Chapter 8

How will Conversion to Organic Cereal Production Affect Carbon Stocks in Swedish Agricultural Soils?

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Abstract Soil carbon changes were modelled over 30 years with the focus on cereal crops, since leys are often managed similarly in organic and conventional agriculture. Other crops were not considered due to difficulties in large-scale cropping of oilseed rape and potatoes organically because of pest problems. Four scenarios were used: 0%, 8% (current), 20% and 100% organic cereal production. Conversion to organic cereal crop production was found to reduce the amount of carbon stored as organic matter in agricultural soils. Three factors contributed to decrease soil carbon levels in a given field: (i) a yield decrease, resulting in less C input through roots and above-ground crop residues; (ii) lower leaf area causing less water uptake, which resulted in higher water content in soil and an increased decomposition rate of soil organic matter; and (iii) more frequent and intensive mechanical cultivation for weed control, which resulted in increased mixing and exposure of soil organic matter to oxidative processes, speeding up decomposition. Due to lower yields in organic agriculture, more land must be used to produce the same amount. With 20% organic cereal production, land currently in fallow would have to be taken into production, while with 100% of cereals produced organically, all fallow land plus conversion of forest land to agriculture would be required. An 8% level of organic cereal production would lead to losses of 0.3 Tg C over a 30-year period, 20% would cause losses of 1.1 Tg C and 100% would cause losses of 12.8 Tg C. The annual CO_2 losses from 100% organic cereal production would be equivalent to the amount emitted by 675 000 average cars in Sweden annually. Losses of soil carbon under organic cultivation would continue for a much longer period than 30 years until a new equilibrium is reached.

Keywords Carbon stocks · CO_2 emission · Cereals · Land use · Modelling · Soil carbon decline

1. INTRODUCTION

Comparisons of soil C content on organically managed and conventional farms often end up with contradictory results. Soil organic matter content has been reported to be higher (Reganold, 1988; Wander et al., 1994; Droogers and Bouma, 1996; Liebig and Doran, 1999; Marriott and Wander, 2006), lower (Lützow and Ottow, 1994; Petersen et al., 1997), or similar (Derrick and Dumaresq, 1999; Burkitt et al., 2007) in organic and conventional production systems. Evidence of higher soil C content on organically managed farms is easily interpreted as a proven advantage of organic agriculture in sequestering more carbon in soil (Smith, 2004), but comparing organic and conventional systems requires great care, since a number of production factors may differ. Purchase of straw, manures or organic wastes is common on organic farms (Goulding et al., 2008; Kirchmann et al., 2008a) and affects soil C content. Incorporation of crop residues in one system and removal and sale in another system also affects the amount of C added. In addition, the large quantities of weeds in organic systems can contribute a significant C input. However, the total input of C from plant residues is usually lower in organic management, even when weeds are taken into account (Kirchmann et al., 2007).

A stringent comparison between systems requires the factors mentioned above to be considered. For example, organic farming systems that use organic matter of off-farm origin in the form of approved organic fertilisers such as composts, manures or organic wastes derived from food industries, etc. generally show higher soil C contents than conventional farming systems not importing the same quantities of organic fertilisers (e.g. Clark et al., 1998; Gunapala and Scow, 1998; Bulluck et al., 2002; Marriott and Wander, 2006). However, direct comparisons are not valid in such cases. Similarly, comparisons of organic systems that rear livestock and return animal wastes to the soil (e.g. Wander et al., 1994; Friedel, 2000; Pulleman et al., 2003) with conventional systems without livestock have no relevance. In addition, comparisons of organic systems using catch crops (Foereid and Høgh-Jensen, 2004) with conventional systems without catch crops lack the stringency required for useful comparisons. The main pitfall when comparing organic and conventional livestock systems is that different amounts of animal manure can be applied. Higher applications of animal manure (through purchased inputs) in the organic system than in the conventional can create non-system-specific differences (Faerge and Magid, 2003; Kirchmann et al., 2007). An appropriate basis for scientific comparisons of cropping systems with different management strategies is that the C input is related to the production level and that purchase of off-farm C sources does not differ significantly. It is therefore not possible to compare soil C levels between systems and attribute the differences to organic or conventional practices (i) if straw is returned in one system but removed in another; (ii) if catch crops are used in the organic system but are not used as an equally integrated countermeasure to reduce N leaching in the conventional system; (iii) if application rates of organic manures are not coupled to production levels; and (iv) if off-farm C sources are applied only in the organic system.

In fact, the number of studies required for a valid comparison is limited. Data from long-term field trials fulfilling the conditions outlined above, the Swiss DOK trial (Alföldi et al., 1993; Fließbach & Mäder, 2000) and the Norwegian model farm study (Korsaeth and Eltun, 2008), show that organic farming could not maintain soil N and thereby soil C content to the same level as conventional farming. In the Norwegian Apelsvoll system only trials with forage production could be compared, as the organic arable system received some animal manure but not the conventional arable system (Breland and Eltun, 1999). A survey of soils by Gosling and Shephard (2005) on four farms managed organically for at least 15 years indicated no significant differences concerning soil organic matter levels between organic and conventional management. Similarly, organic matter C content in soils of Norwegian farms that converted from conventional to organic practices was not different after 5 years (Løes and Øgaard, 1997).

In terms of basic production, organic yields are considerably lower than those of conventional systems (Kirchmann et al., 2008b), which means less C input through roots, above-ground crop residues or animal manure. In addition, lower yields involve less transpiration and thereby higher soil water content, which speeds up decomposition of soil organic matter. The breakdown of soil organic matter in organic farming can be further speeded up by frequent mechanical weeding (more soil cultivation since herbicides are forbidden).

In this chapter, we project soil C dynamics under cereals grown on mineral agricultural topsoils 30 years into the future, excluding soils with more than 12% soil C.

2. CALCULATION PROCEDURES

2.1. Models, data, scenarios and boundary conditions

For the analysis we used the dynamic soil carbon model ICBM (Andrén and Kätterer, 1997), which has been calibrated for a number of long-term experiments (Kätterer and Andrén, 1999) and parameterised to cover different soil and crop types and climatic conditions for geographical regions (Andrén et al., 2004; 2007). The model has also been used for reporting effects of changes in Swedish land use according to the Kyoto protocol (Andrén et al., 2008). A spreadsheet version of the ICBM model for use in projections of future scenarios can be downloaded or run directly (Andrén, 2007). The model has two compartments, called young and old soil organic matter, and the decomposition rate of the young and old pool is set to k_Y = 0.8 and k_O =0.006 year^{-1}, respectively. The decomposer activity (r_e) is multiplied by k_Y and k_O to determine the decomposition rates of the young and old pool, respectively. A humification coefficient (h) determines the fraction of the input that goes through the young pool and into the old (humus, or refractory), and is assumed to be about 0.12 for most crop residues and about 0.35 for manure (Andrén and Kätterer, 1997).

In this study, pedotransfer functions developed from a Swedish soil database containing water retention properties and textural composition (Kätterer et al., 2005) were used to estimate soil water content at wilting point and at field capacity. The soil water balance was based on an FAO concept (Allen et al., 1998). Soil texture data from the nationwide soil monitoring programme (Eriksson et al., 1997; 1999) were used to estimate hydraulic properties. Carbon contents in Swedish agricultural soils were derived from nationwide soil sampling including regional distribution (Eriksson et al., 1997; 1999) and soil properties and data were used to calculate topsoil carbon mass for different soil types and area. Annual crop yield data for eight production regions in Sweden (Table 1) were derived from national Swedish statistics from 1990 to 2004 (e.g. SCB, 2005a). Yield data were used as input to the model to calculate C inputs through crop residues into soil by applying an allometric function with different parameters for each crop type (Andrén et al., 2004). The original calculations included 32 crops, bulked into 9 major crop types for each region. Additions of C to soil through manure applications were estimated from annual regional data obtained from national statistics (Andrén et al., 2004). Annual carbon inputs to soils through crop residues and manure are summarised in the parameter i.

Daily climate data from 22 weather stations managed by SMHI, the Swedish Meteorological and Hydrological Institute (2-4 stations representing each region), were used as driving variables. The input variables were: air temperature (°C), precipitation (mm), and reference evapotranspiration (mm). Air temperature was used to calculate topsoil temperature through an empirical approach (Kätterer and Andrén, 2008).

Decomposer activity in soil expressed as the factor r_e was calculated as the product of three factors, soil water content (r_w), soil temperature (r_t) and soil cultivation (r_c). Soil temperature was assumed to affect decomposer activity according to a quadratic relationship (Kätterer et al., 1998). Water response was assumed to be about 10-fold higher just below field capacity than at wilting point (see Andrén et al., 2004; 2007; 2008).

Separate calculations were made for eight regions, nine crop types and 14 soil types for each year, resulting in 1008 combinations. Averages and sums were calculated, both on a per hectare basis and for the entire area. In this application, we selected only the spring and winter cereal crop types, which constituted two of the nine crop types used in the national C budget calculations (Andrén et al., 2008).

Table 1. Characteristics of Swedish agricultural production regions, 1990-2004. Total area of Swedish agricultural land was 2.76 Mha. Area and yield data from Swedish Official Statistics (SCB, 2005a), climatic data from the Swedish Meteorological and Hydrological Institute, and soil data from Ericsson et al. (1997, 1999)

Region and mean area (ha)	Latitude (°N)	Mean temp. (°C)	Precip. (mm)	Typical crops	Typical soils	Spring barley yield (Mg ha^{-1})	Winter wheat yield (Mg ha^{-1})
South-western coastal, 344 297	55-57	7.8	757	Spring and winter cereals, sugar beet	Sandy loam, loam	5.8	7.9
South-eastern coastal, 324 312	55-58	7.4	612	Grass ley, spring and winter cereals	Sandy loam, loam	4.5	6.5
South central plains, 453 364	58	6.5	570	Spring and winter cereals, grass ley	Sandy loam, loam	4.7	5.9
Central plains, 630 917	59-60	6.6	601	Spring cereals, grass ley	Clay, silty clay	4.1	5.2
Southern forest, 518 783	56-58	6.8	769	Grass ley, spring cereals	Sandy loam, loamy sand	3.5	5
Central forest, 201 789	58-61	5.3	688	Grass ley, spring cereals	Silt loam, silty clay loam	3.3	4.8
North, 166 144	60-65	3.1	600	Grass ley, spring cereals	Silt loam, loam	2.4	NG[a]
North and mountain, 124 642	63-69	2.2	575	Grass ley, spring cereals	Silt loam, sandy loam	2.2	NG[a]

[a]NG = crop not grown in this region

We projected four scenarios 30 years into the future: i) assuming no organic cereal production (0% scenario); (ii) the current situation of 8% of the cereal area being organically cropped (8% scenario); iii) assuming organic cereal production to comprise 20% of the cereal area (20% scenario); and iv) assuming all Swedish cereals to be organically cropped (100% scenario). The 20% scenario was chosen because of the Swedish Government target that 20% of total Swedish agricultural land, including perennial leys, should be under organic agriculture by 2010 (Anonymous, 2005).

Average yields in Swedish organic agriculture are about 50% of those in conventional agriculture for cereals and 75% for leys (SCB, 2004; 2005b; 2006). Significantly lower yields of organically grown crops are also shown by data from a long-term experiment with organic agriculture on low-production soils (Kirchmann et al., 2007). However, since according to SCB (2006) conversion to organic agriculture has been more common on low-production areas than on high-production, yield differences are probably exaggerated. In the following, we thus assumed that yields of organically grown cereals amounted to 60% of those of conventionally grown cereals. Since differences in yields are smaller for leys than for cereal crops, C input through crop residues may not be significantly different for organic and conventional leys. Furthermore, an unknown proportion of the organically managed leys had been cropped without inorganic fertilisers before 'conversion' to organic practices and there may not have been any actual change in management other than registration of the area to obtain subsidies for organic agriculture. For this reason, we simplified our projections and considered only the agricultural area used for cereal production in our calculations.

Yield decline through organic production also needs to be viewed from the perspective of food supply. To maintain the same food and feed supply in Sweden, lower yields through organic practices must be compensated for and replaced by additional production. Consequently, more agricultural area is required, independent of whether the production decline is replaced by goods purchased on the world market or balanced by additional production in Sweden. Thus, the most central boundary condition for a system comparison is that the same total amount of cereal crops has to be produced.

In this study, changes in soil carbon stocks of Swedish agricultural soils were assessed in two steps. In a first step, the effect of organic production on soil C dynamics of the current cropped area was demonstrated without considering the need for increased area. In a second step, the yield decline after conversion to organic agriculture was considered and balanced through an equivalent increase in land use for agricultural production.

3. CHANGES IN SOIL CARBON MASS DUE TO ORGANIC CEREAL PRODUCTION

3.1. Conversion from conventional to organic cereal production

We calculated changes in the C mass of Swedish agricultural soils cropped with cereals when converted from conventional to organic cereal production. Four conversion scenarios were modelled, as shown in Table 2 and Fig. 1.

Conversion to organic cereal production was shown to reduce yields and thereby affect the amount of fresh crop residues returned to soil. Conversion to complete organic cereal production (100% scenario) reduced the annual C input through crop residues to soil by roughly 1 Mg ha^{-1}, from 2.7 to 1.7 Mg C ha^{-1} yr^{-1} (Table 2). In addition, lower yields meant smaller leaf area and therefore lower water uptake, which affected the soil climate factor (r_e), a multiplier for decomposition rate (Table 2). As the water content in soil remained higher under lower production, decomposition rates in the organically cropped soils were 5-10% higher. Concerning the application of animal manure to organic and conventional production systems, it was assumed that the same amount was used in all scenarios, since changes in the total numbers of cattle through conversion to organic cereal production are difficult to predict.

According to the projections in Table 2, a drastic decline in soil C can be expected if all cereals are cropped organically. The 100% scenario shows that in the long-term perspective, i.e. under steady-state conditions, one third of soil C under cereals would be lost, declining from 81.3 to 52.1 Mg soil C ha^{-1} under exclusively organic production. Continuing with the current level of organic cereal production (8% scenario), the soil carbon mass in soil will decrease from 81.3 Mg ha^{-1} to 77.54 Mg ha^{-1} at steady-state. However, as steady-state conditions will take a very long time to reach under Swedish climatic conditions, a more relevant projection of the soil C mass dynamics would be the 30-year period shown in Fig. 1.

Table 2. Amounts of carbon in Swedish arable soils at steady-state conditions when cereals are cropped organically. The parameters used in the ICBM Excel model for winter and spring cereals were 1 197 000 ha for total cereal area and 81.26 Mg C ha^{-1} for initial C mass of 0-25 cm topsoil. Sum of annual C input from crop and manure (*i*), soil climate factor (r_e), humification factor (*h*)

Percentage of cereal land cropped organically	C input (Mg C ha^{-1})		Parameters and steady-state values			
	Crop residues	Animal manure	I	r_e	h	Soil C (Mg C ha^{-1})
0% scenario	2.85	0.356	3.21	1.05	0.154	82.16
8% scenario (current level)	2.76	0.356	3.11	1.09	0.156	77.54
20% scenario	2.62	0.356	2.98	1.11	0.156	73.04
100% scenario	1.71	0.356	2.07	1.15	0.168	52.14

The decomposition curves in Fig. 1 indicate that changes are more rapid during early years, when ‘young’ soil organic matter is reaching steady-state. Different decomposition rates for young and old soil carbon are used in the model (Andrén and Kätterer, 1997) and for the far more decomposition-resistant old soil C, the period chosen was too short to reach steady-state. Even 30 years after complete conversion to organic production (100% scenario), soil C levels were shown to be still declining and were far from the steady-state level of 52.1 Mg C ha^{-1} (Fig. 1).

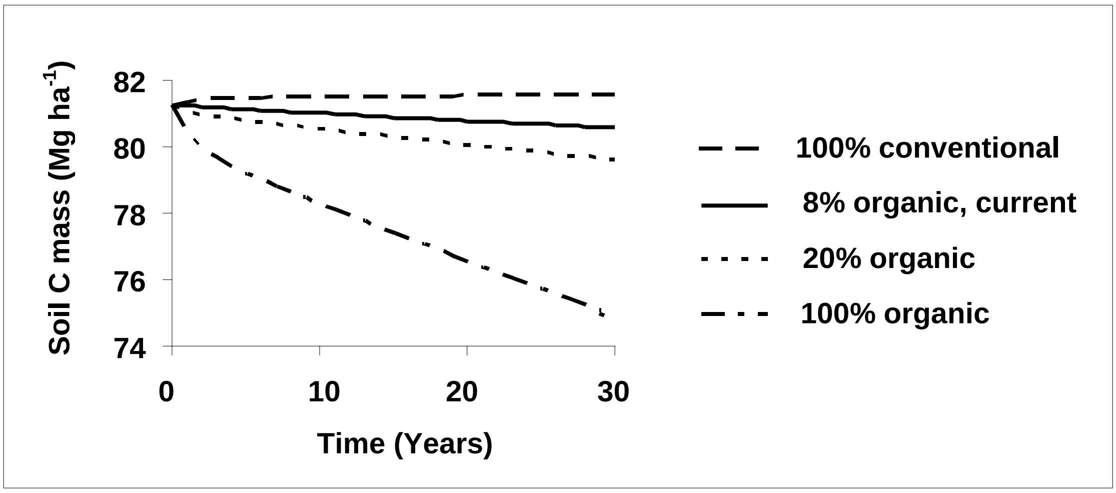

Figure 1. Projecting soil carbon changes in Swedish arable topsoils under cereals starting from current carbon mass (0-25 cm depth, Mg ha^{-1}) for four scenarios over 30 years.

3.2. Conversion from conventional to organic cereal production including additional land required to produce the same amount of cereals

Although differences in soil C stocks between organic or conventional production seem clear enough, the projections in section 3.1 do not consider that the same amount of cereals has to be produced by organic methods as by conventional. Cereal demand remains the same for both systems and therefore lower organic yields per area must be compensated for by cropping of additional land.

A central question is which additional type of land can be used for organic cereal production if the current level of organic production (8% scenario) is increased to 20% or even 100% of total cereal production. Swedish statistics indicate that the total agricultural area classified as fallow increased from 250 000 ha in the year 2000 to about 330 000 ha by 2005 (SCB, 2006). Thus, agricultural land under fallow can be considered for organic production in the first instance. In fact, cropping of parts of the current fallow area with organic cereals would be sufficient to compensate for the production decline in the 20% scenario. However, if all cereals in Sweden were to be produced organically (100% scenario), the current fallow land would not be sufficient and additional land would be required. In that case, the only realistic option would be the use of forested areas formerly used as agricultural land, as permanent pastures are generally difficult to cultivate due to hilly conditions, stone outcrops or other difficult terrain. The conditions for the extended projection and changes in soil C stocks are outlined in Table 3.

If the current organic cereal production level (8% scenario) were to increase to 20%, our calculations show a significant decrease of 1.1 Tg C in Swedish arable soils over a 30-year period. In the 100% scenario, there would be a total soil C loss of as much as 12.8 Tg C, with almost 50% originating from the additional area required to compensate for lower yields. If we were to abandon organic agriculture and grow cereals exclusively through conventional methods (0% scenario), we would slightly increase soil C stocks by 0.33 Tg after 30 years (Table 3).

4. SOIL CARBON DIOXIDE LOSSES CAUSED BY ORGANIC CEREAL PRODUCTION IN RELATION TO EMISSIONS BY CARS

In order to relate the decline in soil C mass and thus CO_2 emissions from Swedish agricultural soils upon conversion to organic cereal production to other emissions in society, we used emissions by cars for comparison. We calculated the number of cars emitting the same amount of CO_2 per year (1.6 CO_2 Tg year^{-1} or 0.42 Tg C year^{-1}) as would be lost from agricultural soil after conversion to 100% organic cereal production.

For this calculation we assumed the following: On average, Swedish cars are run 10 000 km per year and use 0.1 L petrol km^{-1}, resulting in an annual use per car of 1000 L petrol. Petrol has a C content of 84% and a density of 0.74 kg L^{-1}, which means that 622 kg petrol-C are combusted per car and year.

The amount of 1.6 Tg CO_2 emitted per year due to conversion to complete organic cereal production in Sweden is therefore equivalent to the amount emitted by 675 000 cars per year. The comparison illustrates the highly significant contribution of CO_2 emissions from soil.

Moreover, as emissions from cars and other anthropogenic sources are likely to decrease through the introduction of new technologies, CO_2 emissions from organically managed soils may make an even more substantial contribution relative to other anthropogenic CO_2 emissions since they will continue over a very long period.

Table 3. Projected 30-year changes in C content in Swedish soils used for organic or conventional cereal production when the same total amount of cereals is produced. Conditions as outlined in Table 2; initial C mass of 0-25 cm forest soil = 81.26 Mg ha^{-1}

Land use scenarios for cereal production	Cereal area (1000 ha)	Rel. yield	Average grain yield (Mg ha^{-1})	Total yield (Tg)	Portion of yield (%)	Changes in soil C after 30 yrs: Soil C (Mg ha^{-1})	Changes in soil C after 30 yrs: Total soil C (Tg)
0% scenario							
100% conventional	1088	100	5.1	55.5	100	+ 0.33	+ 0.33
8% scenario							
8% organic	90	60	3.0	2.7	4.9	- 6.3	- 0.6
92% conventional	1036	100	5.1	52.8	95.1	+ 0.3	+ 0.3
Sum	1126			55.5	100		- 0.3
20% scenario							
20% organic	225	60	3.0	6.8	12.2	- 6.3	- 1.4
80% conventional	901	100	5.1	45.9	82.7	+ 0.3	+ 0.3
Additional 4% conv. using fallow land[2]	56	100	5.1	2.8	5.1	+ 0.3	0[2]
Sum	1182			55.5	100		- 1.1
100% scenario							
100% organic	1126	60	3.0	33.8	60.8	- 6.3	- 7.1
Additional 17% organic using all fallow land[1]	321	60	3.0	9.6	17.4	- 6.3	0[2]
Additional 40% organic using forested land	485	50	2.5	12.1	21.8	- 11.7	- 5.7
Sum	1932			55.5	100		- 12.8

[1] The fallow area amounted to 321 000 ha in 2005
[2] No change in soil C was assumed when shifting from fallow to conventional cereal production

5. CONCLUSIONS

- Agricultural practices that increase photosynthesis and crop yields will also increase the amount of C stored as organic matter in soil.
- Producing cereals organically will significantly reduce soil C stocks. Lower organic yields result in less crop residues, which in turn results in less soil organic matter formation. Furthermore, reduced crop growth leads to less uptake of water and more moisture in soil, which speeds up decomposition.
- Lower cereal yields in organic production need to be balanced by additional cereal production elsewhere, requiring an additional production area. In a scenario where all cereals are produced organically, all current fallow and some current forest land would have to be converted to agriculture.

- If all cereals are grown organically, soil carbon losses will cause annual CO_2 emissions of 1.6 Tg. This is equivalent to the amount of CO_2 emitted by 675 000 average cars in Sweden during one year.

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