Introduction of grass-clover crops as biogas feedstock in cereal-dominated crop rotations. Part I: Effects on soil organic carbon and food production

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ABSTRACT

Changes of soil organic carbon (SOC) content can have a substantial effect on greenhouse gas emissions, but are rarely included in crop production LCAs. SOC content strongly influences soil fertility and therefore crop yields, but is declining in many European soils. The present study investigated if integration of 1-2 years of grass-clover crops in a cereal-dominated crop rotation can increase the SOC pool and how this would impact food production. Results show that when grass-clover crops are integrated, the potential SOC content at steady state will be 41 to 52% higher than in the conventional cereal-dominated crop rotation. The net increase of wheat yields based on SOC improvements indicate that for a crop rotation with one year of grass-clover crops, the initial loss of food production can be counterbalanced due to the impact on fertility of the SOC increase.

Keywords: soil organic carbon, grass-clover crops, food crop production, crop yield, soil carbon model

1. Introduction

Energy crop production is often claimed to negatively impact food and feed production, i.e. by competition for arable land and by reducing soil quality. On the other hand, current intensively managed agricultural food and feed production systems are often not sustainable: Loss of soil organic carbon (SOC), erosion and compaction are the main processes threatening soil fertility throughout the EU (EC 2002; Soilservice 2012). Intensively cultivated clay soils have in Swedish studies been shown to give up to 20% decreasing food crop harvest yields due to soil compaction and reduced soil organic matter content (Arvidsson and Håkansson 1991).

The build-up or degradation of SOC is a process with dual and important impact on sustainability in crop production. Firstly, SOC content strongly influences soil fertility and crop yields, but due to e.g. unsustainable management practices and crop rotations it is declining in many European soils (Soilservice 2012). Secondly, agricultural soils can act either as carbon sinks, or, if SOC is declining, as contributors to greenhouse gas emissions. Changes in SOC can contribute substantially to greenhouse gas emissions of crop production, but are rarely included in LCA (Brandão et al. 2011).

SOC content is positively influenced by addition of organic materials such as intermediate crops, crop residues and manure or other organic fertilizers. The main negative impacts on SOC are the outflow caused by mineralization processes of the soil organic matter, the degree of which is related to e.g. climatic conditions and the severity of soil management practices. By changing crops in the crop rotation SOC can be influenced actively. However, addition of organic material is often small in comparison to the amount of carbon already stored in the soil. Therefore long-term changes of SOC are often quantified using models that are calibrated with long-term experimental data.

The present study investigated if integration of 1-2 years of grass-clover crops in a cereal-dominated food crop rotation on intensively managed heavy clay soils can increase the SOC pool. The work is presented in two parts, where the present paper, Part I, shows the impacts on the SOC pool and discusses the potential impact on fertility and crop yields. Part II shows the LCA and effects on greenhouse gas emissions of grass-clover crop introduction to the crop rotation (Björnsson and Prade 2014). In areas with little animal husbandry there is no or a very limited market for grass-clover crops as animal feed and limited availability of organic fertilizers such as manure. Therefore, the approach in this study was to integrate grass-clover crops in the crop rotation for use as biogas feedstock. The biogas plant then takes on the role of the absent ruminants, creates a market for the grass-clover as energy crop, and produces biogas and a digestate (the liquid residue of the biogas production), which is used as biofertilizer.

The study was performed as a farm based case study, where the case farm is representative for a large agricultural region in which the low input of carbon in the cereal based crop rotation has been identified as problematic with regards to the high clay content in the soil. The hypotheses of this study were that (a) an increased SOC content can be obtained by introduction of e.g. grass-clover crops as well as by fertilization with biogas digestate; and (b) that the increased SOC content may increase food crop yields enough to compensate the initial food production losses when the crop rotation is changed.

2. Materials and methods

2.1. The case farm

The farm based case study investigates the effects of different crop rotation and biomass utilization scenarios. As a basis for this case study, a farm with mainly clay rich soils in North West Scania (56°6'N 12°58'E) was chosen. This farm, Wrams Gunnarstorp, is located close to the site of long-term SOC content field experiments in Ekebo, performed by the Swedish University of Agricultural Sciences (SLU) (Kirchmann et al. 1999).

This study concentrated on 650 ha of medium to heavy clay soils with soil clay content up to 65%. The soils are rather cold, and crop establishment is often carried out very shortly in the autumn after harvest of the previous crop. Crop establishment is rather slow, and the risk for the plants to be too big for overwintering is little. This leaves no opening for the introduction of after-sown intermediate crops. In this study, introduction of clover-grass crops extending the crop rotation was chosen as a measure to increase SOC content.

The latest analysis of soil carbon content expressed as humus on the Wrams Gunnarstorp farm dated from 1984. That year, the soils had an average SOC content of ~2% and consisted of very heavy clay soils, heavy clay soils and medium clay soils. The fairly high content of humus in the Wrams Gunnarstorp soils at this time was probably a result of the consequent use of cow manure as biofertilizer until 1960.

2.2. Crop Rotation

On the major part of the farm, a 4-year crop rotation typical for the region is used, Table 1. This present crop-rotation was used in the reference scenario. In the investigated alternative scenarios, grass-clover crops were introduced one year in a five year crop rotation (scenario GC1) and two years in a six-year crop rotation (scenario GC2).

Table 1. Typical sowing and harvest dates on the Wrams Gunnarstorp farm for the reference crop rotation (years 1-4) and extension with grass-clover crops.

Year	Crop	Sowing date	Harvest date
1	Winter oilseed rape	1-10 August	20 July
2	Winter wheat	1-20 September	10 August
3	Winter wheat	1-20 September	10 August
4	Oats	1-20 April	20 August
Scenario GC1 years 1-4 plus			
5	Grass-clover crops	1-20 April[a]	Cut 1: 1 June; cut 2: 1 August
Scenario GC2 years 1-4 plus			
5	Grass-clover crops	1-20 April[a]	Cut 1: 20 June; cut 2´: 20 August
6	Grass-clover crops	-	Cut 1: 1 June; cut 2: 1 August

[a] Undersown in oats in the previous year

2.3. Crop production

Average crop yields were estimated based on annual measurements on the Wrams Gunnarstorp farm. For cereal grains and oilseed rape average production yields were calculated, Table 2. Yields for grass-clover crops were estimated from hand-harvested samples and corresponding machinery field losses (20%) within an ongoing research project at SLU, evaluating grass-clover crop yields on the Wrams Gunnarstorp farm (funded by Stiftelsen Lantbruksforskning, SLF). A grass-clover crop system with two harvests per year was assumed.

Grass-clover crops were assumed to be undersown with the preceding crop, oats. After the oats have been harvested, the grass-clover crops grow up. In the year of establishment, grass-clover crops are assumed to be harvested once in the late autumn. Oats are assumed to be harvested 20th of August and grass-clover crops harvested 30th of September are assumed to result in a biomass yield of 1.5 t ha^{-1} of DM. Winter wheat is assumed to be harvested 10th of August. Breaking of the grass-clover crop is assumed to be carried out 1st of August in order to allow establishment of winter oilseed rape (WOSR). In this year, the grass-clover crop is assumed to yield 9.0 t ha^{-1} instead of 12 t ha^{-1} DM in a full production year. A full production year is only possible the first year of a two-year grass-clover crop.

Details on inputs in crop production (machinery, materials, diesel, fertilizer) are based on typical cultivation input and fertilization levels at the model farm and are presented in Part II of the study, where greenhouse gas emissions for the different scenarios are calculated.

2.4. Amounts of crop residues

Crop yields play a central role in this study, since many analysis parameters are directly or indirectly connected to biomass and/or grain yields. Higher crop yields often result in larger amounts of crop residues, e.g. straw, stubble, roots and extra root biomass, which will impact SOC input. Most models for calculation of crop residues assume a linear connection between harvestable biomass (i.e. grains, seeds, beets, above-ground biomass) and remaining residues above- and belowground in the form of fixed mass ratios for the different plant parts. This is the case for the calculation model for amounts of crop residues suggested by IPCC (2006).

Swedish long term field experiments support models that result in high biomass respective carbon inputs from root and extra root material, higher than what is suggested in the IPCC model (Björnsson et al. 2013). This is especially valid for grass-clover crops, where a large number of plant species of grasses and legumes can be mixed in endless combinations. While grasses contribute much harvestable biomass, legumes contribute nitrogen fixation and root biomass. Another aspect of grass-clover crops is the time factor. High production systems may utilize grass-clover crop blends for 1-3 years, while more long-term or permanent grass-clover crop systems exist as well.

Swedish studies fitting long-term soil carbon measurements to a soil carbon model suggest a constant amount root biomass, 6 t ha^{-1} of DM (Bertilsson 2006). However, in this study, a proportional root biomass development was assumed in the base case, limited with a ceiling value of 6 t ha^{-1} of DM. Another issue is that straw yields suggested in the IPCC calculation model are unrealistically high compared to actual straw yields in cereal cultivation in under Nordic conditions (Nilsson and Bernesson 2009).

In the base case calculations of SOC, model parameters from regional studies (called Nordic) are used for the calculation of amounts of crop residues as described above (Table 2) (Björnsson et al. 2013). For comparison the calculations were repeated with the IPCC methodology for crop residue calculation (Table 2).

Table 2. Dry matter (DM) yield data of harvested crop parts (grains, seeds, grass-clover cuttings) and coefficients used in the systems analysis and for calculation of crop residues and SOC. (1 t = 10^6 g; 1 ha=10.000 m^2).

Crop	DM yield	Nordic		IPCC (IPCC 2006)			Humification coefficients[c]	
	[t ha^{-1}]	Slope	B/A ratio[a]	Slope	Intercept[b]	B/A ratio[a]	Above-ground	Below-ground
Winter oilseed rape	2.5	0.92	0.20	1.09	0.88	0.22	0.15	0.35
Winter wheat	6.5	0.57	0.33	1.61	0.40	0.23	0.15	0.35
Oats	4.0	0.50	0.47	0.91	0.89	0.25	0.15	0.35
Grass-clover, 0 year after oats	1.5	0.25	0.58[d]	0.30	0.00	0.00[d]	0.12	0.35
Grass-clover, 1st of one year	9.0	0.25	0.88	0.30	0.00	0.80	0.12	0.35
Grass-clover, 1st of two years	12.0	0.25	0.26[d]	0.30	0.00	0.00[d]	0.12	0.35
Grass-clover, 2nd of two years	9.0	0.25	0.88	0.30	0.00	0.80	0.12	0.35

[a] Belowground residues/aboveground biomass ratio: aboveground includes stubble and harvested biomass; belowground in Nordic includes extra-root material.

[b] DM in [t ha^{-1}]

[c] (Kätterer et al. 2011); Digestate: 0.41

[d] Only extra-root biomass is accounted for.

Another carbon input with relevance for the SOC calculations in the GC1 and GC2 scenarios is the added biofertilizer, the digestate, which is the residue from the harvested above ground part of the grass-clover crops after biogas production. The details of biogas production are presented in Björnsson and Prade (2014). The data used in the SOC calculation in the present part of the study are presented in Table 3.

Table 3. Harvested grass-clover crop biomass for use as biogas feedstock and resulting digestate for the grass-clover scenarios.

Parameter	Unit	Scenario GC1		Scenario GC2	
		Biogas feedstock[a]	Digestate[b]	Biogas feedstock[a]	Digestate[b]
Dry matter	[kg ha^{-1} a^{-1}]	1995	867	3563	1543
Carbon	[kg ha^{-1} a^{-1}]	904	430	1614	766

[a] Feedstock indicates the average amount of grass-clover removed in the crop rotation after field drying to 35% DM and ensiling.

[b] Digestate indicates what is returned to the field as biofertilizer in average for the whole crop rotation after biogas production and losses during digestate storage.

2.5. SOC model

In order to calculate changes in the SOC content as influenced by the choice of crop rotation, Introductory Soil Carbon Balance Model (ICBM) was used (Andrén and Kätterer 1997; Kätterer and Andrén 2001). The model was applied to calculate the SOC content according to carbon inputs and mineralization rates. The model was modified to account for different input types with specific humification factors (Figure 1).

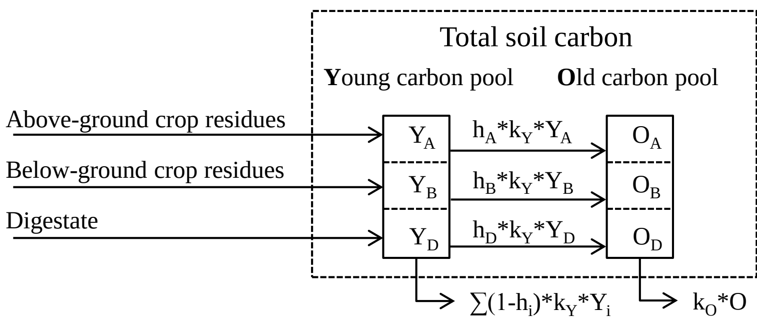

Figure 1. Introductory Soil Carbon Balance Model (ICBM)

All carbon from aboveground residues (A), belowground residues (B) and digestate additions (D) enters the young carbon pool (Y). From this pool, easily degradable carbon is released as CO_2 by mineralization according to a degradation function, while only a material-specific fraction is humified, i.e. stored in the humus part of soil carbon, or, in this model, the old carbon pool. Y has an outflow of carbon with a relatively high reaction coefficient of k_Y=0.8, i.e. within one year 1-exp(-0.8)=55% of the carbon leaves the young carbon pool again (Andrén and Kätterer 1997). The output from the old carbon pool follows a much lower reaction coefficient (k_O) than the young carbon. Carbon content of crop dry matter was assumed to be 45% (Kätterer et al. 2011). A starting value of 2% SOC content was assumed. In the base case, annual SOC content changes were calculated as average values over a time span of 40 years.

2.6. Model calibration

In order to adapt the ICBM to Nordic conditions, the model was calibrated against data derived from the long-term soil carbon field experiment in Ekebo, Sweden (Kirchmann et al. 1999). The Ekebo soil carbon field experiment includes two different crop rotations. One was designed as a crop rotation for an animal production farm, with all cereal straw and sugar beet tops removed. The other crop rotation was designed for a pure plant production farm, with all straw and sugar beet tops left in the field. For each rotation 16 different fertilization regimes (all combinations of 4 nitrogen and 4 phosphorous/potassium fertilization levels) were tested. The experiment started 1957 and is ongoing with regular soil carbon content analyses.

Calibration was done using the reaction coefficient of the old carbon pool (k_O) as a variable to fit model soil carbon predictions to the measured soil carbon data. This was done using crop residue data as computed by (a) the IPCC calculation and (b) by the Nordic calculation for comparison. The prediction power of the model was computed by maximizing the coefficient of determination (R^2) of the measured and predicted data.

2.7. Yield impact

Food crop grain and seed yields have been shown to increase corresponding to the SOC content (Lal 2004; Soilservice 2012). Yield changes due to SOC increases have been calculated for wheat grain yields assuming a DM yield increase of around 0.4-0.8 t ha^{-1} $\%_{SOC}^{-1}$ (Lal 2004). For the SOC content of the case farm soils, each percent of SOC corresponds to approx. 20 t ha^{-1} carbon.

2.8. Sensitivity analysis

In the base case, calculations follow the Nordic methodology, while in the sensitivity analysis IPCC methodology was applied (Table 4).

Table 4. Parameters use in the base and the alternative case.

Parameter	Nordic – base case	IPCC – alternative case
Aboveground crop residues	Only slope	Slope and intercept
Belowground crop residues	Limited to 6 t ha^{-1} of DM; extra root residues correspond to 65% of root residues[a]	Unlimited
Time span for calculation of average annual carbon changes	40 years	20 years

[a] (Bolinder et al. 2007)

3. Results

3.1. SOC changes

The soil carbon content develops positively for all scenarios, but with largely different long-term results, Figure 2. The reference scenario has the conventional cereal based 4-year crop rotation, where all of the straw is left in the field. In this scenario, the steady state of SOC content was reached at 2.9% after approx. 145 years. In the GC-scenarios, grass-clover is introduced in the crop rotation, and the amount of digestate produced from grass-clover digestion is large enough to cover substantial shares of the fertilizer need at the farm, i.e. 15 and 24% of nitrogen, 23 and 34% of phosphorous and 42 and 50% of potassium for scenarios GC1 and GC2, respectively (Björnsson and Prade 2014). The GC-scenarios contribute to a much higher increase in SOC content with steady states at 4.1 and 4.4% after approx. 125 years for scenarios GC1 and GC2, respectively.

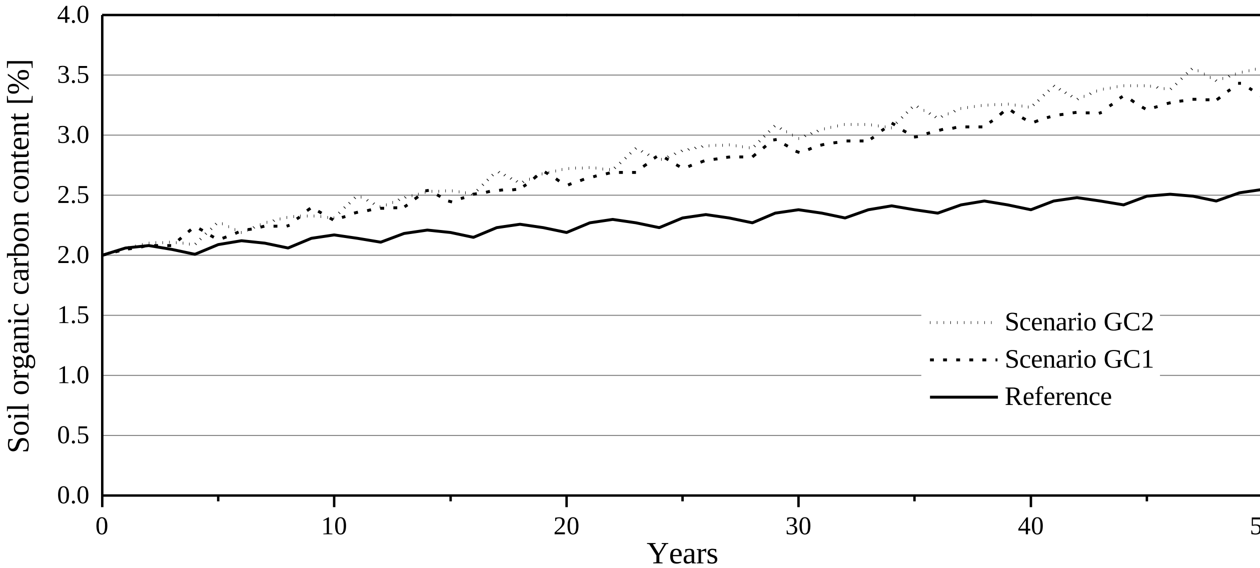

Figure 2. Change in soil carbon content in the investigated scenarios over a 50-year period according to base case calculations.

Figure 3 shows the average annual SOC changes for the crops and the crop rotations studied calculated both with the Nordic and the IPCC methodology. For oilseed rape, oats and grass clover crops, the Nordic methodology results in lower annual SOC additions than the corresponding IPCC methodology, but with relatively small differences. For wheat, using the IPCC methodology results in 168% higher crop residue inputs.

These differences are reflected in the average annual SOC changes calculated for the complete crop rotations. Using the IPCC methodology resulting annual SOC changes are 170%, 47% and 18% higher for the reference scenario, GC1 and GC2 respectively than using the Nordic methodology.

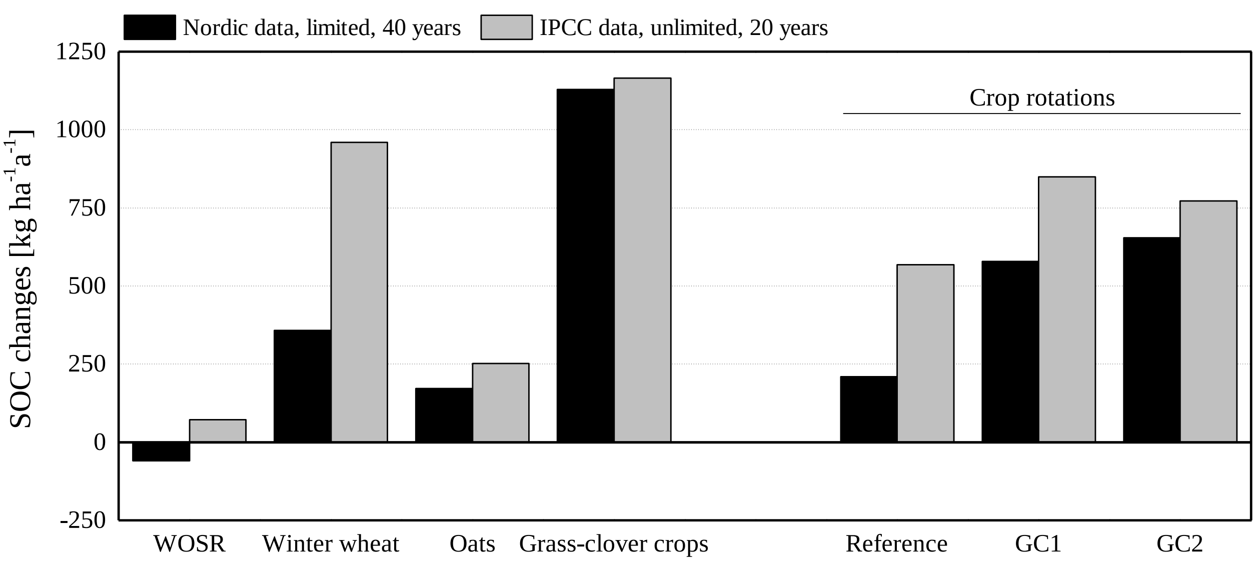

Figure 3. Annual SOC changes of crops and crop rotations according to Nordic and IPCC methodology. For crops, continuous cultivation was assumed. Data for crop rotations represent average annual SOC changes from crop residues and digestate application. 'Limited' and 'Unlimited' refer to root SOC contribution for grass-clover crops. Years given refer to the time span used for the calculation of the average annual SOC changes. WOSR=winter oilseed rape.

The SOC content after 50 years and at steady state (SS) calculated both with Nordic and IPCC methodology are shown in Figure 4. With the rapid and large SOC increase in the GC1 and GC2 scenarios (Figure 2), SOC after

50 years will be more than 0.6-0.8% higher (GC1) to 0.5-1.0% higher (GC2) than in the reference scenario.

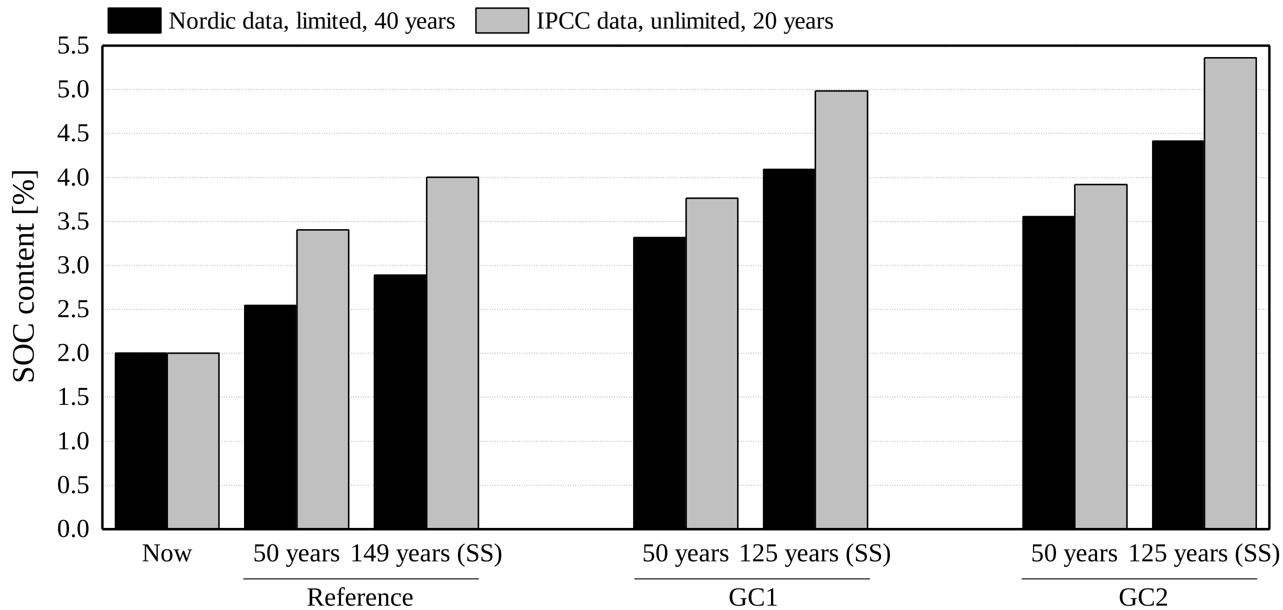

Figure 4. Predicted SOC content at the case farm after 50 years and at steady state (SS) for to the different scenarios according to the Nordic and IPCC calculation methodologies.

3.2. Yield changes

The SOC values after 50 year (Figure 4) would mean 5-10% and 6-12% net increase in yield of wheat grain for scenarios GC1 and GC2, respectively compared to yields in the reference scenario (Figure 5). At steady state, the decrease in food crop production of 20 % - which is the consequence of introducing one year of grass-clover crops in the crop rotation (scenario GC1) - could be offset to a major extent by the yield increase. In scenario GC2, the yield increase at steady state would correspond to around half of the initial food production losses for Nordic and IPCC approach.

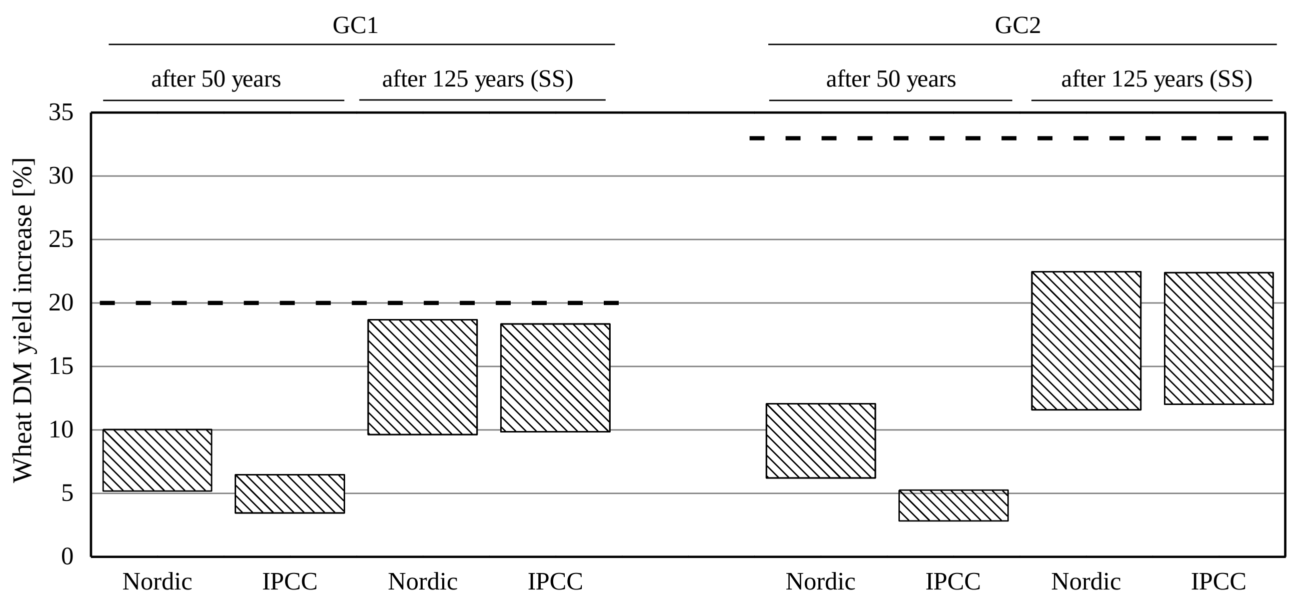

Figure 5. Predicted wheat yield increase relative to the reference scenario at the case farm after 50 years and at steady state (SS). Dashed lines correspond to the initial food production losses caused by the crop rotation changes in the scenarios.

4. Discussion

4.1. SOC changes

SOC content is a parameter that connects soil fertility, crop yields and greenhouse gas issues and therefore is a crucial factor for the environmental performance of a cropping system. Processes leading to changes in carbon soil content are often slow; therefore the time perspective becomes important for life-cycle assessment of agricultural production systems.

This study has shown that extension of a cereal-dominated crop rotation with one or two years of grass-clover crops can improve SOC content in a heavy clay soil substantially, given that the change is a medium to long-term commitment. In fact, the case farm currently operates a second crop rotation on a smaller fraction of the farm, including three years of meadow fescue for seed production in order to decrease problems associated with heavy clay soils and to improve soil fertility. However, the area on which this improved crop rotation is used is limited by the marketing possibilities for meadow fescue seeds. A biogas plant in a region characterized by crop production and lack of organic fertilizers could help create a potential market for grass-clover crops and in return deliver digestate, the liquid effluent from the biogas process, for utilization as organic fertilizer. The results further indicate that improvements of SOC content by including one year of grass-clover crops can potentially offset the initial food production losses caused by the crop rotation change.

Soil carbon content affects many cultivation factors such as nutrient availability, water retention capacity, soil density, soil temperature etc. An increase of soil carbon content may lead to, but is no guaranty for, increased soil productivity, i.e. increased crop yields. But also decreased requirements for fertilization can be a positive result of soil carbon increase. Other, more short-term effects may contribute positively to food production in the system, e.g. the pre-crop effect of grass-clover crops.

Another strategy for improving SOC content would be to implement grass-clover crops in order to boost SOC content to the steady state of the reference scenario in only 29 and 26 years for scenarios GC1 and GC2, respectively, e.g. if return to the crop rotation in the reference scenario is desired.

4.2. Yield increases

The estimates of food crop yield increases in the present study are rather conservative, since calculations neglect two effects. First, in the short term, soil structure improvements by grass-clover crop cultivation could help decrease yield losses due to soil compaction and standing water. Secondly, these short-term yield increases and SOC-related yield increases have a positive impact on crop residue input. Therefore, these calculations underestimate potential yield increases. Therefore, the next step for a follow-up project is to implement yield impacts, accumulated food production losses and impacts on fertilization requirements in the SOC model.

4.3. Calculation methodology

While changes in a crop rotation have a small short-term effect, the long-term effects may lead to significant changes in soil fertility, crop yields and greenhouse gas emissions of a cultivation system. It is therefore important to investigate potential long-term effects of carbon input on the soil carbon content. IPCC suggests a period of 20 years to be used for this purpose. In theory, changing from one established cropping system to another with a change in the average carbon input may result in a change of soil carbon content. How quickly the change will take place and the time required to reach a new steady state depends on many factors. However, the soil carbon content will change along an asymptotic curve, with the highest absolute changes in the beginning. With time, these differences will become smaller and smaller until a new steady state is reached. Therefore, the shorter period for calculating the average annual carbon change as suggested by IPCC will result in higher changes compared to a longer calculation period and may therefore potentially overestimate the effect of crop residue additions.

Another issue with the IPCC calculation methodology is the overestimation of wheat crop residues, at least compared to Nordic conditions. The straw yields suggested in the IPCC calculation model are unrealistically high compared to actual straw yields in cereal cultivation in Sweden (Nilsson and Bernesson 2009). IPCC data gives thus higher SOC accumulation for all the investigated scenarios, but with larger impact on the reference scenario with 75% cereals in the crop rotation.

5. Conclusions

The investigated change from an agricultural food production system only producing food crops to a system with integrated production of food and energy crops was shown to be a potentially important tool to improve SOC content considerably. Securing future food production will require sustained or even increased SOC content. While extending food crop rotations with grass-clover crops results in a direct decline in food production, the long-term effect of SOC increase may increase food yields, both due to improved soil fertility and structure.

Extending cereal-crop dominated crop rotations with grass-clover crops could help integrate biofuel and food production. Plant nutrients in the biogas digestate can be recycled, including SOC building carbon. This diversification of crop rotation is especially interesting in regions with no demand for cattle feed.

Finally, carbon sequestration by increasing SOC content and greenhouse gas mitigation by biogas production from grass-clover crop biomass may improve the carbon balance of food production considerably, which is further discussed in Part II of this study (Björnsson and Prade 2014). This study demonstrated the importance of SOC changes in agricultural production systems and such changes should be accounted for in future LCA studies.

6. References

Andrén O, Kätterer T (1997) ICBM: The Introductory Carbon Balance Model for Exploration of Soil Carbon Balances. Ecol Appl 7:1226-1236

Arvidsson J, Håkansson I (1991) A model for estimating crop yield losses caused by soil compaction. Soil Tillage Research 20:319-332

Bertilsson G (2006) Perspectives on soil carbon. Greengard AB: Hastar och miljö. http://www.greengard.se/cpersp.htm. Accessed 2013-08-27

Björnsson L, Prade T (2014) Introduction of grass-clover crops as biogas feedstock in cereal-dominated crop rotations. Part II: Effects on greenhouse gas emissions, In: Schenck R, Huizenga D (Eds.), Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector (LCA Food 2014), 8-10 October 2014, San Francisco, USA. ACLCA, Vashon, WA, USA, p. 134-141.

Björnsson L, Prade T, Lantz M, Börjesson P, Svensson S-E, Eriksson H (2013) Impact of biogas crop production on greenhouse gas emissions, soil organic matter and food crop production – A case study on farm level. Report No 2013:27, f3 - The Swedish Knowledge Centre for Renewable Transportation Fuels and Foundation, Sweden.

Bolinder MA, Janzen HH, Gregorich EG, Angers DA, VandenBygaart AJ (2007) An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. Agric Ecos Env 118:29-42

Brandão M, Milà i Canals L, Clift R (2011) Soil organic carbon changes in the cultivation of energy crops: Implications for GHG balances and soil quality for use in LCA. Biomass Bioenerg 35:2323-2336

EC (2002) Towards a thematic strategy for soil protection. COM (2002) 179 final. Communication from the Commission to the Council and the European Parliament, the European Economic and Social Committee and the Committee of the Regions. European Environment Agency, Commission of the European Communities. .

IPCC (2006) IPCC guidelines for national greenhose gas inventories vol 4.

Kirchmann H, Eriksson J, Snäll S (1999) Properties and Classification of Soils of the Swedish Long-Term Fertility Experiments: IV. Sites at Ekebo and Fjärdingslöv. Acta Agric Scand, Section B - Soil & Plant Science 49:25-38

Kätterer T, Andrén O (2001) The ICBM family of analytically solved models of soil carbon, nitrogen and microbial biomass dynamics — descriptions and application examples. Ecol Model 136:191-207

Kätterer T, Bolinder MA, Andrén O, Kirchmann H, Menichetti L (2011) Roots contribute more to refractory soil organic matter than above-ground crop residues, as revealed by a long-term field experiment. Agric Ecos Env 141:184-192

Lal R (2004) Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. Science 304:1623-1627

Nilsson D, Bernesson S (2009) Halm som bränsle : Del 1: Tillgångar och skördetidpunkter. Department of Energy and Technology, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Soilservice (2012) SOILSERVICE - Conflicting demands of land use, soil biodiversity and the sustainable delivery of ecosystem goods and services in Europe. Department of Ecology, Lund University, Lund, Sweden.

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