

Long-term effects of crop rotations with and without perennial leys on soil carbon stocks and grain yields of winter wheat

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Abstract A change from cultivated land to grassland generally increases soil organic matter (SOM) content and is a potential option to mitigate greenhouse gas emissions. We investigated the effects of two-year perennial grass and mixed grass/legume leys in a six-year crop rotation on topsoil (0–0.25 m depth) carbon content and on grain yields of winter wheat over a period of 31 years. Different nitrogen fertilisation regimes were included and no manure was added to the experimental plots. We used data from long-term crop rotation experiments at three sites in southern Sweden: Säby (59°49' N/17°42' E), Lanna (58°20' N/13°07' E) and Stenstugu (57°36' N/18°26' E). At Säby, the reduction in topsoil carbon content was smaller in the ley crop rotations than in the crop rotation with only annual crops. There were no statistically significant effects of crop rotation on topsoil carbon at the other two sites. At Lanna, the grain yield increase in winter wheat over time was

higher in the mixed legume/grass ley crop rotation than in the other two rotations. Together, these effects of ley on topsoil carbon and winter wheat yield suggest that replacing annual crops with leys in the crop rotation could reduce losses of soil carbon without decreasing total yield of annual crops on a regional scale. We also applied the Introductory Carbon Balance Model (ICBM) to simulate topsoil carbon content at the three sites. Based on the results, measures to improve the model predictability are proposed.

Keywords Annual crops · Carbon sink · ICBM · Mineral fertiliser · Nitrogen · Soil carbon reduction · Two-year ley

Introduction

A number of empirical investigations (Cuvardic et al. 2004; Singh et al. 1998) and modelling approaches (Andrén and Kätterer 1997; Hyvönen et al. 1996; Powlson et al. 1996) have shown that land use and management practices affect soil organic carbon content. The possibility of using soil carbon sequestration to decrease atmospheric carbon dioxide has been extensively investigated (Bruce et al. 1999; Conant et al. 2001; Lal et al. 1999; Sperow et al. 2003). This can be achieved by e.g. reduced tillage, a decrease in fallow harrowing operations and increased use of cover crops in annual cropping

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(Sperow et al. 2003). Conversion from cultivated land to perennial grassland has also been shown to increase soil carbon stocks (Conant et al. 2001), whereas cultivation of native soils normally results in a decline in soil carbon content (Paustian et al. 1997).

The inclusion of perennial leys in crop rotations is regarded as an important tool to increase soil fertility due to the positive effect of leys on soil organic matter (SOM) (Paustian et al. 1997). A positive effect of rotational leys on yield quantity and quality of subsequent annual crops has also been found in experiments where high doses of mineral N fertilisers were applied (Uhlen et al. 1994). The positive effects of leys on SOM relative to continuous annual cropping is mainly due to the associated reduction in tillage and the change in the amount and distribution of carbon input to soils (Paustian et al. 1997). However, in many studies demonstrating that perennial grasslands (Conant et al. 2001) and rotational leys (Paustian et al. 1997) have an absolute or relative positive effect on soil carbon content compared with continuous annual cropping, more manure had been applied to the grassland system than to the control system. This coincidence of grassland or ley cultivation and manure application in field experiments is due to the fact that in practical farming, grasslands and leys are normally associated with dairy, beef cattle or sheep rearing, which produces manure (Conant et al. 2001). Since manure itself has a positive impact on SOM (Jenkinson and Johnston 1977; Persson and Kirchmann 1994), it is difficult to distinguish the direct effects on soil carbon content of changing from annual to perennial crops from the effects of manure application. It is largely unknown whether short rotational leys per se can turn arable land into a carbon sink, or whether their positive effects on soil carbon balances are due to the associated application of manure or other organic amendments. Quantification of the direct long-term effects of perennial leys receiving no or only negligible amounts of manure on SOM is therefore essential in evaluating the use of arable land as a carbon sink to mitigate greenhouse gas emissions. In addition, investigating the effects of perennial leys on the yield of annual crops would provide information about the scope of replacing annual crops with perennial crops within a region, without decreasing the total overall crop yield. Higher yields of annual

crops would mean that the need for arable land assigned to growing these crops could decrease, given constant demand over time. Thus, relative positive effects on soil carbon compared with the effects of crop rotations without perennial crops and positive effects on yields of subsequent annual grain crops would have a synergetic effect on the potential to reduce emissions of carbon dioxide by crop rotation planning.

The objectives of this study were (i) to quantify the long-term effects of leys within arable crop rotations on the topsoil carbon balance, (ii) to test whether a simple soil carbon model previously calibrated for a Swedish long-term field experiment [Introductory Carbon Balance model (ICBM); (Andrén and Kätterer 1997)] could describe the effects of crop rotations and N fertiliser on long-term topsoil carbon content on a regional scale and (iii) to determine whether two-year ley periods within crop rotations have a positive long-term effect on grain yields of winter wheat.

Materials and methods

Experimental description

Soil and crop data from three long-term crop rotation experiments in southern Sweden: Säby (59°49' N/17°42' E), Lanna (58°20' N/13°07' E) and Stenstugu (57°36' N/18°26' E) were used in the analyses. Mean air temperature, annual precipitation and soil texture classes are presented in Table 1. The experiments at Lanna, Stenstugu and Säby were started in 1965, 1968 and 1969, respectively. The original objective of the experiments was to study the effects of two-year leys on yields of crops in the rotations under different nitrogen fertilisation regimes (Wallgren and Rådberg 1989). The experiment has a split-plot design at Säby and Lanna, with crop rotation as main plots and N doses as sub-plots. At Stenstugu, the experiment is arranged as a strip-plot with crop rotation in columns and N doses in rows (Gomez and Gomez 1984). All crops are included each year in adjacent blocks. Thus, there are as many replicates as there are crops in the rotation. However comparisons can only be made over time, since each block is in a different position in the rotation.

Table 1 Thirty-year (1961–1990) annual mean temperature and precipitation at the nearest weather station with available 30-year means, soil texture and soil organic matter content (SOM) at the experimental sites

	Säby	Lanna	Stenstugu
Temperature (°C)	5.3 ^a	6.0 ^b	6.6 ^c
Precipitation (mm)	565 ^a	558 ^b	513 ^c
Texture class ^d	Silt loam	Silty clay loam	Loam
Clay (%)	23.0	35.0	21.0
Silt (%)	53.0	49.0	31.0
Sand (%)	20.0	11.8	45.2
SOM (%)	4.0	4.2	2.8

^a Ultuna, Swedish University of Agricultural Sciences (SLU)

^b Lanna, SLU

^c Visby, Swedish Meteorological and Hydrological Institute (SMHI)

^d Classification of soil particle size according to the International Society of Soil Science

Crop data

Three crop rotations (A–C) that differ in 2 years out of six are being compared in the experiments (Table 2). The oilseed crops were initially winter turnip rape at Säby and winter oilseed rape at the other sites, but due to problems with winter survival of rape, spring oilseed rape has been grown at Lanna and Säby in latter years. In the occasional years with poor winter survival of wheat, the plots are spring harrowed and sown with spring wheat. The long-term effect of different crop rotations on grain yield of

winter wheat was analysed in the present study. The winter wheat crop was used for these yield comparisons because it had the same preceding crop and was equally fertilised in all rotations and because there were few wheat crop failures.

Four levels of mineral nitrogen fertiliser (N0, N1, N2 and N3) are included in sub-plots at Säby and Lanna and as a row factor at Stenstugu (Table 2). No manure has been applied since 1970. During a crop rotation, phosphorous (72 kg ha⁻¹) and potassium (137 kg ha⁻¹) are added to the oilseed crops and the undersown barley in rotations A and B (78 kg P ha⁻¹; 278 kg K ha⁻¹) and to the barley in rotation C (72 kg P ha⁻¹; 137 kg K ha⁻¹). In the first year of the experiments, cereal and oilseed straw was removed after harvest. Since 1971, straw is only removed in the barley crops with undersown leys in crop rotations A and B. The straw is ploughed under after all other annual crops (Wallgren and Rådberg 1989). The choice of cultivar is conservative, i.e. changes are made only when a cultivar is no longer in use in practical farming. Pesticides are applied according to recommendations for practical farming and according to the occurrence of pests and weeds (Wallgren and Rådberg 1989).

Soil data and calculations

The soil texture at the experimental sites is loam, silt loam or silty clay loam (Table 1). Topsoil (0–0.25 m depth) samples were analysed for carbon after oats in

Table 2 Crop rotations and nitrogen fertilisation treatments

Year	Crop rotation A		Crop rotation B		Crop rotation C	
	Crop	N-fertilisation (kg ha ⁻¹) ^a	Crop	N-fertilisation (kg ha ⁻¹)	Crop	N-fertilisation (kg ha ⁻¹)
1	Oilseed crop	N0 = 0; N1 = 60; N2 = 120; N3 = 180	Oilseed crop	0; 60; 120; 180	Oilseed crop	0; 60; 120; 180
2	Winter wheat	0; 45; 90; 135	Winter wheat	0; 45; 90; 135	Winter wheat	0; 45; 90; 135
3	Spring oats	0; 40; 80; 120	Spring oats	0; 40; 80; 120	Spring oats	0; 40; 80; 120
4	Spring barley, undersown ley	0; 60; 60; 60	Spring barley, undersown ley	0; 60; 60; 60	Spring barley	0; 40; 80; 120
5	Red clover/grass ley	0; 0–80; 0–160; 0–240 ^b	Grass ley	0; 45 + 35; 90 + 70; 135 + 105	Spring wheat	0; 60; 120; 180
6	Red clover/grass ley	0; 0–45; 0–90; 0–135 ^b	Grass ley	0; 45; 90; 135	Black fallow	No fertilisation

^a The N0 treatment was fertilised with 30 kg ha⁻¹ before sowing of grass leys and oilseeds to facilitate the establishment of these crops

^b The N fertilisation was based on the percentage of legume crops; the higher the percentage of legumes, the lower the N fertilisation

the high-N (N3) and low-N (N1) treatments. Since 1975, total carbon has been analysed according to the LECO method (Anonymous 1997). In this study, carbon concentrations were converted to carbon mass per unit area by assuming a soil bulk density of $1,300 \text{ kg m}^{-3}$, which is a normal value for mineral soil in Sweden (Kirchmann et al. 1994). We used the same bulk density for all three crop rotations based on results from an experiment at Ultuna, close to Säby, where the bulk density was not significantly lower after almost 50 years with an eight-year rotation that included a two-year ley and animal manure than after a rotation with only annual crops (Bergkvist unpublished). The topsoil layer was set to 0.25 m, which corresponds approximately to the depth of ploughing and sampling.

Statistical analysis of soil carbon and grain yields of winter wheat

Soil carbon data for the years after 1975 were analysed separately for each site. Plot was included in the model as a normal distributed random variable and year as a continuous variable in the MIXED procedure of SAS (Littell et al. 1996). The model included crop rotation, N-level, year and all interactions. The purpose of the model was to determine whether there were significant differences in the rate of change of soil carbon content over the years depending on crop rotation and/or nitrogen application. Such interactions were considered to motivate the use of the experimental data to calibrate parameters in the ICBM for the variables investigated. Data from almost all experimental years between 1975 and 2005 (some data were missing) were used to analyse the effect of crop rotation level of nitrogen fertilisation on the rate of change in carbon input over time using the same procedure in SAS. Mean carbon inputs were compared using LSMEANS. All available data from the start of the experiments until 2005 were used to analyse the rate of change of winter wheat grain yields over time.

Description of the carbon model

The Introductory Carbon Balance model (ICBM) (Andrén and Kätterer 1997) has previously been

applied to describe management effects on soil carbon stocks in different agricultural soils in northern Europe (Kätterer and Andrén 1999). ICBM is a minimum soil carbon model where the soil carbon is divided into the two pools Young (Y; kg m^{-2}) and Old (O; kg m^{-2}). The model is described in the following two analytically solvable equations:

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

and

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

where i (kg m^{-2}) is the carbon input to the soil, k_Y (yr^{-1}) and k_O (yr^{-1}) are rate constants determining decomposition of Y and O carbon pools respectively, h is a humification coefficient determining the fraction of Y that becomes stabilised and enters O and r_e is a rate modifier describing other environmental effects on k_Y and k_O (Andrén and Kätterer 1997; Kätterer and Andrén 1999).

Estimation of carbon input

Both above- and below-ground sources of carbon input were considered. The carbon concentration was assumed to be 450 mg g^{-1} dry matter in all material, in accordance with Kätterer and Andrén (1999). The carbon input from bare fallow was set to 0, which due to weed occurrence during periods between weed treatments was a slight underestimation. However, no data were available on weed biomass in the fallows. Straw biomass was measured in most, but not all, years during the experimental period. Harvest index was calculated by regressing straw mass on grain yield. We subsequently used the regression to calculate the above-ground input from cereals and oilseed rape for all years. In the plots where straw was exported, input, representing stubble, weeds and spillage from harvest, was set to 35% of the calculated straw mass (Pettersson 1989).

The above-ground carbon input from first-year mixed legume/grass leys and grass leys was assumed to be 30% of estimated total above-ground production. This fraction represents a non-harvested stubble fraction and biomass re-growth between the second harvest and the end of the growing season. The carbon input during the second year of ley cultivation was assumed to be 30% of the yield at the first

harvest plus a fraction corresponding to the ratio between the first and second harvest in year 1. The latter fraction is based on the assumption that the growth from first harvest until ploughing of the ley was the same as between first and second harvest in year 1.

No observations on below-ground biomass were available. Instead, the below-ground fraction for annual crops was set at 0.17 of total biomass as reported for spring barley (Paustian et al. 1990) under similar environmental and nutritional conditions. Thus, possible differences in shoot/root ratios among annual crops in the crop rotations were not accounted for. Below-ground input from timothy and meadow fescue was set to 31% of ley production according to field investigations of the latter species in central Sweden (Hansson and Andrén 1986) and to 36% for legume crops as determined for lucerne (Pettersson et al. 1986). The estimated below-ground input in rotation A varied between 0.31 and 0.36 due to variations in the legume fraction (unpublished data). It was assumed that nitrogen fertilisation did not change the shoot/root ratio. Only a few grain and ley yield measurements were missing in the data set. In these cases, input was set as the mean of the calculated inputs from 1975 to 2006 for each crop and nitrogen fertilisation treatment.

Model parameterisation

Differences in climate and soil type between the three experimental sites were accounted for according to the concept proposed by Andrén et al. (2004). We used daily weather data for the period 1970–2006 from nearby meteorological stations and soil type to calculate mean annual r_e -values for each site. The r_e -values were adjusted for cereal crops according to Bolinder et al. (2007).

Table 3 Parameters in the Introductory Carbon Balance Model (ICBM)

Parameter name	Symbol	Value	Unit	Source ^a
Initial young C pool	Y_0	0.3	kg m ⁻²	1
Initial old C pool	O_0	Varying	kg m ⁻²	Measured C— Y_0
Humification coefficient	h	0.125	–	2
Decomposition rate young pool	k_Y	0.8	yr ⁻¹	2
Decomposition rate old pool	k_O	0.006	yr ⁻¹	2
External response factor	r_e	Site-specific	–	3

^a (1) Kätterer and Andrén (1999); (2) Andrén and Kätterer (1997); (3) Andrén et al. (2004)

Total initial topsoil carbon was set according to the earliest measurement in each plot from 1975. The initial size of the young pool (Y_0) was set to 0.3 kg m⁻² at all sites according to previous studies (Andrén and Kätterer 1997; Kätterer and Andrén 1999) and that of the old C pool (O_0) was set as the difference between total C and Y_0 . The other parameters (Table 3) were set according to the original calibration of the model to a long-term spring cereal field experiment in Sweden (Andrén and Kätterer 1997).

Results

Grain yields of winter wheat

The effect of N fertiliser on the grain yield of winter wheat increased significantly over time ($p < 0.0001$) at both Lanna and Stenstugu (Fig. 1a, c), but not at Säby (data not shown). There was practically no yield change with N0 at any of the sites. The increase in yields was larger ($p < 0.03$) in the A rotation at Lanna than in the other rotations (Fig. 1b). However, no effect of the crop rotation on the rate of yield increase over time could be found at Stenstugu (Fig. 1d) and Säby (data not shown).

Carbon input

The carbon input did not change differently over time depending on crop rotation or N fertiliser dose at any of the sites. The calculated annual input of carbon in the C rotation at the three sites was only about half that in the A and B rotations. The carbon input was up to 50% larger for the N3 treatment than the N1 treatment and the relative differences in carbon input between N treatments were larger in the B and C rotations than in the A rotation (Table 4).

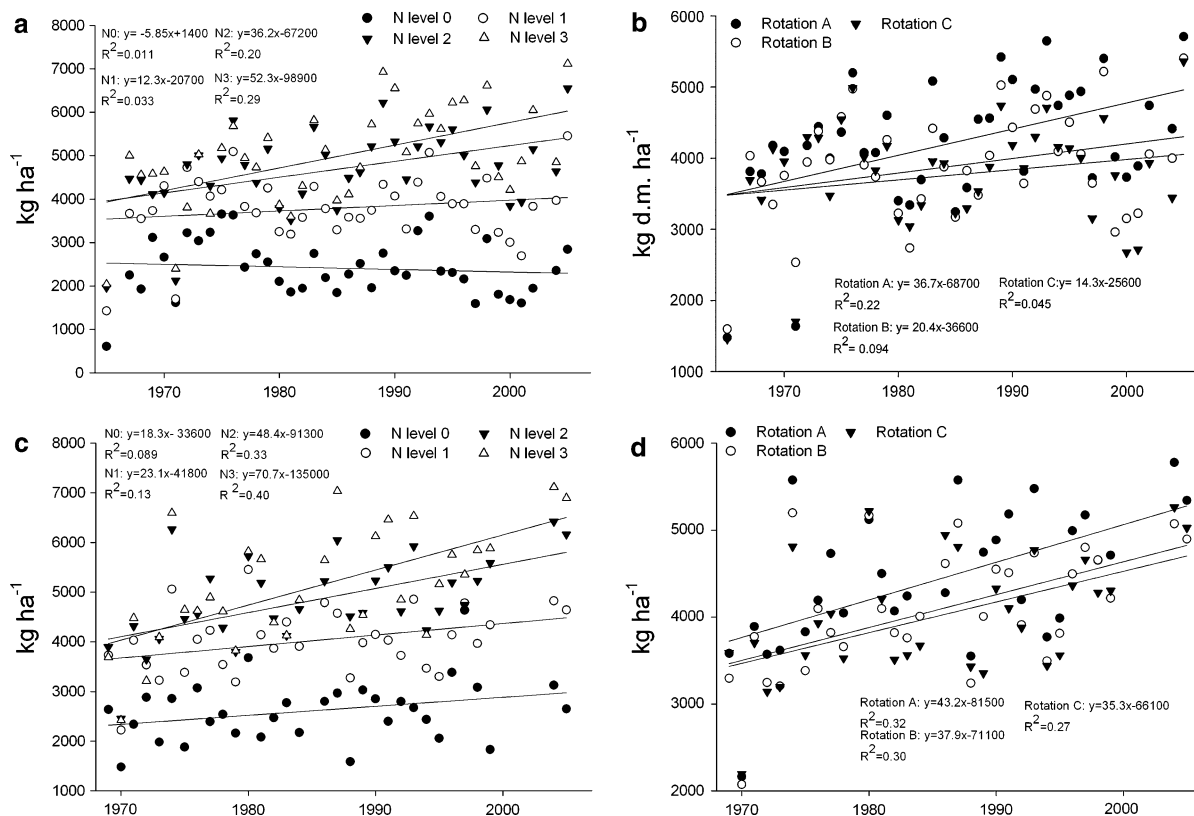


Fig. 1 Dry matter grain yields of winter wheat at Lanna (a, b) and Stenstugu (c, d) as affected by N dose (a, c) and crop rotation (b, d). Abbreviations are explained in Table 2

Table 4 Mean total carbon input (kg C m⁻² yr⁻¹) (±standard error of the mean) 1975–2006

Crop rotation	Säby		Lanna		Stenstugu	
	N1	N3	N1	N3	N1	N3
A	0.34 (0.022)	0.37 (0.024)	0.34 (0.023)	0.36 (0.022)	0.36 (0.025)	0.42 (0.029)
B	0.34 (0.024)	0.42 (0.030)	0.30 (0.022)	0.44 (0.031)	0.32 (0.023)	0.43 (0.029)
C	0.16 (0.0068)	0.21 (0.0090)	0.14 (0.0058)	0.20 (0.0085)	0.16 (0.0068)	0.22 (0.0092)

Soil carbon

The carbon content in the soil at Säby gradually decreased in all treatments between 1975 and 2006 (Fig. 2). The rate of decline was lowest in the rotations with leys and differed significantly between treatments. There was also a significant ($p = 0.0003$) interaction between crop rotation and year. However, the amount of N applied did not significantly affect the rate of change. At Lanna and Stenstugu, there was only one observation available after 1992 (2006), which makes the analyses weak, and no statistical

differences were found in the rate of change in soil carbon content between treatments at these two sites.

Model application

The r_e -value, which includes the effects of climate, soil texture and crop, was 1.07 at Säby, 1.08 at Stenstugu and 0.97 at Lanna. During the study period, a ± 0.1 change in r_e resulted in changes in simulated topsoil carbon of 0.07–0.15 kg m⁻². Using the calculated r_e -values, the model resulted in both

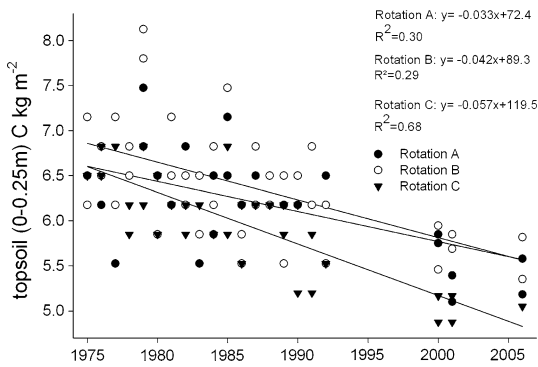


Fig. 2 Topsoil carbon at Säby. Changes over years for each rotation

decreases and increases in topsoil carbon depending on initial topsoil carbon and carbon input. The simulated topsoil carbon represented a general underestimation of the topsoil carbon decrease at all three sites. The model also underestimated topsoil carbon decrease across all crop rotations and both nitrogen fertilisation levels (N1 and N3). The model prediction (R^2) tended to be higher in the Lanna simulation than in the other two simulations across crop rotations and nitrogen fertilisation levels. Crop rotation did not have any clear effect on the model prediction at any of the simulated sites or nitrogen fertilisation levels. However, the fit between simulated and observed topsoil carbon was better in the N1 treatments than in the N3 treatments (Fig. 3a–f).

Discussion

The higher increase rate in winter wheat yields in crop rotation A than in the other two crop rotations at Lanna illustrates how the planning of crop rotations can be used to increase grain yields of annual crops in the long term. At Säby, winter wheat yields were negatively affected by higher water tables during the 1990s, which might explain why there were no statistically significant differences in grain yield increase over time between nitrogen fertilisation level and crop rotation at this site. The general increase in wheat yield observed in all fertilised treatments is in line with the general trend in grain yield increases during the period, which has often been regarded as being the result of crop breeding (Foulkes et al. 2007) and better farm management practices.

The lower content of soil carbon in the crop rotations without ley at Säby compared with those with ley could be expected from previous studies, in which cultivation of perennial grasslands and leys resulted in higher soil carbon content than in crop rotations only including annual crops (Paustian et al. 1997; Uhlen et al. 1994). The higher topsoil carbon mass in crop rotations that include perennial leys is probably a result of larger carbon input and decreased tillage, which promote the accumulation of soil carbon (Paustian et al. 1997). Our results show that two-year leys can have a positive effect on soil carbon content, even though, unlike in most previous experiments (Conant et al. 2001; Paustian et al. 1997), these leys were not accompanied by manure applications. The decrease in topsoil carbon at Säby also corresponds well with the calculated carbon inputs, which were lowest in the C rotation. However, unlike the results of Clement and Williams (1964), in which an absolute increase in soil carbon due to four years of pasture was reported, the carbon content in the soils included in our study also decreased in the crop rotation that included a perennial ley. These contrasting results could be at least partly due to the lack of manure application. However, other factors may also explain why the ley rotation could not contribute to increasing soil carbon content, but only slow the decrease, at Säby. First, a higher proportion of leys in the rotation would probably have resulted in higher soil carbon content. Second, farm history may have influenced the effects of crop rotations on soil carbon content. Kätterer and André (1999) found that the initial topsoil carbon pool as a result of farm history in terms of e.g. frequency of perennials and manure applications has a great effect on the change in soil carbon content after farm practices have changed. Unfortunately there are no details available about crop rotations in the fields included in our study before the 1960s. However, it is probable that the crop rotations at the experimental sites, like virtually all fields in Sweden during the first half of the 20th century, included perennial leys and also manure applications, which would have been beneficial to the soil carbon content. Long-term effects of leys on carbon content may be different in soils that have a long history of only annual cropping and no manure application.

The lack of statistically significant differences among crop rotations with and without leys at two of

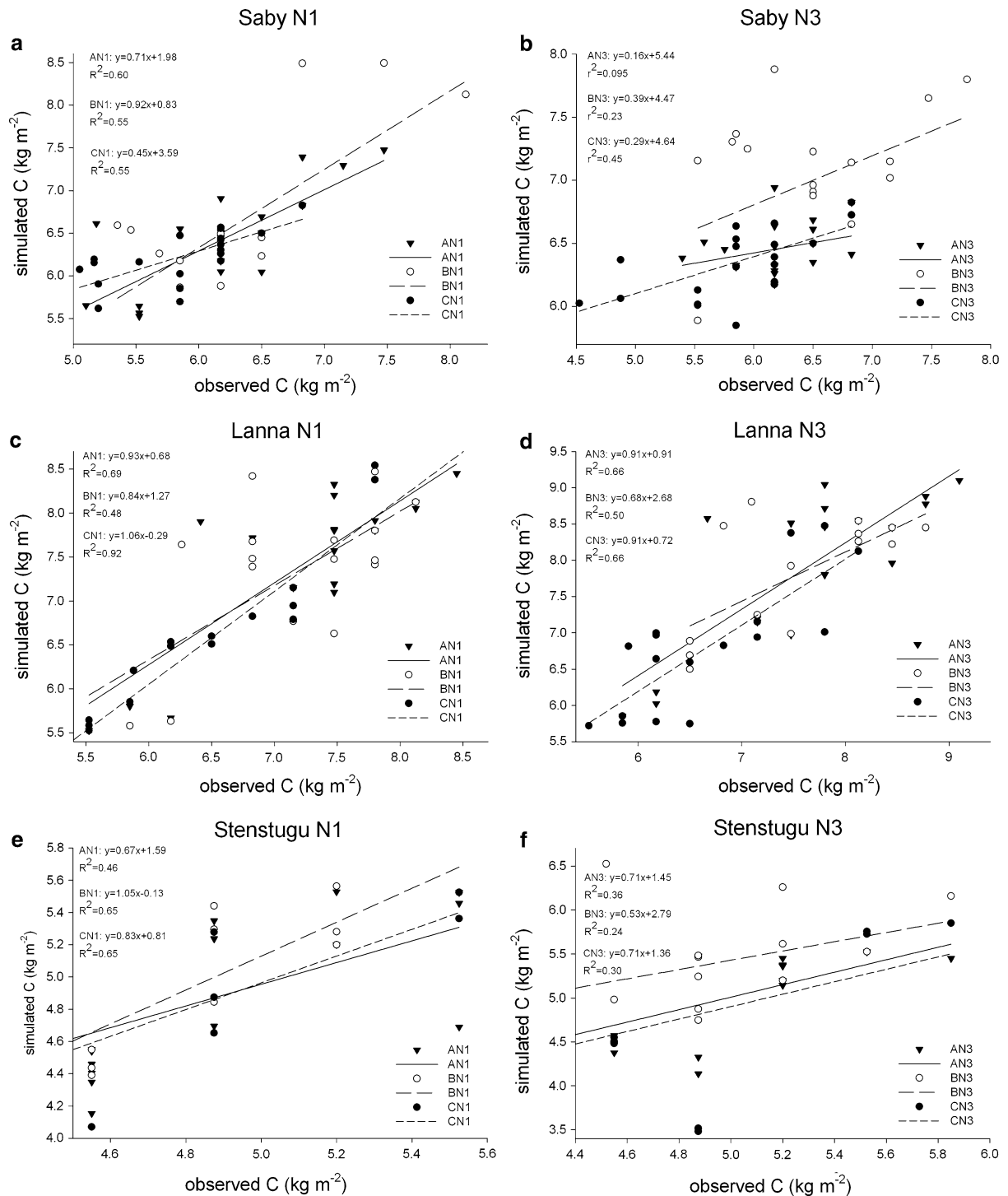


Fig. 3 Simulated versus observed topsoil (0–0.25 m) carbon at Säby (a, b), Lanna (c–d) and Stenstugu (e–f)

the sites and between nitrogen fertilisation levels despite the higher carbon input to the crop rotations with leys and in the N3 treatment could have several

possible explanations. The relatively few points of measurement during latter years is a likely explanation for the lack of detectable ley effects on soil

carbon at Lanna and Stenstugu. In previous studies showing changes in soil carbon due to different crop and fertilisation strategies (Cuvardic et al. 2004; Jenkinson and Johnston 1977; Kirchmann et al. 1994), the periods studied were also often much longer than 31 years.

Another possible explanation for the lack of effect of leys on soil carbon content is that the carbon concentration was analysed only in the upper 25 cm of the soil profile. Significant amounts of soil carbon from crop residues may be stored in deeper soil layers (Gerzabek et al. 2005). In crop rotation A in particular, which includes legumes with a deep root system (Hansson and Andréén 1987), considerable amounts of carbon could have been translocated to deeper soil layers. It is also likely that the fraction of carbon in deeper layers could be higher in the N1 treated plots, since lack of soil nitrogen may stimulate root growth (Lawlor et al. 2001). Consequently, the difference between total soil carbon input between N1 and N3 treatments may have been smaller than the calculated value. There are also several sources of error in the calculations of soil carbon input. Errors in the estimations of ley carbon input due to lack of measurements between harvest and end of the growing period might have produced an incorrect relationship between calculated biomass in crop rotations A and B on the one hand and rotation C on the other hand. The fact that we did not allow nitrogen fertilisation to affect shoot/root ratio in the calculation of root biomass might have caused incorrect estimations of relative root biomass between the two nitrogen fertilisation levels. Changes in ploughing depth or soil bulk density over the experimental period might also have interfered with the topsoil carbon measurements and calculations. To better estimate the complete effects of the different crop rotations on soil carbon, experimental practices should include more frequent measurements of soil carbon than was the case between 1993 and 2005. Measurements from deeper layers in the soil profile and measurements of above- and below-ground plant tissues would also help make a soil carbon content analysis that takes into account in the whole soil profile.

The underestimation of soil carbon reduction by the ICBM simulation might reflect errors and uncertainties in the measurements of soil carbon over the study period. Possible incorrect estimates of soil carbon input, changes in ploughing depth and soil

bulk density would of course also have affected the results of the model simulation. A few changes in soil sampling practices could increase the possibility of accurately predicting soil carbon in future model applications. Such changes should include an extension of the period of measurement and changes in crop and soil carbon measurements as discussed above. Once calibrated against more detailed measurements and against a longer experimental period, comparisons of model predictability and environmental differences between the sites could give more information on how the model should be modified to also take into account crop rotational effects on soil carbon content. For such a model application, measured data on below-ground plant tissue would be useful in order to determine an appropriate value for the humification factor in the ICBM, which may differ considerably among crops (Rasse et al. 2005) and thus account for differences among crop rotations.

Conclusions

The decline in topsoil carbon content at Säby was relatively slower in plots subject to crop rotations including a two-year ley in a six-year crop rotation than in plots where no perennial crops had been grown. Thus, perennial leys in crop rotations could, at least under certain environmental conditions, be used as a tool to reduce losses of carbon in the topsoil. The positive effects of perennial mixed legume/grass leys on winter wheat yield at one site suggest that the land area needed to grow annual crops would decrease with the inclusion of perennial leys, given a constant demand for the annual crops over time. Together, these results show that planning of crop rotations could, in combination with other measures, be a useful tool to mitigate emissions of carbon dioxide. However, since no effect on soil carbon content could be assessed at two sites out of three, it is difficult to estimate how general the crop rotational effects are over climate and soil conditions. Reasons for the lack of effects might have been the rather short duration of the study period and the low number of carbon observations in the last years of the study period. The experiments need to continue with annual measurements of soil carbon content to satisfactorily quantify the ability of two-year leys in six-year rotations to

sequester carbon. Such changes in experimental practices could also be useful in further applications of the ICBM to predict crop rotational effects on soil carbon.

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