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The impact of altered management on long-term agricultural soil carbon stocks – a Swedish case study

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Abstract

Land use in general and particularly agricultural practices can significantly influence soil carbon storage. In this paper, we investigate the long-term effects of management changes on soil carbon stock dynamics on a Swedish farm where C concentrations were measured in 1956 at 124 points in a regular grid. The soil was re-sampled at 65 points in 1984 and at all grid points in 2001. Before 1956 most of the fodder for dairy cattle was produced on the farm and crop rotations were dominated by perennial grass leys and spring cereals with manure addition. In 1956 all animals were sold, crop rotations were thereafter dominated by wheat, barley and rapeseed. Spatial variation in topsoil C concentration decreased significantly between 1956 and 2001. C stocks declined in fields with initially large C stocks but did not change significantly in fields with moderate C stocks. In the latter fields, soil C concentrations declined from 1956 to 1984, but increased slightly thereafter according to both measurements and simulations. Thus, the decline in C input due to the altered management in 1956 was partly compensated for by increasing crop yields and management changes, resulting in increased C input during the last 20 years. A soil carbon balance model (ICBM) was used to describe carbon dynamics during 45 years. Yield records were transformed to soil carbon input using allometric functions. Topsoil C concentrations ranging between 1.8 and 2.4% (depending on individual field properties) seemed to be in dynamic equilibrium with C input under recent farming and climatic conditions. Subsoil C concentrations seemed to be unaffected by the management changes.

Introduction

The global pool of soil organic carbon (SOC) down to a depth of 1 m is about twice the amount present in the atmosphere (Eswaran et al., 1993; Post et al., 1982). The size of this pool indicates that even small changes in the global stock of SOC could cause a significant change in atmospheric CO_2 (Schimel et al., 1994). Present soil carbon stocks reflect the history in land use and management, soil type, hydrology and climatic conditions. Unfortunately, changes in SOC are difficult to measure, since C stocks change slowly. Due to spatial variation, measurements of soil carbon changes as affected by land use and management seldom yield significant differences within a time span of a few years. Thus, long-term field experiments and soil C monitoring are essential for estimating parameters controlling SOC dynamics.

In this paper, we investigate the long-term effects of changed management on soil carbon stock dynamics on a Swedish farm where C concentrations were measured in 1956, 1984 and 2001 at points in a regular grid. Before 1956 most of the fodder for dairy cattle was produced on the farm fields, and crop rotations were dominated by perennial grass leys and spring cereals. In 1956 all animals were sold, a change fairly typical for this period, and thereafter crop rotations were dominated by wheat, barley and rape. No farmyard manure was applied after 1956.

The farm investigated here is typical for the county Västmanland in central Sweden, where the animal density decreased from about 50% to 30% of the national average between 1956 and 1995 (Hoffmann et al., 2000). The soil mapping conducted during 1984 showed a decline in soil C stocks in three out of four fields (Persson, 1984). We hypothesised that after 45 years, SOC stocks are approaching a new steady state. Thus, annual changes between 1984 and 2001 were presumed to be lower than those between 1956 and 1984. In the field where the initial C concentration was lowest, even an increase in SOC stock during the last two decades could be expected due to higher crop yields and residue input.

Material and Methods

Site description

The farm Uknö is situated between the cities Kungsör and Köping in Central Sweden at 59.4°N, 16.0°E. Mean annual temperature and precipitation is 5-6°C and 600-700 mm, respectively. Crop rotations were dominated by perennial leys before 1956. After 1956, crop rotations were dominated by cereals (Table 1) and neither farmyard manure nor other external organic amendments were applied to the fields except for small amounts of poultry manure that was applied for a few years around 1960. Almost all crop residues were incorporated into the soil after 1956. Straw was exported when timothy for seed was grown and during a few years when winter wheat was grown. Here we consider four fields which were managed as eight separate units until 1968-74. In 1968, three units (Skären Ö, Skären M and Skären S) were merged into one, SKÄ; in 1970 two units (Mjölkväg and Gatan V) were merged to MVG; and in 1974, two units (Ängen Ö and Ängen V) were merged to ÄNG. The field Gatan Ö (acronym GAT) was treated as one unit since 1956.

The field MVG slopes gently from the farm houses which are built on moraine. Differences in elevation between the highest and lowest point in this field is 2.0 m. Elevation in the other three fields differs by less than 0.4 m between the lowest and highest point. The soils have developed on fine post-glacial sediments with clay content between 15 and 45% (Table 2).

Soil sampling and analysis

Soil pH (average over all fields) increased from 5.8 in 1956 to 6.2 in 1984 (Persson, 1984) and to 6.3 in 2001 (Table 2). Correspondingly, P concentrations (measured in a 0.1 M ammonium lactate solution buffered with 0.4 M acetic acid, according to Swedish standards) increased (average over all fields) from 30 in 1956, to 36 in 1984 (Persson, 1984) and to 48 µg/g dry soil in 2001 (Table 2). Concentrations of both K and Mg measured in ammonium lactate solution decreased slightly between 1956 and 1984 (Persson, 1984). However, in 2001, concentrations were similar to those in 1956.

In 1956 the fields were sampled in a regular grid and the dried samples were stored at our Department. The sampling points could be identified on maps and were re-sampled in 1984 and 2001. Field sampling and analysis was conducted for all 125 sampling points in 2001. For 1956, 124 samples were available and 65 samples were available for 1984. In 1956 and 1984 soil samples were taken at 0-25 and 25-60 cm depth. In 2001, we sampled the soil at 0-25, 25-35 and 35-60 cm depth. In the field SKÄ, no samples are available for the depth 25-35 cm.

Three sub-samples were taken within a radius of about 1 m from each grid point and pooled into one. However, at one grid point per field, the three sub-samples were kept separately for estimating the variance at each grid point. To facilitate future investigations at the farm, a GPS receiver was used to document the coordinates for each sampling point.

The dry soil samples were milled and sieved (2 mm) before analysing. Carbon concentrations were measured using wet combustion for 1956 and 1984 (Jansson and Valdmaa, 1961) and with dry combustion and infrared gas analysis for 2001 (LECO CNS-2000).

Carbon stocks

Soil dry bulk density (ρ_b) was not measured but assumed to be a function of carbon concentration. Analysis of covariance was used to quantify the effect of C concentration on ρ_b in 520 agricultural topsoil samples from 84 Swedish sites, which were used as classifying variable in the model. In the data base (see ftp://www.lwr.kth.se/CoupModel/CoupModel.pdf), ρ_b is not given explicitly but was calculated from soil porosity, *f*, according to the equation

$$\rho_b = (1 - f)\rho_s \tag{1}$$

where the particle density ρ_s was assumed to be 2.65 g cm^{-3}. The concentration of organic C (gC g dry soil^{-1}) was assumed to be 60% of soil organic matter content as given in the data base. The slope of the numerical covariate C concentration was significant and the model explained 75% of the variance. According to this analysis, we used the equation

$$f = 0.447 + 0.0252 * C\% \tag{2}$$

to estimate the porosity. From dry bulk density, C concentration and layer thickness we could calculate C stocks.

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, only approximate estimates of exported yields are known according to sale records received from the farm manager. For estimating C inputs into the soil we calculated allometric relationships between exported yields and other sinks of assimilated C. For cereals, straw production as estimated in a national survey (Anonymous, 1983) was related to regional averages of exported grain yield (Table 3). For rape and turnip rape straw production was set to 1.7 times exported seed yield which corresponds to a harvest index of 0.37 as reported by Petersen et al. (1995). For peas, we assumed the proportion of straw to be the same as for spring cereals. Carbon input in fallowed fields due to weed production was assumed to be 1 ton C per hectare and year, whereof 95% as input into the topsoil. For the few years when straw was exported, we assumed the proportion of stubble and harvest residues incorporated into the soil to 40% of total straw biomass according to estimates for barley (Pettersson, 1989) and winter wheat (Flink et al., 1995). When grass for seeds (timothy) was grown, straw was always exported and total topsoil C input was assumed to be 1.8 ton ha^{-1}. Carbon content in dry mass was assumed to be 45% for all organic input.

Estimates for below-ground C input were based on a recent review where data from different tracer experiments were analysed (Kuzyakov and Domanski, 2000). According to mean values presented in this review, 16% of total assimilated carbon in winter wheat ends up in root biomass, microorganisms and soil organic matter (excluding root respiration). This corresponds to 25% of net assimilated C or 32% of total shoot biomass C (Kuzyakov and Domanski, 2000). Similar values were reported for barley according to comprehensive field and laboratory studies in central Sweden (Andrén et al., 1990; Paustian et al., 1990). According to simulations, about 25% of rape gross primary production is allocated below ground (Petersen et al., 1995). In average over spring and winter rape this corresponds to 21% of net assimilated C or 71% of seed yield (Petersen et al., 1995). Corresponding proportions of C translocated below ground in grass leys are higher (Andrén et al., 1990; Paustian et al., 1990; Kuzyakov and Domanski, 2000). Since no perennial crops occurred in the cropping systems and detailed tracer studies for the other crops are not available as far as we know, we assumed the amount of C translocated below ground to be 32% of total shoot biomass for all other crops. Multiplication factors used to calculate C input from reported yield are summarised in Table 3.

The partitioning of below-ground production between topsoil (0-25 cm) and subsoil (below 25 cm) was assumed to be 70:30 for winter wheat according to a study in the same region (Kätterer et al., 1993). Corresponding ratios 80:20 and 90:10 were assumed for barley (Hansson and Andrén, 1987) and for grass ley (Kätterer and Andrén, 1999a), respectively. The values cited above for winter wheat were assumed to be valid for winter wheat and winter rye in our study and those for barley were used for barley, spring wheat, oats, peas, rape and turnip rape, and that for grass leys was used for timothy.

C input to the topsoil was assumed to be proportional to harvested yield (Table 3). For example, for a winter wheat dry matter yield of 7 ton grain ha^{-1}, 3.15 ton C was exported as grain yield, 4.88 ton was in straw and 2.58 ton C was translocated below ground, whereof 1.81 ton to 0-25 cm depth.

Statistical analyses

Paired two-sample Student's t-tests were applied to test differences in C concentration between years. This t-test does not assume that the variances of both populations are equal. Pooled variances (s^2) where calculated according to the formula

$$s^2 = \frac{n_1 s_1^2 + n_2 s_2^2}{n_1 + n_2 - 2} \qquad (3)$$

where n is the number of sampled grid points. A critical significance level of 5% was used in all tests.

Carbon balance

For each sampling point, input and output of carbon was balanced for the topsoil using the Introductory Carbon Balance Model (ICBM; Andrén and Kätterer, 1997), which was adapted to handle discontinuous annual input. SOC is divided into two pools, a ‘young’ pool (*Y*) consisting of recently added organic material and an ‘old’ pool (*O*) consisting of stabilized SOC. Outflows from both pools follow first-order kinetics with corresponding rate constants k_Y and k_O. External influences (mainly climatic, but also edaphic) are condensed into one parameter, r_e, which affects both decomposition rates equally. The parameter r_e does not affect the “humification coefficient” (*h*), i.e., the fraction of the outflow from *Y* that enters *O*.

The differential equations describing the state variable dynamics are:

$$\frac{dY}{dt} = -k_Y r_e Y \tag{4}$$

$$\frac{dO}{dt} = r_e\left(hk_Y Y - k_O O\right) \tag{5}$$

For correspondence with the original ICBM parameter settings, the model is continuous within a single year. Since soil sampling was conducted after harvest but before the incorporation of harvest residues and visible below-ground crop debris was discarded before milling of the soil samples, input (*i*) from year *T* is entering *Y* immediately after each discrete annual time step *T* and decomposes at the same rate as *Y*. Thus, each year *Y* is upgraded with input and thereafter, *Y* and *O* decompose continuously within that year, until *Y* is upgraded again one year later.

The equations describing the dynamics of the states are

$$Y_t = \left(Y_{T-1} + i_{T-1}\right)e^{-k_Y r_e t} \tag{6}$$

$$O_t = \left(O_{T-1} - h\frac{k_Y\left(Y_{T-1} + i_{T-1}\right)}{k_O - k_Y}\right)e^{-k_O r_e t} + h\frac{k_Y\left(Y_{T-1} + i_{T-1}\right)}{k_O - k_Y}e^{-k_Y r_e t} \tag{7}$$

where *T* is a positive integer (whole year) and *t* is a rational number ($0 \leq t < 1$; fraction of year).

Total SOC stocks are equal to the sum of *Y* and *O*:

$$SOC_t = Y_t + O_t \tag{6}$$

Model parameterisation

The initial values for Y in 1956 were set to 3 ton C ha^{-1} in all model calculations. The initial size of the O-pool was set as the difference between the measured C stock in 1956 and the initial value for Y. The value for parameter k_Y (=0.8) was set according to the original calibration of the model (Andrén and Kätterer, 1997).

The values for h and r_e were roughly adjusted to soil texture in the fields. Corresponding to the approximate 10% mean difference in clay content between the fields (Table 2), h was calculated according a regression proposed by Kätterer and Andrén (1999b), which resulted in a h of 0.112 for ÄNG and SKÄ and 0.125 for the MVG and GAT. According to our data base for Swedish agricultural soils, the water capacity, i.e., the difference between water content at field capacity and wilting point, is about 20% higher for loams than for clay loams. Assuming a direct proportionality between water capacity and r_e, the values 1.2 and 1.0 were used for SKÄ/ÄNG and MVG/GAT, respectively. Parameter k_O was estimated by minimizing the sum of differences between measurement and simulated amounts of SOC at each point in the sampling grid.

Results and discussion

Changes in soil carbon concentrations

Management changes in 1956 induced a decline in topsoil carbon concentrations in the two fields with relatively high initial C stocks, whereas those in the two fields with relatively low initial C stocks remained fairly constant (Figs. 1 and Table 4). Thus, the latter two fields seem to be close to steady state. Perennial leys and application of farmyard manure which positively affected the C balance of the soils before 1956 seemed to be compensated for by increasing inputs from crop residues as a consequence of an increase in crop productivity. Calculated inputs increased with time and were 50% higher during 1992-2001 than those during 1956-1965 (Fig. 2). In one field, GAT, this increased input resulted in a slight but not statistically significant increase in topsoil C between 1984 and 2001, after a significant decrease between 1956 and 1984 (Table 4). However, in the two fields with high initial C concentrations, the increase in intensity could not prevent a decrease in soil C. The name (Swedish for meadow) suggests that ÄNG was not tilled in earlier times and that its high initial C content was built up during a long time before 1956. Also in the field SKÄ, the reason for the relatively high initial C concentrations may be due to its history as a meadow. This field is situated lower in the landscape than the other fields and has hydromorphic features in the subsoil.

Subsoil C concentrations did not change significantly between 1956 and 2001 but differed between the fields (Table 5). As in the topsoil, C concentrations were lower in MVG and GAT than in ÄNG and SKÄ. However, contrary to the topsoil, subsoil C concentrations were higher in SKÄ than in ÄNG. This is probably due to the influence of a high ground water table which reduced the turnover rate of soil organic carbon in the subsoil.

Spatial variation

The spatial variation of C concentrations at one sampling point (3 soil cores) was considerably lower than that within one management unit. For single sampling points, the coefficient of variation (CV; standard deviation/mean) was 2.6-3.6% for the topsoil and 2.2-16% for subsoil in 2001. Corresponding CVs for the management units in 2001 varied between 3.5 and 20% in the topsoil and between 6.8 and 21% in the subsoil (Tables 4 and 5). It is interesting to note that the mean variation of topsoil carbon within the eight management units decreased significantly with time (paired two sample t-test), i.e., from 11% in 1956 to 7.3% in 2001. CV in 1984 was intermediate at 10%, and was not significantly different from those in 1956 and 2001. We suggest that this could be due to patchy application of manure and possibly crop residues until 1956 and more homogenising management methods (tractors instead of horses, tile drainage etc.) during recent decades.

Soil carbon dynamics

For calculating soil C mass per unit area, layer thickness and bulk density (ρ_b) are needed. Bulk densities as estimated from the Swedish soil data base were used here. For the whole range of C concentrations in the management units considered here, i.e., from 1.8 to 3.4%, the corresponding values for ρ_b varied between 1.35 and 1.24. The resulting calculated topsoil C mass in each management unit is presented in Fig. 3 and the corresponding k_O resulting in the best model fit are presented in Table 6. The k_O estimated for each individual sampling point differed significantly between the two fields with high and those with low initial C content but differences between management units within the four fields were not significant. The range of mean values for k_O varied between 0.0039 and 0.0079 for the eight management units (Table 6) with an overall mean of 0.0062 and a CV of 34%, which is similar to k_O (= 0.006) in the original model calibration for a long-term field experiment (Andrén and Kätterer, 1997).

So far we assumed that all factors that were not considered in the simulations are due to k_O, i.e., the decomposability of ‘old’ SOM. However, there might be several factors that have contributed to the relatively wide range of estimated k_O -values. All assumptions made to estimate i, r_e and h can be questioned, and sampling accuracy and carbon analysis were sources of variation.

Siddique (1989) found higher ear/stem ratios in modern hexaploid wheat than in old varieties. On the contrary, recent studies on diploid, tetraploid and hexaploid varieties of wheat and barley have shown that plant dry matter partitioning between roots, leaves, ears and stems seems to be very conservative and has probably not changed during the domestication of wild species (Wacker et al., 2002). Nevertheless, the partitioning of plant C may have been affected by fertilization, climatic/soil conditions or efficiency of combine harvesters and yield records provided by the farmer may be erroneous. These factors were not included in our allometrical functions for calculating C input to the soil.

Compared with C concentration determined by modern high-temperature dry combustion methods (Carlo-Erba, Perkin-Elmer or LECO analyzer), the amount of C determined by wet oxidation methods has usually to be multiplied by a correction factor (Nelson and Sommers, 1996). For the first two samplings in our study, a wet combustion method using the manometric Van Slyke-Neil apparatus had been used (Jansson and Valdmaa, 1961). In the same paper, Jansson and Valdmaa compared this method with a dry combustion method and showed that C determined by the two methods followed a 1:1 line. According to our experience, which is based on many comparisons between the two methods used in this paper, we judge this to be a minor source of bias in the C analysis of Swedish agricultural soils.

Precipitation and air temperature may be assumed to be identical at the farm scale, so these external variables should only indirectly affect the decomposition rates. The amount of water that can be retained against gravity in a certain volume of soil generally increases with its carbon content (e.g. Rawls et al., 2003). Thus, it is reasonable to assume that soil moisture is less often limiting for decomposers in a soil with high C content than in one with low C content. In this study, only a textural effect on r_e was accounted for (Table 6). Formulating r_e as a function of soil C would result in higher order kinetics of the model pools. This would imply that r_e-values were initially higher in ÄNG and SKÄ than 1.2, where after they would gradually decrease with decreasing C content and approach this value when the C stocks in these fields approach those in MVG and GAT. Consequently, higher r_e-values would have resulted in lower k_O -values in the former fields and thus narrowed the range of estimated k_O-values.

It is often observed that decomposition rates are lower in fine-textured soils than in coarse-textured soils (Verberne et al., 1990). This may be due physical protection of soil organic material in aggregates (Hassink et al., 1997) and/or chemical sorption to mineral surfaces (Kaiser and Guggenberger, 2000). Hassink (1997) hypothesised that the amount of organic material that can be stabilized through association to clay and silt particles is limited, which means that decomposition proceeds at a higher rate above a certain critical soil carbon content. This “clay” effect was considered by assuming lower values for h in the two fields with lower clay content (Table 6) but its dynamic nature, i.e., its dependence on actual soil C, was not.

The implementation of the feedbacks of C on both k_O and h discussed above, would have altered the dynamics of simulated C and narrowed the range of estimated k_O -

values. However, intrinsic differences in the quality distribution of SOM would still remain due to differences in input quality and quantity before 1956. Assuming that the differences in field history before 1956 will be of minor importance for the future development of C stocks at this farm, we calculated the C stocks at steady state using the average k_O (=0.006) and the average i (=3.5 ton C ha^{-1} year^{-1}) over all fields during the period 1992-2001. The resulting C stocks were 58 ton C ha^{-1} in the fields MVG and GAT and 77 ton C ha^{-1} in the fields and ÄNG and SKÄ. This corresponds to C concentrations of about 1.8 and 2.4%, respectively, which are reasonable estimated when compared with the average C concentrations of 2.3% in agricultural mineral topsoils in the county of Västmanland (Eriksson et al., 1997).

We know very little about the changes in decomposability of SOM along with soil depth. According to the allometric functions presented here, the C input to the subsoil is about 0.25 ton ha^{-1} year^{-1}. Using the same settings for h, r_e and k_y as for the topsoil, k_O would have to be about one order of magnitude lower for the subsoil (25-60 cm) than for the topsoil (0-25 cm) to maintain steady state, which is about 45 ton C ha^{-1}, corresponding to a concentration of about 1% C. In a laboratory comparison between an agricultural top- and subsoil, we found that the respiration per g C in the subsoil was about 2.5 of that in the topsoil (Lomander et al., 1998a,b), so the calculated difference seems too high. However, a lower r_e due to lower oxygen pressure etc. would increase steady-state k_O, and a major source of uncertainty is the assumed C input to the subsoil, both its quantity and quality. We simply do not have enough knowledge about subsoils, and this is an area where major efforts are needed if we are going to be able to describe and project the fluxes. For the topsoils, the approach and data sets used here seems to work reasonably well, although the precision can be improved.

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Tables

Table 1. Crop frequency (years of a total of 46 years) in the fields and corresponding management units between 1956 and 2001. Number of years when crops were grown on about half of the management unit is shown in parenthesis

Crop	Crop frequency							
	ÄNG		MVG		GAT	SKÄ		
	Ängen Ö	Ängen V	Mjölkväg	Gatan V	Gatan Ö	Sären N	Skären M	Skären S
Barley	12	12	7	6	9	10	12	11
Oats	11	12	13	8	13	12	15	13
Winter wheat	10(2)	9	9	9	5	4	5	4
Winter rye	0	0	0	0	0	2	1	1
Rape	3	3	1	0	3	3	2	3
Turnip rape	(2)	4	3	3	2	3	3	3
Timothy	1	0	4	9	3	0	0	2
Fallow	(1)	1	2	2	0	3	2	3
Spring wheat	5	3	6	7	9	8	6	6
Peas	1(1)	1	1	1	2	1	0	0

Table 2. Field area (ha), clay content (%), pH and P, K and Mg concentrations (µg/g dry soil measured in buffered ammonium lactate extracts) determined in 1999

Field	Area	Clay	pH	P-AL	K	Mg
SKÄ	14	15-25	6.2	62	260	580
ÄNG	13	15-25	6.4	23	240	450
MVG	7	25-40	6.3	52	300	400
GAT	4	25-40	6.4	54	260	490

Table 3. Multiplication factors (x reported yield) used to calculate straw dry mass at harvest including all above-ground harvest residues, total below-ground input and topsoil below-ground input relative to exported grain yield. For cereals, straw mass was calculated from regional average yields according to a national survey conducted in 1982 (Anonymous, 1983; n=6 regions for wheat and rye and n=8 regions for barley and oats; standard deviation in parenthesis)

Crop	Straw		Total	Topsoil
Barley	1.21	(0.120)	0.71	0.57
Oats	1.50	(0.197)	0.80	0.64
Winter wheat	1.55	(0.079)	0.82	0.57
Winter rye	1.66	(0.171)	0.85	0.60
(Turnip) Rape	1.7		0.71	0.57
Spring wheat	1.46	(0.124)	0.79	0.57
Peas	1.4		0.77	0.61

Table 4. Carbon concentrations in topsoil (0-25cm), coefficient of variation (CV; standard deviation relative to mean in percentage) and number of samples (*n*) per management unit and field. Different character superscripts indicate significant differences between years within the same field according to paired t-tests (p<0.05)

Field	Management unit	1956			1984			2001		
		C%	*CV*	*n*	C%	*CV*	*n*	C%	*CV*	*n*
ÄNG										
	Ängen Ö	3.36^a	15	32	2.81^b	8.9	17	2.67^c	9.4	32
	Ängen V	3.04^a	8.9	15	2.85^b	6.0	10	2.54^c	5.9	15
MVG										
	Gatan V	2.03^a	7.9	11	2.07^a	8.7	7	2.05^a	5.9	11
	Mjölkväg	1.83^a	23	18	1.76^a	19	9	1.95^a	20	18
GAT										
	Gatan Ö	2.01^a	11	18	1.91^b	6.8	7	1.94^{ab}	5.7	18
SKÄ										
	Skären N	2.78^a	14	10	2.18^b	27	5	2.19^b	4.1	10
	Skären M	2.49^a	4.8	12	2.18^b	4.1	6	2.02^c	3.5	12
	Skären S	2.41^a	6.6	8	2.09^b	1.0	4	1.95^c	3.6	8

Table 5. Subsoil carbon concentrations (25-60 cm), coefficient of variation (CV; standard deviation relative to mean in percentage) and number of samples (*n*) per field. Different superscript characters indicate significant differences between years within the same field according to paired t-tests ($p<0.05$)

Field	n	1956		1984		2001	
		C%	CV	C%	CV	C%	CV
ÄNG	4	1.02^{ab}	27	1.06^{a}	12	0.94^{b}	18
MVG	1	0.62	*	0.51	*	0.60	*
GAT	3	0.97^{a}	23	0.83^{ab}	24	0.67^{b}	27
SKÄ	2	1.17^{ab}	10	1.10^{b}	8.2	1.18^{a}	6.8

*only one sample

Table 6. Estimated average annual C input (i; ton C ha^{-1}), number of soil sampling points (n), soil climate factor (r_e), humification coefficient (h) and k_O-values resulting in the best fit between measured and simulated mean C stocks per management unit (k_O mean) and averages for simulations at each sampling point (k_O indiv) within the corresponding management unit (CV = standard deviation relative to mean in percentage). Values with the same superscript letter were not significantly different according to multiple two-tailed t-tests ($p<0.05$)

Field	Management unit	i	n	r_e	h	k_O mean * 10^{-4}	k_O indiv * 10^{-4}	CV
ÄNG								
	Ängen Ö	3.15	32	1.2	0.112	69	66^{ab}	26
	Ängen V	3.05	15	1.2	0.112	53	55^{bc}	20
MVG								
	Gatan V	2.71	11	1.0	0.125	43	39^{d}	54
	Mjölkväg	2.85	18	1.0	0.125	51	50^{cd}	60
GAT								
	Gatan Ö	3.11	17	1.0	0.125	68	66^{ab}	26
SKÄ								
	Skären N	3.09	10	1.2	0.112	85	73^{a}	16
	Skären M	3.14	12	1.2	0.112	74	75^{a}	13
	Skären S	3.08	8	1.2	0.112	76	79^{a}	14

Figure captions

Figure 1. Changes in topsoil carbon concentration between 1956 and 2001 as a function of C concentration in 1956.

Figure 2. Annual topsoil C input (average over all fields) calculated from yield records using allometric functions (Table 3).

Figure 3. 'Measured' (symbols, per management unit) and simulated (lines) topsoil C stocks (0-25 cm depth) in eight management units within four fields. 'Measured' amounts of C were calculated from measured C concentrations and calculated bulk densities (see text). Note that the Y axis scale differs between fields. See table 4 for statistics and table 6 for values of the values of the fitting parameter (k_O mean).

Fig.1. Kätterer et al.

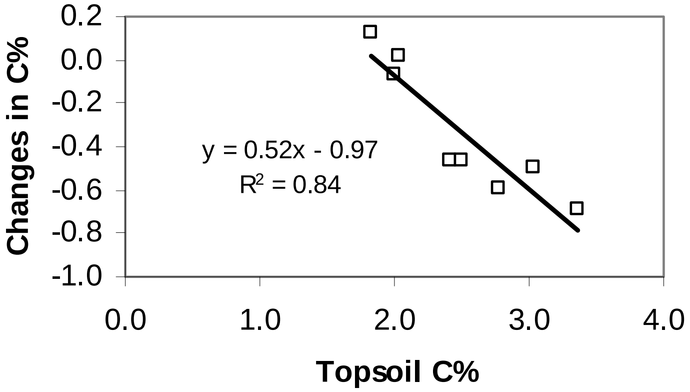

Fig. 2. Kätterer et al.

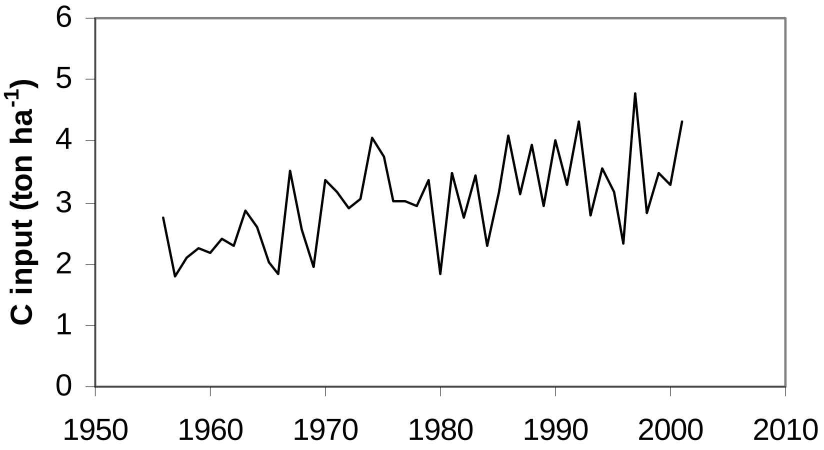

Fig. 3. Kätterer et al.