when winter cereals were grown were assumed to be compensated for by lower inputs during years when spring-sown oilseeds were grown, or by increased decomposition rates (higher values of parameter r_e) during years with more frequent soil cultivation when root crops were grown. The effect of soil cultivation on carbon mineralization is well known, but poorly quantified (see Paustian et al., 1997). Soil cultivation effects were, however, studied in a Danish experiment. After 10 years of annual rotavotion, soil C was 7% lower than with no tillage (average for four sites in Denmark). The corresponding decrease for ploughing was 4% (Schjønning, 1986). In terms of the ICBM model rotavoting, which could be used for row-crops, would increase r_e considerably, whereas no tillage would decrease r_e compared with conventional ploughing.

3.3. Correlation between carbon input (i) and external conditions (r_e)

Under steady-state conditions, i and r_e are linearly correlated in ICBM (Fig. 2). Also, when current C stocks do not deviate greatly from steady-state, this relation is close to linear (Fig. 2). Thus, when fitting to a dataset, overestimates of i result in compensatory overestimates of r_e and vice versa. Further, under field conditions, these two parameters are usually influenced in the same way by climate. In climates with wet and warm growing seasons both i and r_e are higher than in climates with cool and dry growing seasons (see, e.g. Kätterer and Andrén, 1996, 1997).

3.4. Management influences on parameter r_e

Even in a constant climate, r_e usually changes slowly over time depending on land use and management. Manure application has, for example, been shown to increase soil aggregation, aggregate stability, the volume of macropores, saturated hydraulic conductivity, water infiltration rate and soil water-holding capacity, and to decrease bulk density, penetration resistance and compaction effects from heavy machinery (see Schjønning et al., 1994). All these physical factors were more or less affected during the time between the initial and final C-stock measurements. Actually, this is an example of how long-term differences in i (manure addition) can affect r_e, that is, there can be an interaction between i and r_e.

3.5. Treatments affecting parameter r_e

Higher r_e values for bare fallow than for cereal cropping indicated differences in the abiotic conditions (Table 4). Owing to lower evapotranspiration in fallow plots, soil moisture was probably higher than in cropped plots, which increased C mineralization. The same mechanism probably also explains the relatively high r_e in class B (straw removed, no or low N fertilization), where crop growth and, thus, transpiration was lower than in the fertilized classes.

Generally, r_e estimated for cereal-related cropping (r_{e_cer}) and fallow conditions were about 1.2 (1.09–1.35) times those estimated for the calibration dataset when the clay content was considered (see below) and about 1.4 (1.21–1.53) when the clay content was not considered in the model (Tables 2 and 4). Naturally, the optimized r-values for the different classes (Table 4) were also dependent on proper estimates of other parameters, especially i, as discussed above. However, the relative r_e differences are similar to those between the treatments in the calibration dataset (A–E), that is, r_e was highest under bare fallow, intermediate in unfertilized crops and lowest in fertilized crop rotations. In F, the use of leys reduced r_e considerably. However, in G this was not the case. In this class, r_{e_ley} was even higher than r_{e_cer} (Table 4). An overestimation of i for leys could not explain this great difference in r_{e_ley} between F and G. For example, a decrease of i_{ley} by 50% would have reduced r_{e_ley} by not more than 25%. No information was given regarding the temporal sequence of different crops and fallow. The exact factors that caused the covariance with leys are not known. One factor might have been the use of root crops which, with intense soil cultivation and transpiration, create excellent conditions for

Table 4
Optimized values for the 'climate' parameter r_e in each class, and coefficients of determination (R^2) for the non-linear regression model[a]

Class	r_{e_cer}	r_{e_fallow}	r_{e_ley}	R^2
Using h				
A	–	1.77	–	0.94
B	1.54	–	–	0.91
C	1.29	–	–	0.94
D	1.50	–	–	0.96
E	1.68	–	–	0.90
F	1.41	–	0.43	0.91
G	1.41	2.69[b]	2.38[b]	0.92
Using h (clay)				
A	–	1.76	–	0.94
B	1.38	–	–	0.91
C	1.17	–	–	0.93
D	1.35	–	–	0.96
E	1.33	–	–	0.90
F	1.17	–	0.40	0.91
G	1.40	2.64[b]	2.42[b]	0.94

[a]Parameter values are shown for models both considering or not considering the clay content when parametrizing the humification quotient, h and h (clay), respectively (see Eqs. (4)–(8)). Definitions for classes and r_e are given in the text. The initial C amounts in the topsoil, Y_0 and O_0, were set to 0.3 and 4 kg m^{-2}, respectively, and the rate constants k_Y and k_O were the same as those used before, 0.8 and 0.006 year^{-1}, respectively.
[b]see text for interpretation of these values.

decomposition in G. Taking into account the lack of information and the general observation that r_e would decrease under ley (Andrén, 1987; Paustian et al., 1990) it was assumed that the r_e estimates for G are due more to lack of information than to actual conditions.

In the present study we also tested whether latitude at the we sites and/or clay content of the soils (Table 1) could explain differences between predicted and measured C amounts. Linear regressions were conducted for each class using predicted relative changes in soil C between initial and final C amounts in the soils as the dependent variable, and measured relative changes as an independent variable. For classes A–F, neither latitude nor clay content could significantly reduce the deviations between measured and predicted changes. However, for class G the effect of clay content was significant.

Clay content was therefore introduced into the parametrization routine for G (Eqs. (5)–(8)). Running ICBM for G with this new model for h resulted in an improved fit between predicted and measured values (Table 4). The optimized value for β was 0.0112. This means that h was about 40% lower in a sandy soil containing 5% clay than in clay soils containing 50% clay. When this front-end model for h, h(clay), was also applied to the other classes, only marginal changes in R^2 resulted (Table 4). However, the values for the three parameters optimized simultaneously for class G (r_{e_cer}, r_{e_fallow} and r_{e_ley}) were affected by introducing this additional parameter h_{clay} (Table 4).

The reason why latitude did not significantly affect estimated r_e-values could be explained by the close correlation between i and r_e as discussed above. For example, inputs derived from straw are higher at more southern latitudes in Sweden. Average annual biological yields of barley straw ranged between 2.72 and 4.78 Mg dry mass ha^{-1} in northern and southern Sweden, respectively, during 1980–1982 (Anon., 1992). Straw yields in central Sweden (about 3 Mg) were below the weighted mean for the whole of Sweden (3.98 Mg) used for the estimation of i in this paper. Thus both i, and consequently r_e, were probably underestimated at lower latitudes in the present application.

Assuming that h is dependent on the clay content in all classes, steady-state values were calculated for each class according to Eq. (10). The predicted C stocks at steady-state were similar to those predicted by the static model (Fig. 4; Table 3). For example, for 25% clay, the C stocks predicted with ICBM were 2.7,

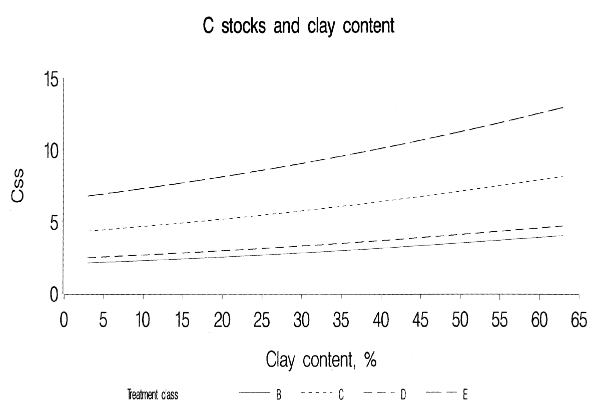

Fig. 4. Soil carbon stocks at steady state (C_{ss}; g m^{-2}) as a function of clay content for classes B–E as predicted using the ICBM model.

Table 5
Measured final carbon (C_{fin}; kg m^{-2}) in the topsoil (mean values from experiments in southern Sweden with four levels of PK fertilizer applications in six fields) after 19 years (Jansson, 1983))[a]

N-level	CR1				CR2			
	i	h	C_{fin}	r_e	i	h	C_{fin}	r_e
No N	0.208	0.166	4.48	1.33	0.240	0.125	4.03	1.65
Low N	0.221	0.164	4.55	1.28	0.267	0.125	4.25	1.38
Medium N	0.236	0.163	4.58	1.31	0.307	0.125	4.30	1.50
High N	0.246	0.161	4.60	1.32	0.340	0.125	4.35	1.58

[a]The effects of 4 N application-levels on soil C were reported for two 4-year-crop rotations: CR1: barley, ley, winter wheat, sugar beet (receiving 20 t manure, straw exported), and CR2: barley, oil seed, winter wheat, sugar beet (all straw incorp. no manure). Annual input (i) was weighed according to the frequency of ley and other crops in the rotation, and the humification quotient (h) was weighed according to the contribution of manure to total C input. The initial C amounts in the topsoil, Y_0 and O_0, were set to 0.3 and 4 kg m^{-2}, respectively, assuming the 'medium N' treatment in CR2 to be in steady state, and the rate constants k_Y and k_O were the same as those used before, 0.8 and 0.006 year^{-1}, respectively. ICBM was solved for the abiotic response, r_e.

5.5, 3.1 and 8.6 g m^{-2}, for classes B–E, respectively. Corresponding values were 3.1, 5.3, 3.1 and 8.5 g m^{-2}, when using the static model. Naturally, the steady-state C stock for bare fallow, as predicted by ICBM, is zero. The steady-state values for classes F and G were not considered here due to the contradictory influences of ley on r_e (Table 4).

3.6. An example of using ICBM on even less complete data

There are a great number of agricultural long-term experiments, not originally designed to investigate changes in soil C, but to study the effect of different mineral and organic inputs on crop yields. However, with no measurements of initial C content, these experiments were outside the criteria set for this report. The assumptions regarding the parameter i made for classes A–G were tested on several field experiments conducted in southern Sweden (Jansson, 1983). In those experiments, initial C content was not known, but C was measured in the topsoil (mean values from experiments with four levels of PK fertilizer applications in six fields) after 19 years (Table 5). The effects of four N levels on soil C were reported after almost five 4-year crop rotations: CR1: barley, ley, winter wheat, sugar beet (receiving 20 Mg manure ha^{-1} and crop rotation, crop residues were exported), and CR2: barley, oilseed, winter wheat (*Triticum* sp.), sugar beet (*Beta* sp.) (crop residues were incorporated, no manure was added). As for classes A–G, annual input (i) was weighted according to the frequency of ley and other crops in the rotation, and the humification quotient (h) was weighted according to the contribution of manure to total C input. Further, the initial C amounts in the topsoil, Y_0 and O_0, were set to 0.3 and 4 kg m^{-2}, respectively, assuming the 'medium N' treatment in CR2 to be in steady-state, and the same rate constants k_Y and k_O as before, that is, 0.8 and 0.006 year^{-1}, respectively. ICBM was solved for r_e, which resulted in values (Table 5) close to those reported for the classes A–G. Thus, even when datasets are less complete as in this case, ICBM can be used to give reasonable estimates for trends in soil C stocks.

4. Conclusions

Initial C stocks and soil management are the major determinants for soil C balances. The influence of soil texture on C balances was only significant for one class of treatments and of minor importance for the other classes in the dataset analyzed here. The hypothesis that the influence of climatic gradients in Northern Europe on decomposition and primary production counterbalance each other could not be rejected. The ICBM model was able to describe C dynamics in the analyzed long-term agricultural field experiments. Thus, the results indicate that the ICBM modeling concept is robust enough to be applicable for the evaluation of C balances at a larger scale, even when a complete dataset is lacking. However, the crude estimates regarding plant C inputs to the soil necessary due to lack of both theory and data make strict model validation impossible, and further research in this area is recommended.

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References

Andrén, O., 1987. Decomposition of shoot and root litter of barley, lucerne and meadow fescue under field conditions. Swedish J. Agric. Res. 17, 113–122.

Andrén, O., Kätterer, T., 1997. ICBM – the introductory carbon balance model for exploration of soil carbon balances. Ecol. Appl. 7(4), 1226–1236.

Andrén, O., Lindberg, T., Paustian, K., Rosswall, T. (Eds.), 1990. Ecology of arable land-organisms, carbon and nitrogen cycling. Ecol. Bull. (Copenhagen), p. 40.

Anon., 1992. Jordbruksstatistisk Årsbok 1992 (in Swedish). Statistiska Centralbyrån, Örebro, Sweden.

Bjarnason, S., 1989. The long-term soil fertility experiments in Southern Sweden. III. Soil carbon and nitrogen dynamics. Acta Agriculturae Scandinavica 39, 361–371.

Buurman, P., 1996. Use of soil analyses and derived properties. In: Buurman, P., van Lagen, B., Velthorst, E.J. (Eds.), Manual for Soil and Water Analysis. Backhuys, Leiden, Netherlands, pp. 291–314.

Christensen, B.T., 1990. Sædskiftets indflydelse på jordens indhold af organisk stof (in Danish). Tidskrift for Planteavl 94, 161–169.

Christensen, B.T., 1993. Askov long-term experiments: Changes in soil organic matter content and studies on soil movement between plots. In: Eriksson, T. (Ed.), Har markens långsiktiga produktionsförmåga förändrats? Erfarenheter från långliggande försök. Kungl. Skogs- och Lantbruksakademien, Stockholm, pp. 15–46.

Christensen, B.T., Johnston, A.E., 1997. Soil organic matter and soil quality: Lessons learned from long-term field experiments at Askov and Rothamsted. In: Gregorich, E.G., Carter, M.R. (Eds.), Soil Quality for Crop Production and Ecosystem Health. Elsevier, Amsterdam, Netherlands, pp. 399–430.

Coleman, K., Jenkinson, D.S., 1996. RothC-26.3 – A model for the turnover of carbon in soil. In: Powlson, D., Smith, P., Smith, J.U. (Eds.), Evaluation of Soil Organic Matter Models. Springer, Berlin, Heidelberg, pp. 237–246.

Edwards, C.A., Lofty, J.R., 1977. Biology of Earthworms. Chapman and Hall, London.

Erviö, R., 1995. Decline in soil organic matter in plough layer during three decades (in Finnish, with English summary). Maatalouden tutkimuskeskus, Tiedote 11/95, 1–12.

Erviö, R., Talvitie, H., 1995. Affecting the humus content and physical structure of arable land by cultivation (in Finnish, with English summary). Maatalouden tutkimuskeskus, Tiedote 11/95, 13–19.

Eswaran, H., van den Berg, P., Reich, P., 1993. Organic carbon in soils of the world. Soil Sci. Soc. Am. J. 57, 192–194.

Howard, P.J.A., Loveland, P.J., Bradley, R.I., Dry, F.T., Howard, D.M., Howard, D.C., 1995. The carbon content of soil and its geographical distribution in Great Britain. Soil Use Manage. 11, 9–15.

Hyvönen, R., Ågren, G.I., Andrén, O., 1996. Modelling long-term carbon and nitrogen dynamics in an arable soil receiving organic matter. Ecol. Appl. 6(4), 1345–1354.

Jansson, S.L., 1983. Tjugofem års bördighetsstudier i Sverige (in Swedish). Swedish University of Agricultural Sciences, Department of Soil Sciences, Division Soil Fertility. Rapport 151.

Jenkinson, D.S., Johnston, A.E., 1977. Soil organic matter in the Hoosfield Continuous Barley experiment. Rothamsted Experimental Station Report for 1976, Part 2, pp. 87–101.

Jenkinson, D.S., Rayner, J.H., 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. Soil Sci. 123, 298–305.

Johnston, A.E., McGrath, S.P., Poulton, P.R., Lane, P.W., 1989. Accumulation and loss of nitrogen from manure, sludge and compost: Long term experiments at Rothamsted and Woburn. In: Hansen, J.A., Henriksen, K. (Eds.), Nitrogen in Organic Wastes Applied to Soils. Academic Press, London, pp. 126–139.

Kätterer, T., Andrén, O., 1996. Measured and simulated nitrogen dynamics in winter wheat and a clay soil subjected to drought stress or daily irrigation and fertilization. Fert. Res. 44, 51–63.

Kätterer, T., Andrén, O., 1997. Winter wheat biomass and nitrogen dynamics under different fertilization and water regimes: Application of a crop growth model. Ecol. Modelling 102, 301–314.

Kirchmann, H., Persson, J., Carlgren, K., 1994. The Ultuna long-term soil organic matter experiment, 1956–1991. Swedish University of Agricultural Sciences, Department of Soil Science, Reports and Dissertations, p. 17.

Kofoed, A.D., 1960. The effect of soil tillage on the movement of superphosphate in soil using labelled phosphorus (in Danish, with English summary). Tidskrift for Planteavl 63, 285–306.

Lenz, K., 1969. Auswirkungen fortgesetzt gleicher Düngung auf den Boden (in German). Thaer-Arch. (Berlin) 13, 919–932.

Mattsson, L., 1987. Four Swedish long-term experiments with N, P and K. 2. Soil data and plant nutrient balances. Swedish J. Agric. Res. 17, 161–167.

Mattsson, L., 1991. Effects of annual straw application on soils and crops. Swedish University of Agricultural Sciences (in Swedish, with English summary), Department of Soil Science, Division of Soil Fertility, Report 180.

Mattsson, L., 1992. Effects on soil organic matter, N balance and yield of straw and N additions in a long term experiment in Central Sweden. Swedish University of Agricultural Sciences (in Swedish, with English summary), Department of Soil Science, Division of Soil Fertility, Report 186.

Paul, E.A., Paustian, K., Elliott, E.T., Cole, C.V., 1997. Soil Organic Matter in Temperate Agroecosystems, CRC Press, Boca Raton, p. 414.

Paustian, K., 1994. Modelling soil biology and biochemical processes for sustainable agricultural research. In: Pankhurst, C.E., Doube, B.M., Gupta, V.S.R., Grace, P.R. (Eds.), Soil Biota: Management in Sustainable Farming Systems. CSIRO Information Services, Melbourne, pp. 182–193.

Paustian, K., Andrén, O., Clarholm, M., Hansson, A.-C., Johansson, G., Lagerlöf, J., Lindberg, T., Pettersson, R., Sohlenius, B., 1990. Carbon and nitrogen budgets of four agro-ecosystems with annual and perennial crops, with and without N fertilization. J. Appl. Ecol. 27, 60–84.

Paustian, K., Collins, H.P., Paul, E.A., 1997. Management controls on soil carbon. In: Paul, E.A., Paustian, K., Elliott, E.T., Cole, C.V. (Eds.), Soil Organic Matter in Temperate Agroecosystems, CRC Press, Boca Raton.

Persson, J., 1981. Växtföljdens och skörderesternas effekt på skördeutvecklingen. Sveriges lantbruksuniversitet (in Swedish), Instituionen för markvetenskap, Avdelningen för växtnäringslära, Rapport 138.

Persson, J., Kirchmann, H., 1994. Carbon and nitrogen in arable soils as affected by supply of N fertlizers and organic manures. Agric. Ecosys. Environ. 51, 249–255.

Pettersson, R., 1989. Above-ground growth dynamics and net production or spring barley in relation to nitrogen fertilization. Swedish J. Agric. Res. 19, 135–145.

Post, W.M., Emmanuel, W.R., Zinke, P.J., Stangenberger, A.G., 1982. Soil carbon pools and world life zones. Nature 298, 156–159.

Powlson, D., Smith, P., Smith, J.U., 1996. Evaluation of Soil Organic Matter Models. Springer, Berlin, Heidelberg, p. 429.

Ralston, M.L., Jennrich, R.I., 1979. DUD, a derivative-free algorithm for non-linear least squares. Technometrics 1, 7–14.

SAS Institute, 1982. SAS User's Guide: Statistics. SAS Institute, Cary, NC.

Sauerbeck, D.R., 1980. Influence of crop rotation, manurial treatment and soil tillage on the organic matter content of German soils. Land Use Seminar on Soil Degradation, Wageningen, 13–15 October 1980, pp. 163–179.

Schjønning, P., 1986. Nedmuldning af halm ved ensidig dyrkning af vårbyg. II. Indflydelse af halm og stubbearbejdning på jordens inhold af kulstof, kvælstof, kalium og fosfor (in Danish). Tidsskrift for Planteavl 90, 141–149.

Schjønning, P., Christensen, B.T., Carstensen, B., 1994. Physical and chemical properties of a sandy loam receiving animal manure, mineral fertilizer or no fertilizer for 90 years. Eur. J. Soil Sci. 45, 257–268.

Schimel, D.S., Braswell, B.H., Holland, E.A., McKeown, R., Ojima, D.S., Painter, T.H., Parton, W.J., Townsend, A.R., 1994. Climatic, edaphic, and biotic control over storage and turnover in carbon in soils. Global Biochem. Cycles 8, 279–293.

Sibbesen, E., 1986. Soil movement in long-term field experiments. Plant and Soil 91, 73–85.

Sibbesen, E., Andersen, C.E., Andersen, S., Flensted-Jensen, M., 1985. Soil movement in long-term field experiments as a result of cultivation. I. A model for approximating soil movement in one horizontal dimension by repeated tillage. Exp. Agric. 21, 101–107.

Steineck, S., Djurberg, L., Ericsson, J., 1991. Stallgödsel (in Swedish). Swedish University of Agricultural Sciences. Speciella skrifter 43, p. 91.

Smith, P., Smith, J.U., Powlson, D.S., 1997. Soil Organic Matter Network (SOMNET): 1996 Model and Experimental Metadata. Global Change and Terrestrial Ecosystem Report No. 7. GCTE Focus 3 Office, Wallingford, UK.

Uhlen, G., 1991. Long-term effects of fertilizers, manure, straw and crop rotation on total-N and total-C in soil. Acta Agric. Scand. 41, 119–127.