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Long-term impact of chronosequential land use change on soil carbon stocks on a Swedish farm

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Original paper

Abstract

Agricultural practices and land use significantly influence soil carbon storage. The processes that are affected by land use and management are generally understood, but uncertainties in projections are high. In this paper, we investigate the long-term effects of chronosequential land use change from grassland to cropland and *vice versa* on soil carbon stock dynamics in four fields on a Swedish farm. Between 1850 and 1920, three of the fields were converted from grassland into cropland, and one was converted back to grassland in 1971. The fourth (control) field is a grassland that has never been ploughed. In 1937, the four fields were sampled at 111 points in a regular grid (25 or 50 m) and the dried soil samples were stored at our Department. In 1971 and 2002, the original grid points were revisited and re-sampled. Land use changes affected the soil C stock significantly. In 1937, carbon stocks were significantly smaller in the arable fields than in the grassland soil. In the field that was converted from arable back to grassland, soil C increased significantly at an average rate of about 0.4 Mg ha^{-1} year^{-1}. A soil C balance model (ICBM) driven by standard meteorological data and soil carbon input estimated from yield records described soil carbon dynamics reasonably well, although the range of simulated relative changes in C stocks between 1937 and 2002 in the four fields (from -7.4 to +8.8%) was narrower than those measured (from -19.5 to +16.5%). There are only few long-term studies in Northern Europe available for quantifying the effect of land use change on soil carbon stocks and the results presented here are therefore useful for improving predictions of changes in soil carbon driven by land use change.

Introduction

Soil organic carbon (SOC) is probably the most widely used soil quality indicator (Shukla et al., 2006). There is also a widespread interest in the role of soils in sequestering carbon, since decreases in SOC stocks lead to greenhouse gas emissions. Present soil carbon stocks (SOC) reflect land use and management history given a certain soil type and hydrological regime under prevailing climatic conditions. Quantifying the effects of different land use and management options on SOC is crucial for the implementation of the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC).

There is generally more SOC under grassland than under cropland (Cole et al., 1993) as a result of several factors including the lack of disturbance, greater return of plant residues, higher root biomass, manure applications and the return of dung during grazing. Thus, the conversion of arable land into grassland is considered to be an effective option for carbon sequestration, although predictions of the magnitude of the increase in SOC are associated with great uncertainty (Freibauer et al., 2004; Smith et al., 2000; Vleeshouwers and Verhagen, 2002). Generally, the conversion of arable land to grassland is considered to increase SOC by about 0.8 Mg C ha^{-1} year^{-1} during a 50 year period (IPCC, 2000). The sequestration potential of short-duration leys in pure arable cropping systems is about half of this figure (Soussana et al., 2004). In contrast, a reverse change of land use, from grassland to arable, usually results in a greater decrease in SOC (Whitehead, 1995; Potter et al., 2000; Accoe et al., 2004), which has been estimated at 0.95 Mg C ha^{-1} year^{-1} in France (Soussana et al., 2004).

Unfortunately, changes in SOC are difficult to measure, since stocks change slowly, and due to high spatial variation, statistically significant changes can seldom be detected within a time span of a few years (e.g. Conen et al., 2003). Thus, long-term field experiments and soil C monitoring, in which small annual differences accumulate, are essential to quantify the impact of land use and management on SOC. These experiments or inventories are essential for the calibration of models, which are needed for assessments at regional or national level.

The processes that govern the C balance must be quantified to achieve a better understanding of the changes in C storage. The scientific basis for quantifying carbon inputs and outputs of, which are necessary to understand why a soil has a particular carbon content, is still not strong (Rees et al., 2005).

The impact of land use and management change on the soil carbon balance has been studied in many long-term field experiments (see e.g. Kätterer and Andrén, 1999 and papers cited therein). In this paper, we investigate these effects on four fields on a working farm during 65 years. Grassland that has never been ploughed is compared with (i) arable fields that were converted to arable cropping in the 19th century, and (ii) one that was converted to agriculture in the 1920s, and converted back to grassland after about 50 years. Recently measured SOC stocks were compared with those measured on samples taken in 1937 and 1971. We also applied a simple SOC model to the initial field data, using management and sales records from the farm and meteorological data from a nearby station, and compared the model projections with the measured changes.

Material and Methods

Site description

The Kungsängen farm is situated east of the river Fyris, just outside the city of Uppsala in Central Sweden, 59°50'N, 17°40'E. Mean annual temperature and precipitation are 5.1°C and 542 mm, respectively. The land is flat (slope <1%) and the soil has developed on river sediments with a high clay (50-56%) and low sand content (5-7%) throughout the soil profile, with characteristics typical of 'Gyttja' clay (Table 1). The soil is classified as a *fine, illitic, frigid Typic Haplaquept* according to Soil Taxonomy and as a *Gleyic Cambisol* in the FAO-system (Kirchmann, 1991). A detailed soil description is given by Berglund et al. (1989).

Land rise during recent centuries made cultivation possible. Before the 19th century, the area was regularly flooded. However, during the 19th century, some areas were converted from permanent grassland to agriculture. Here, we consider four fields which differ with respect to the time of change of land use. The field 'Skifte 1' was ploughed for the first time in ca 1850, 'Hofstallängarna' in ca 1880, 'Ängen' in the 1920s, while 'Reservatet' to our knowledge has never been ploughed. The latter two fields are occasionally flooded during spring. Therefore, cereal production on the field Ängen ceased in 1970, and it was instead used as permanent grassland for hay production. Crop rotations in Hofstallängarna are dominated by winter wheat, spring wheat and ley and those in Skifte 1 by spring barley, spring wheat and ley (Table 2). Crop sequences before 1965 are not known, but probably consisted of both cereals and perennial leys.

Soil sampling and analysis

Between 1935 and 1939 the fields were sampled in a regular grid (25 or 50 m) and the dried samples were stored at our Department (Torstensson and Eriksson, 1941). Persson (1974) used the archived maps to identify the original sampling points. Between 1970 and 1972, these points were re-sampled and the soil from that and from the original sampling was analyzed for soil C using a wet combustion method (Jansson and Valdmaa, 1961). In the following, these two samplings are referred to according to the years 1937 and 1971. In autumn 2002, we used the maps to re-sample the same grid (Andersson, 2003). The coordinates were determined with a Global Positioning System receiver and archived for future investigations. Five sub-samples were randomly taken with an auger within a radius of 3 m around the center of the sampling point, down to 20 cm, which is the same sampling depth as in the earlier investigations. At three points within each field (only two in Skifte 1), soil samples were also taken at 20-40 cm and 40-60 cm depth. The samples were dried at 40 ^{o}C for 48 hours, ground and sieved (2 mm mesh size) and analyzed for carbon using dry combustion and infrared gas analysis (LECO CNS-2000). For all points within each field, the five samples per sampling point were pooled before analysis, except for one point where the samples were analyzed separately. C stocks were calculated from C concentrations using the same bulk density (1.05 g cm^{-3} according to Berglund et al., 1989).

Statistical treatment

Analysis of variance and Student’s t-tests were used to test for differences in C concentrations between fields. Paired two-sample Student’s t-tests were used to test for differences in C concentration between years within each field. This t-test does not assume equal variances between populations and accounts for the correlation between the two samples. Unfortunately, the location of the earlier sampling grid was not available for one field (Skifte 1), for which only mean C concentrations were available from 1937 and 1971. Thus, temporal changes in soil C could not be tested statistically. Some sampling points in the other fields were also missing from the earlier samplings.

Soil carbon input

The main sources of carbon input into the soil are shoot and root residues and root-derived organic compounds released into the rhizosphere during plant growth. In this case study, we assumed these C inputs to be proportional to exported yields. We adapted the linear allometric relationships proposed by Andrén et al. (2004), which differ between crops. For example, for a barley yield of 5 Mg grain ha^{-1}, 0.79 Mg C enters the soil from stubble and other above-ground residues and 0.95 Mg C enters via roots. If straw is not exported from the field, the input increases by 1.72 Mg C. In our calculations we assumed that all straw was left in the field after harvest. This corresponds to recent practices, but we are not sure if this was the case during the whole period since 1937.

For the years between 1965 and 2002, yields from annual crops were obtained from sale records received from the farm manager. Sale records for the years before 1965 were not available. Therefore, for this period, we used typical crop sequences and yields according to official regional statistics. In this region, the production of leys after a first cut for hay in summer usually corresponds to about 50% of the hay yield. On this farm, this production is mostly used for grazing. Thus, yields in meadows and leys in the fields Reservatet and Ängen were assumed to be 150% of hay yields. The input of dung during grazing by cows was assumed to be 30% of biomass production, which on average over the period is similar to the values used by others (Vleeshouwers and Verhagen, 2002; Whitehead, 1986). The resulting annual average dung input between 1965 and 2002 was 0.66 Mg C ha^{-1} in Reservatet and Ängen. For the fields Hofstallängarna and Skifte 1, occasional manure inputs during the period 1971-2002 (0.1 and 0.4 Mg C ha^{-1} year^{-1}, respectively) were estimated from the management plans at the farm. Total mean annual C inputs between 1937 and 2002 were 3.2, 2.7, 2.8 and 2.5 Mg C ha^{-1} in the fields Reservatet, Ängen, Hofstallängarna and Skifte 1, respectively (Fig. 1; Table 3).

Carbon balance

For each field, C inputs to the topsoil as described above and outputs due to decomposition were calculated using the Introductory Carbon Balance Model (ICBM; Andrén and Kätterer, 1997; Kätterer and Andrén, 2001), which was modified to handle input as a variable instead of a constant (Kätterer et al., 2004). Here, we propose a model version where total SOC is divided into three pools, a ‘young’ pool (Y) consisting of recently added crop residues, a ‘manure’ pool (*M*) consisting of recently added dung and manure and an ‘old’ pool (*O*) consisting of stabilized SOC. Total soil organic carbon at time *t* is given by

$$SOC_t = Y_t + M_t + O_t \tag{1}$$

where

$$Y_t = \left(Y_{t-1} + i_{t-1}\right)e^{-k_Y r_e} \tag{2}$$

$$M_t = \left(M_{t-1} + m_{t-1}\right)e^{-k_Y r_e} \tag{3}$$

$$\begin{aligned} O_t = {} & \left(O_{t-1} - h_Y \frac{k_Y\left(Y_{t-1} + i_{t-1}\right)}{k_O - k_Y} - h_m \frac{k_M\left(M_{t-1} + m_{t-1}\right)}{k_O - k_M} \right) e^{-k_O r_e} \\ & + h_Y \frac{k_Y\left(Y_{t-1} + i_{t-1}\right)}{k_O - k_Y} e^{-k_Y r_e} + h_m \frac{k_M\left(Y_{t-1} + m_{t-1}\right)}{k_O - k_M} e^{-k_M r_e} \end{aligned} \tag{4}$$

where *i* is the C input from crop residues and *m* is that of dung or manure.

Outflows from the pools follow first-order kinetics with corresponding rate constants k_Y, k_M and k_O. Here, we assume the same values for k_Y and k_M. External influences (climatic, edaphic and management related) are condensed into one parameter, r_e, which affects both decomposition rates equally, but does not affect the “humification coefficients” (h_Y and h_M), i.e., the fraction of the outflow from *Y* and *M* that enters *O*. Decomposition is assumed to occur continuously within each year.

Model parameterisation

The initial values for *Y* and *M* in 1937 were estimated by assuming that these pools were in an approximate dynamic equilibrium with the conditions during the first years after

1937 (Table 3). The initial size of the O pool was set to the difference between the measured C stock in 1937 and the sum of the initial values for Y and M. The default values for parameters h_Y (=0.125), h_M (=0.31), k_Y (=0.8) and k_O (=0.006) were taken from Andrén and Kätterer (1997), who calibrated the model for a long-term field experiment in Central Sweden. To account for differences in site conditions (soil and vegetation) between the original parameterization of the model for a nearby site (about 2 km distance), we used the concept proposed by Andrén et al. (2004) and Andrén et al. (2007), which is briefly described below. We also conducted a sensitivity analysis to examine the relative influence of model parameters and driving variables on model output in a medium time perspective (65 years).

Estimating the climate/management factor (r_e)

The climate/management factor, r_e, which summarizes the external influences on soil biological activity in one parameter, is governed by soil water content, soil temperature and cultivation intensity. These three components, r_w, r_T and r_c, respectively, are assumed to be multiplicative. The r_e factor was normalized (set equal to 1) for fertilized spring cereal cropping at the reference site, Ultuna, Sweden (Andrén and Kätterer, 1997).

Water response, r_w, increases linearly with volumetric soil water content and the temperature response, r_T, increases according to a quadratic relationship with soil temperature (Ratkowsky et al., 1982) and is zero below -3.8°C (Kätterer et al., 1998). Standard meteorological data from a nearby station (about 2 km distance from the farm), which were available from 1956 to 1999, were used to calculate soil temperature and soil water content for Kungsängen. We used a semi-empirical model developed for spatial modelling (Kang et al., 2000) for deriving daily soil temperatures in the four fields from daily air temperatures measured at a nearby meteorological station, which was modified to be applicable to cooler temperature conditions (Kätterer and Andrén, submitted). A simple tipping-bucket water balance model was used to calculate daily soil water contents from standard meteorological data and leaf area index (Andrén et al., 2004), based on FAO guidelines (Allen et al., 1998). The model parameters used to characterise the soil are the water content at wilting point (θ_{wp}; water content at -1.5 MPa) and at field capacity (θ_{fc}; water content at -0.1 MPa water potential).

The soil at the reference site is a clay loam with 37% clay and 41% silt formed from post-glacial sediments. A comprehensive description is given by Kirchmann et al. (1994). The two soil characteristic parameters θ_{wp} (=0.172 m^3 m^{-3}) and θ_{fc} (=0. 285 m^3 m^{-3}) were set according to Wiklert et al. (1983) and Kirchmann and Gerzabek (1999), respectively. The crop rotation at the reference site was dominated by spring cereals fertilized with calcium nitrate. The seasonal development of leaf area index was calculated using a continuous function calibrated for a fertilized barely crop as described by Kätterer and Andrén (submitted).

For each day between January 1956 and December 1999 values for the water and temperature responses r_w and r_T were calculated for the reference site. The daily product $r_{e\_wT\_ref} = r_{w\_ref} \times r_{T\_ref}$ was calculated for all days in the period 1956 - 1999, and the overall mean was used as the climate normalisation factor, which characterizes the abiotic conditions in the reference soil under spring cereals. For all other sites, the climate factor becomes: $r_{e\_wT} = r_w \times r_T / r_{e\_wT\_ref}$. The cultivation intensity factor r_c is unity by definition for normal soil tillage practices in cereal cropping (annual mouldboard ploughing and conventional seedbed preparation practices for spring cereals). Thus, for the reference site, $r_e = r_{e\_wT} = 1$ and for other sites: $r_e = r_{e\_wT} \times r_c$.

The temperature and water models were then run for the four fields at the farm. The two soil parameters (Table 1) were taken from Berglund et al. (1989) and those describing leaf area index development were scaled to approximate the growth dynamics and yield levels in the different crops. The resulting annual means of the product $r_w \times r_T$ calculated for each day were then divided by $r_{e\_wT\_ref}$ as described above. The cultivation factor r_c was set to 0.9 for the meadows and perennial leys, which implies a reduction of the decomposition rates by 10% compared with spring cereal cropping systems. This leads to a reduction of decomposition by about 3 Mg C ha^{-1} during the 65 years simulated here, corresponding to an annual average of about 0.05 Mg C ha^{-1}, which is quite low compared with recent reviews comparing conventional tillage and no-till practices (e.g. Alvarez, 2005; Follett, 2001). However, since reduced tillage effects are not consistent between climatic zones (Chan et al., 2003; VandenBygaart et al., 2003) and can even negatively affect soil C stocks (Alvarez, 2005), we made this conservative estimate here. The resulting r_e-values were then used as decomposition rate modifiers in the C balance model (eq. 1-3). Meteorological data were only available for the period 1956-1999. For the periods 1937-1955 and 2000-2002 we therefore set the annual r_e-values to the mean calculated for the measured period. All model parameter values, initial states and mean values for the driving variables i, m and r_e are presented in Table 3.

Results and discussion

Topsoil C concentrations were significantly larger in Reservatet than in the other fields in all years (Table 4). Mean SOC concentration increased slightly but not significantly (*p*=0.23) in Reservatet during the 65 years. In Ängen and Hofstallängarna, SOC decreased significantly between 1937 and 1971, but increased thereafter in Ängen, where it was significantly larger in 2002 than in both 1937 and 1971. In Hofstallängarna, SOC remained low and changes between 1971 and 2002 were not significant. Since the measurements in Skifte 1 were total field averages for 1937 and 1971, no statistical tests could be applied. However, the mean values are quite similar and it seems that no dramatic changes had occurred between 1937 and 2002 in this field. In 1937, SOC was significantly smaller in Ängen than in Hofstallängarna, while the reverse was the case in 2002.

Subsoil C concentrations were lower in Hofstallängarna than in the other fields according to pairwise t-tests (Table 5). The F-test (one-way ANOVA) gave results slightly above the 5% significance level (*p*=0.07) at 20-40cm depth, but the difference was highly significant at 40-60cm depth (*p* =0.008).

Spatial variation in C concentration at a single sampling location was only slightly lower than the variation within the whole field (Table 6). The variation, both within whole fields and among replicate samples at one location, was generally highest at the intermediate depth (20-40cm), and in the field Reservatet, especially at shallow depth. This high variation at the meter scale around a single grid ‘point’ explains the low correlation between consecutive grid samplings, particularly since the samplings were not made at exactly the same point due to the imprecision of GPS equipment and maps. The Pearson Correlation Coefficient for consecutive samplings at the grid-points within fields varied between 0 and 0.65. The correlation was highest between the samplings in 1937 and 1971 in Ängen (r=0.65). The samplings in 1937 and 1971 in Reservatet were moderately correlated (r=0.52), which means that 27% of the variance of SOC changes between consecutive samplings at the same grid points (within the accuracy of simple GPS-receivers) could be explained by C concentrations from the first sampling. Thus, the likelihood of detecting significant differences between consecutive samplings by grid-sampling versus random sampling increases correspondingly. In our example, soil C concentrations in Reservatet would have to change on average by 9.9% over the field to be significant at the 5% level using a random sampling design, and by 8.6% using the grid-sampling design.

Average SOC concentrations in Reservatet increased by 8.4% during the 65 years and should therefore be detectable in a future sampling if the increase is real and continuous. Although increases in soil C can be expected as a result of higher production and C input, they are hardly detectable within a few decades if land use has not changed dramatically (e.g. Conen et al., 2003), or very elaborate sampling schemes are used. This stresses the importance of long-term studies for identifying the causal factors and quantifying their impact on soil C balances.

On average, about 0.4 Mg C year^{-1} were sequestered in Ängen during the three decades following the land use change from cropland to grassland. This is less than the sequestration potential reported elsewhere in Europe (Smith, 2004; Vleeshouwers and Verhagen; 2002) and the IPCC (2000) default values, but only slightly smaller than that found for a French data set (Soussana et al., 2004). However, Ängen was not under continuous arable cropping before the conversion to grassland in 1971, but was cultivated in a rotation including cereals, oilseed and perennial leys. Moreover, most crop residues were left in the field. Conversion to grassland from continuously-cropped arable land with straw export probably has a much higher sequestration potential.

The overall dynamics of the measured C stocks in the topsoil were well reproduced by the model without any model tuning (Fig. 1). However, C stocks in Hofstallängarna were overestimated by 13-15% (8-9 Mg ha^{-1}) in1971 and 2002. The initial C stock in 1937 was much larger in this field than in the other arable fields. Initializing the model with a C stock corresponding to one standard deviation below the mean for 1937 would have resulted in an almost perfect model fit. On the other hand, this field had less carbon in the subsoil (Table 5). This may indicate that the history of this field between the initial ploughing in the 1880's and 1937 was different from that of the other fields, perhaps with respect to the crop rotation, soil bulk density, local groundwater level, crop residues or manure applications. Other potential error sources which are not consistent over time such as ploughing depth, earthworm activity or analytical methods (e.g. wet vs. dry combustion) could have affected the calculated C stocks as discussed by Kätterer and Andrén, 1999).

The dynamics of the model were governed by C input and r_e since all other parameter values were the same for all fields. Along with increasing yields during recent decades, estimated C input increased significantly, on average by 12.6 kg C ha^{-1} year^{-1} in Reservatet (Fig. 2). This trend was similar for the other fields, although inter-annual variation of input was higher due to different crops. During the whole period, mean annual crop-derived C inputs varied within a quite narrow range (between 2.3 and 2.7 Mg ha^{-1}) in the four fields, although inputs from dung and manure were greater in Reservatet and Ängen (Table 3).

The series of annual r_e-values did not show any trend over time. On average over the whole period, r_e-values were smallest in Reservatet and largest in Hofstallängarna and Skifte 1 (Table 3). The main reason for these differences was the influence of vegetation on the soil climate. The grassland fields had a longer vegetation period and the grass sward dampened radiation transfer to the soil. Thus, soil temperature was lower under the grass sward than under arable crops, especially during spring. On average over the years, calculated soil temperature was 0.43 ^{o}C lower in Reservatet than in Hofstallängarna (6.23 and 6.66 ^{o}C, respectively). The corresponding average value of the temperature response factor (r_T) was, for example, 11.4% higher in Hofstallängarna than in Reservatet.

Soil water content was also affected by the crops, and on average it was higher in the arable fields than under grass, due to the shorter vegetation period and thus lower total transpiration. The annual mean value of the water response function (r_w) was 2.3% smaller in Reservatet than in Hofstallängarna. Comparing all years with annual crops with those under grass, the average combined effect of soil temperature and water content on decomposition rates ($r_T \times r_w$) was 18% greater for arable land than grassland. In addition, the cultivation factor (r_c), which is partly related to the increased accessibility of organic matter to the decomposer community resulting from cultivation (here set to 0.9 for grass ley and 1.0 for cereals) increased these differences. The product (r_e) of the three components r_T, r_w and r_c was 31% greater for arable cultivation compared to grassland. The difference between Reservatet and Hofstallängarna was 26%.

C stocks at steady-state are proportional to C input and reciprocally proportional to r_e. Therefore, at steady-state, C stocks under grassland should approach a value that is 31% larger than continuous arable cropping with annual ploughing, if input quality and quantity was the same in both systems. For the management conditions at the farm during the years 1990-1999, we estimated that the steady-state carbon stocks (0-20 cm depth) would approach 95 Mg ha^{-1} in Reservatet and Ängen, 65 Mg in Skifte 1 and 62 Mg in Hofstallängarna.

Estimated annual C inputs and r_e-values were not correlated, but both varied greatly between years (Figs. 2, 3). The calculated r_e-values in Reservatet varied least and those in Ängen, where management changed considerably, varied most. Comparing two extreme years (1961 and 1976), r_e differed by a factor 2 in Ängen, 1.6 in Reservatet and 1.9 in the other two fields, as illustrated for Reservatet in Figure 4. This large variation is explained by the temporal dynamics of precipitation and temperature during these two extreme years. These differences were mainly due to the moist summer and warm autumn in 1961 and the dry summer in 1976. However, the inter-annual variation of i and r_e had a very limited effect on C stock projections. Using mean values for i and r_e instead of variables affected the dynamics of C evolution but the projected C stocks after 65 years were affect by only 0.02% in Reservatet and by less than 0.7% in the other fields. Thus, the effect of this simplification on the following sensitivity analysis can be neglected.

The local sensitivity of the projected C stocks after 65 years to changes in the fixed parameters (k_Y, k_O, h_Y, h_M) and the driving variables i, m and r_e was tested by varying each of these one-at-a-time (Fig. 5). The parameters estimated for Reservatet (Table 3) were used as a reference for this analysis. The model responses to changes in i

or h are perfectly linear (which is obvious from equations 1-3, where these parameters only appear in the linear terms and not in the exponents) and responses to changes in k_O and r_e were only slightly concave and almost linear within a reasonable range of parameter values. A 30% change of i or h affected projected C stocks by 11%. A 30% increase of k_O and r_e decreased C stocks by 8 and 9%, and 30% reductions resulted in increases by 9 and 10%, respectively. The model response to changes in k_Y was strongly non-linear but only at extremely low values. In a reasonable parameter interval, i.e. +/-50% of the value set in this application, the sensitivity of projected C stocks to changes in k_Y can be neglected in this time perspective.

Conclusions

Data series from long-term field experiments or repeated monitoring as presented here are necessary to quantify the effects of land use and management on SOC. Although the assumptions needed to estimate C inputs and decomposition rates were crude, due to the lack of detailed site-specific information, C dynamics could be reasonably well described with the ICBM concept, without any model tuning. The results from this case study will contribute to improving confidence in soil C budgets and projections driven by land use changes at the regional level.

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Tables

Table 1. Selected soil physical properties at three depths (cm) at the Kungsängen farm according to Berglund et al. (1989): Dry bulk density (ρ; g cm^{-3}), clay and sand (%) and volumetric soil water content at wilting point and field capacity (θ_{wp} and θ_{fc}; g cm^{-3})

Depth	ρ	Clay	Sand	θ_{wp}	θ_{fc}
0-20	1.05	50	7	0.21	0.48
20-40	1.00	52	5	0.22	0.49
40-60	0.96	56	6	0.25	0.48

Table 2. Crop frequency (%) in the two arable fields between 1965 and 2002

Crops	Hofstallängarna	Skifte 1
Winter wheat	26	13
Spring wheat	21	21
Ley	21	21
Spring barley	11	24
Spring rapeseed	11	5
Oats	5	5
Other crops	5	11

Table 3. Initial mass (Mg C ha^{-1}) in the 'young' (*Y*), 'manure' (*M*) and 'old' (*O*) carbon pools and corresponding decompositions rates (*k;* year^{-1}) and humification coefficients (*h*) and average annual mean values 1937-2002 of carbon input (Mg ha^{-1}) from crop residues (*i*) and dung/manure (*m*) and the climate response factor (r_e).

Fields	Y_0	M_0	O_0	k_Y	k_M	k_O	h_Y	h_M	i	m	r_e
	Mg	Mg	Mg	year^{-1}	year^{-1}	year^{-1}	-	-	Mg	Mg	-
Reservatet	2.2	0.6	74.3	0.8	0.8	0.007	0.13	0.31	2.49	0.75	0.86
Ängen	1.5	0	53.0	0.8	0.8	0.007	0.13	0.31	2.26	0.40	0.94
Hofstallängarna	1.5	0	63.9	0.8	0.8	0.007	0.13	0.31	2.72	0.07	1.08
Skifte 1	1.5	0	53.1	0.8	0.8	0.007	0.13	0.31	2.32	0.22	1.08

Table 4. Mean percent topsoil C (0-20 cm depth) and number of soil samples (n) in each field. Different capital letters indicate significant differences ($p < 0.05$) between fields during one year and different small letters indicate significant differences between years within each field. Skifte 1 not included in the statistical analysis.

Fields	1937		1971		2002	
	n	C%	n	C%	n	C%
Reservatet	24	3.68Aa	24	3.84Aa	27	3.99Aa
Ängen	33	2.60Cb	34	2.43Bc	36	3.02Ba
Hofstallängarna	48	3.11Ba	48	2.42Bb	48	2.51Cb
Skifte 1	1	2.60	1	2.33	6	2.51C

Table 5. Mean percent subsoil C in 2002. Different letters indicate significant differences ($p < 0.05$) between fields.

Fields	20-40cm	40-60cm
Reservatet	1.56AB	1.36A
Ängen	2.03A	1.45A
Hofstallängarna	1.35B	0.82B
Skifte 1	1.99A	1.47A

Table 6. Coefficient of variation (standard deviation divided by mean, %) in C concentrations sampled in 2002 at three depths within all sampling points within whole fields, and within one sampling point in each field (n=5).

Fields	Whole field			Sampling point		
	0-20	20-40	40-60	0-20	20-40	40-60
Reservatet	24	23	17	8	19	6
Ängen	13	16	12	7	16	9
Hofstallängarna	10	9	12	2	11	14
Skifte 1	6	16	6	3	8	8

Figure captions

Fig. 1. Measured (symbols) and simulated (lines) topsoil carbon stocks (0-20cm) in the four fields. Error bars correspond to standard deviation of the mean. Note differences in scale of the ordinate.

Fig. 2. Estimated annual topsoil C input in Reservatet. The slope of the regression line is significant ($p < 0.05$).

Fig. 3. Estimated annual r_e values for Reservatet.

Fig. 4. Upper: Monthly accumulated precipitation and mean monthly air temperatures in 1961 and 1976. Lower: Daily calculated r_e-values for Reservatet for 1961 and 1976.

Fig. 5. Calculated changes in soil carbon stocks after 65 years as an effect of varying the model parameter one at a time relative to the setting for Reservatet as presented in Table 3. The initial labile pools (Y and M) were assumed to be in steady state for all parameter settings. The changes in h correspond to proportional changes in i h_Y and h_M and changes in i also imply proportional changes in m.

Figure 1

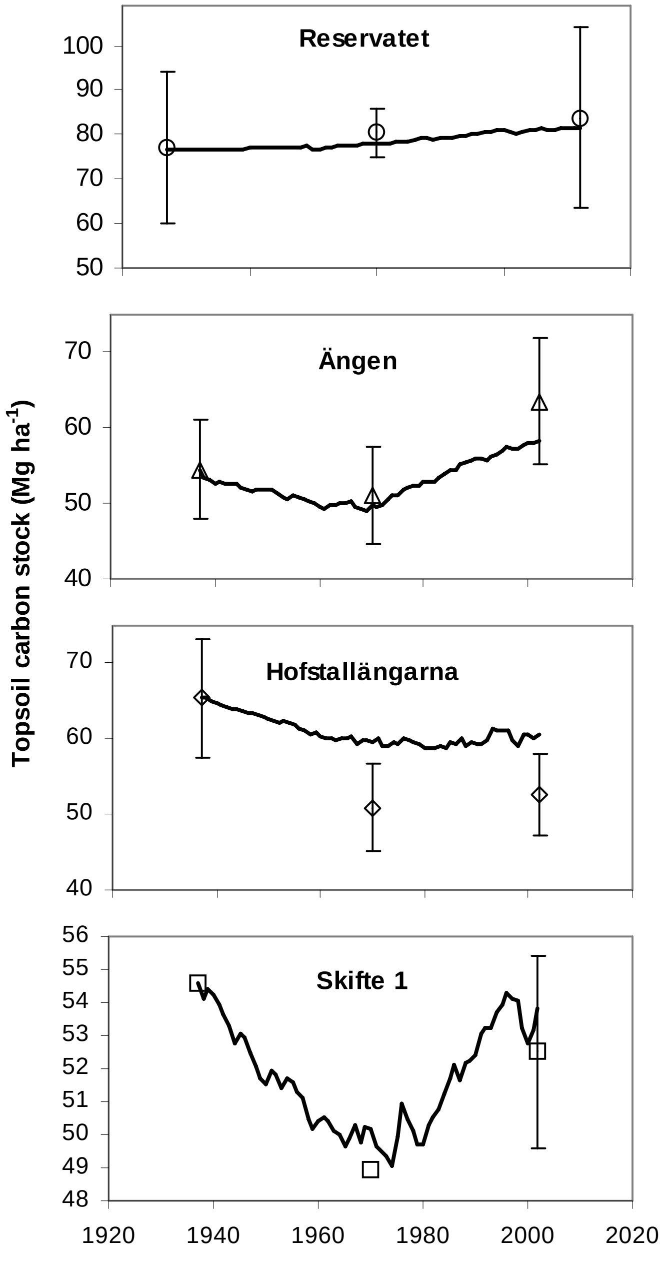

Reservatet
100
90
80
70
60
50
Ängen
70
60
50
40
Hofstallängarna
70
60
50
40
Skifte 1
56
55
54
53
52
51
50
49
48
1920
1940
1960
1980
2000
2020
Topsoil carbon stock (Mg ha-1)

Figure 2

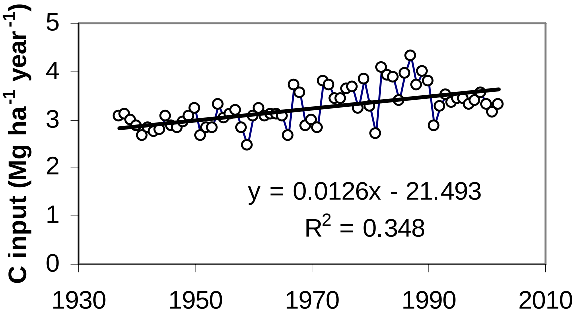

C input (Mg ha-1 year-1)
5
4
3
2
1
0
1930
1950
1970
1990
2010
y = 0.0126x - 21.493
R2 = 0.348

Figure 3

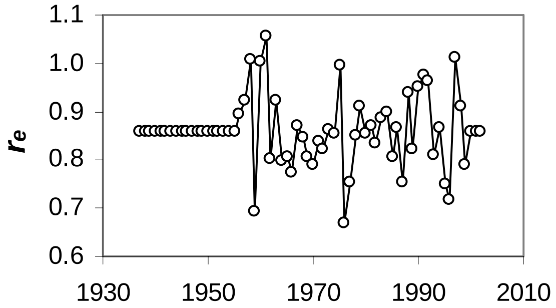


Figure 4.

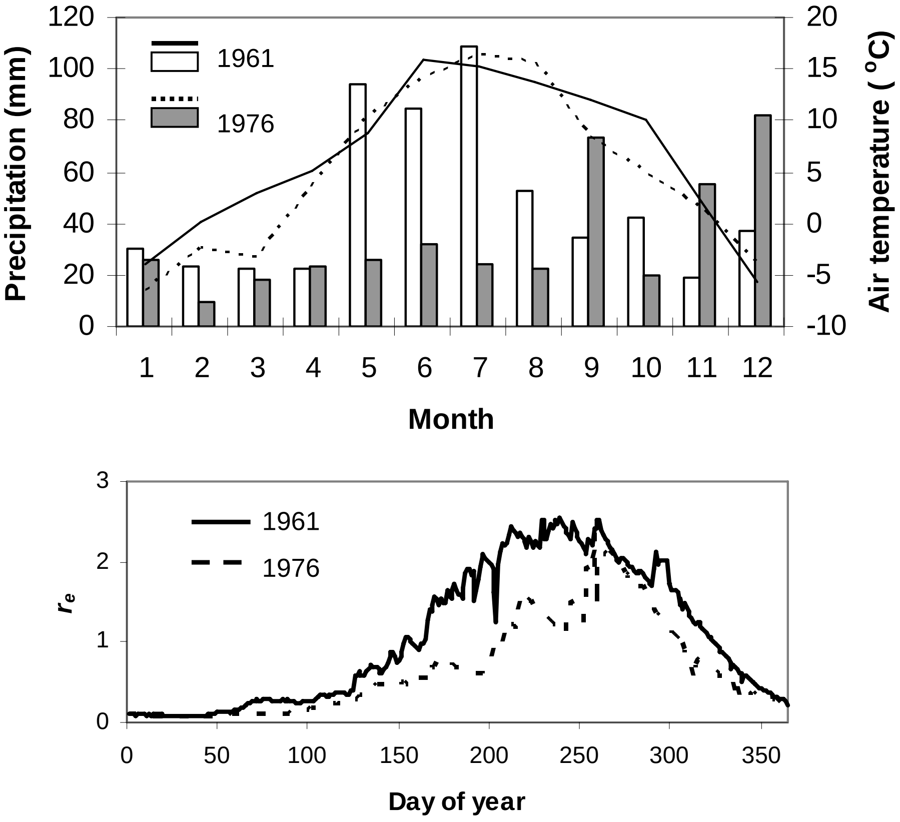
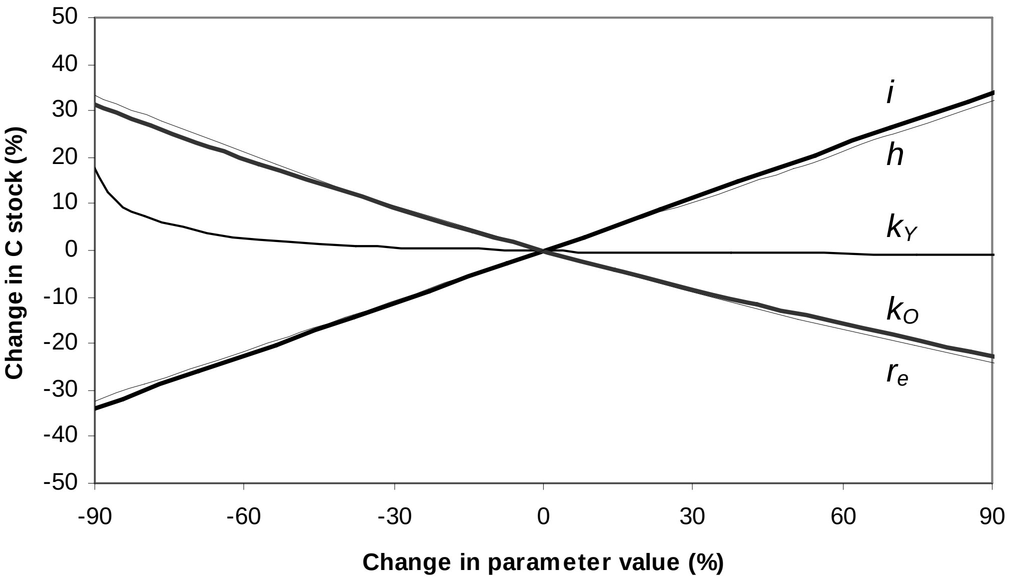

Precipitation (mm)
Air temperature (°C)
120
100
80
60
40
20
0
20
15
10
5
0
-5
-10
1961
1976
1
2
3
4
5
6
7
8
9
10
11
12
Month
r_e
3
2
1
0
1961
1976
0
50
100
150
200
250
300
350
Day of year

Figure 5


50
40
30
20
10
0
-10
-20
-30
-40
-50
-90
-60
-30
0
30
60
90
Change in C stock (%)
Change in parameter value (%)
i
h
k_Y
k_O
r_e