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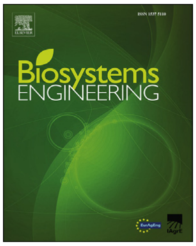

Research Paper

Including a one-year grass ley increases soil organic carbon and decreases greenhouse gas emissions from cereal-dominated rotations – A Swedish farm case study

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Increased soil organic carbon (SOC) content has been shown to increase soil fertility and carbon sequestration, but SOC changes are frequently neglected in life cycle assessment (LCA) studies of crop production. This study used a novel LCA application using simulated SOC changes to examine the greenhouse gas (GHG) impact of a combined food and energy crop production from a crop rotation perspective. On a case pig farm, introduction of one year of grass ley into a cereal-dominated crop rotation was simulated. The grass and pig manure were used for biogas production and the digestion residues were used as fertiliser on the farm. This crop rotation shift increased the SOC stocks by an estimated 27 and 49% after 50 years and at steady state, respectively. The estimated corresponding net wheat yield increase due to higher SOC was 8–16% and 16–32%, respectively, indicating that initial loss of low-yield oat production can be partly counterbalanced. Net SOC increase (corresponding to 2 t CO_2-eq ha^{-1} a^{-1}) was the single most important variable affecting the GHG balance. When biogas replaced fossil fuels, GHG emissions of the combined energy-food crop rotation were approx. 3 t CO_2-eq ha^{-1} a^{-1} lower than for the current food crop rotation. Sensitivity analyses led to variation of only 2–9% in the GHG balance. This study indicates that integrated food and energy crop production can improve SOC content and decrease GHG emissions from cropping systems. It also demonstrates the importance of including SOC changes in crop production-related LCA studies.

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1. Introduction

Soil degradation is a widespread problem, with erosion, loss of soil organic carbon (SOC) and compaction being some of the degradation processes that are threatening agricultural soil fertility throughout Europe (Smith et al., 2005). Intensively cultivated clay soils have been shown in Swedish studies to lose up to 20% of potential food crop yield due to soil compaction and reduced SOC content (Arvidsson & Håkansson, 1991). Restoration of degraded soils has been identified as a measure with high potential impacts on climate stabilisation (Canadell & Schulze, 2014). Accumulation of SOC has also been shown to be positively correlated to several other ecosystem services (Albizua, Williams, Hedlund, & Pascual, 2015). Restoration of SOC content can be achieved by practises such as application of organic amendments, biofertilisers or green manure, or through the introduction of cover crops into the crop rotation (Kätterer, Bolinder, Berglund, & Kirchmann, 2012). Moreover, crop residues, especially roots, contribute to SOC build-up (Kätterer, Bolinder, Andrén, Kirchmann, & Menichetti, 2011). However, in cereal-dominated crop rotations, contribution from root biomass may be relatively low compared to grass leys (Bertilsson, 2006; Nilsson & Bernesson, 2009).

The SOC content affects many soil factors such as nutrient availability, water retention capacity, soil bulk density and soil temperature (Bronick & Lal, 2005). An increase in SOC content may lead to, but is no guarantee of, increased soil productivity (Oelofse et al., 2015). A decreased fertiliser requirement due to higher soil nutrient reserves can be another positive result of a SOC increase (Bronick & Lal, 2005). Integrating grass leys into rotations of solely annual crops can contribute to improve cropping system productivity. Swedish long-term field experiments with or without grass leys in the crop rotation have shown that two years of perennial grass ley in a six-year crop rotation can increase winter wheat yield (Persson, Bergkvist, & Kätterer, 2008). This yield increase would partly compensate for the food-producing acreage lost when grass leys are introduced. Thus, it has been suggested that initial food crop production losses due to crop rotation changes of including grass leys could be compensated for under certain conditions, while this inclusion could also mitigate greenhouse gas (GHG) emissions by soil carbon sequestration (Lal, 2004). Despite this, changes in SOC are neglected in many crop production life cycle assessments (LCAs) (Brandão, Milài Canals, & Clift, 2011), and in GHG emissions calculations for crop-based biofuels required by the EU Renewable Energy Directive (EC, 2009, 2015).

In regions specialising in cereal cropping, declining SOC concentrations are a concern. Unfortunately, a low areal proportion of perennial forage crops in these regions typically coincides with low availability of animal manure. In the major grain-producing areas in Sweden, for example, on average less than 20% of agricultural area is under ley and the amount of manure available corresponds to less than 0.4 animal unit per hectare arable land (Björnsson, Prade, & Lantz, 2016). In a study based on three consecutive national soil inventories, changes in the areal proportion of ley and the amount of manure available were identified as the main drivers for SOC changes in Swedish arable soils (Poeplau, Bolinder, Eriksson, Lundblad, & Kätterer, 2015). Although a rapidly growing horse population in periurban areas was identified in that study as the major driver for increasing SOC stocks in Swedish mineral soils, in other areas ley area and total manure production are to a large extent governed by the size of the domestic ruminant population, which is tightly coupled to non-CO_2 GHG emissions. Growing ley as feedstock for biogas could be a way to increase SOC storage without the negative climate impact of ruminants, and could also be a way to improve cereal-based crop rotations in agricultural regions where ley production is currently not a viable option.

The objectives of this case study were to: (i) analyse the extent to which introduction of grass leys into a cereal-dominated food crop rotation increases SOC content, (ii) evaluate the impact of grass ley introduction on food crop production, and (iii) include SOC changes in the assessment of GHG emissions, in order to evaluate the impact on overall emissions from the cultivation system. Instead of the commonly used single crop approach, this novel systems approach included simulation of SOC development on crop rotation level within the systems boundaries. This allowed a more complete evaluation of the global warming potential impacts of energy crop production in relation to, and integrated with, the underlying food crop rotation. The study was designed as a case study of a farm where SOC content was identified as critical factor for long-term crop productivity. The overall aim was to investigate to what extent assessment of crop production sustainability from a GHG perspective may be biased when the SOC aspect is excluded.

2. Background data and scenarios

The impact of introduction of grass leys into a cereal-dominated crop rotation was investigated as a farm case study. Impacts were modelled for the current crop rotation and compared with those of a modified crop rotation including grass. The case farm was chosen for its crop rotation typical for southern Sweden (Rasmussen, 2012; SBA, 2006), its proximity to a long-term SOC field experiment and its integration with a biogas plant. The farm kept dairy cows until 1960 and the manure was spread on the farm's fields. Since milk production ended, decreasing SOC content has been identified as problematic in the clay-rich soils. Problems with soil compaction and crop failure due to standing water have become more common and crop yields are falling below the regional average (Rasmussen, 2012). Due to these increasing problems, the conventional food crop rotation maintained for decades is seen as being no longer economically sustainable (Rasmussen, 2012).

The farm had access to pig manure after the dairy enterprise was terminated, but more biofertiliser was required to increase the SOC content (Rasmussen, 2012). This was one of the main reasons for constructing a biogas plant within the farm in 2006 (Rasmussen, 2012). Today, pig manure is one of the feedstocks to this biogas plant, where it is treated together with residues from the local food industry (Lantz & Börjesson, 2014). The digestate (the liquid residues from the biogas plant) is used as biofertiliser and meets the nutrient demand that would have been met by mineral fertilisers on the farm. However, competition for food industry residues is increasing and the future for the food industry in the region is uncertain, requiring alternative feedstock supplies. In the present study, grass was investigated as an alternative feedstock by integrating grass ley into the current crop rotation on the farm. This would lead to a higher degree of self-sufficiency in biogas production and would also ensure the supply of biofertiliser for the farm. This study investigated two scenarios, *current* and *modified*, which refer to the current crop rotation without grass and the modified crop rotation with grass, respectively. For both scenarios, a base case was defined in which both scenarios share specific data for a number of variables. In a number of sensitivity analyses, data for these variables were changed for both scenarios simultaneously to study the impact on the global warming impact of changing from the current to the modified scenario.

a. Current scenario

The case farm (56°6′N 12°58′E) comprises 650 ha of medium to heavy clay soils with soil clay content up to 65% and a bulk density of 1.02 t m^{-3} (determined 1984). Soil analyses in 1984 showed that the farm had an average soil organic matter (SOM) content of about 4% (Rasmussen, 2012). The main agricultural regions of southern Sweden are characterised by similar clay and SOC content (Eriksson et al., 2010), which was another reason the farm was chosen. Despite having soils with an average SOC level, the case farm faces considerable problems caused by the high soil clay content leading to decreasing crop yields.

The farm currently applies a four-year crop rotation with winter oilseed rape followed by two years of winter wheat and one year of oats (Table A.1 in the Appendix). Crop sowing on the farm is often carried out in the autumn, very shortly after harvest of the previous crop, since the high clay content leads to less favourable tillage conditions during late autumn and spring under the prevailing humid conditions. This also leaves no opening for other measures to increase SOC, such as after-sown cover crops.

The on-farm biogas reactor is fed with 5500 metric tonnes (t) per year of pig manure (8% DM content), which is produced on the farm. In the present analysis, we included transport of this pig manure to the biogas plant, storage of the digestate in a covered tank and application of the biofertiliser to fields within the farm, while the pig production unit itself was left outside the system boundaries. The biofertiliser was complemented with mineral fertiliser to cover the crop nutrient requirements. As practiced on the case farm, the biogas produced was assumed to be upgraded, compressed, spiked with propane and injected into the natural gas grid (Lantz & Börjesson, 2014). As a measure to increase SOC, the case farm incorporates all straw on their medium to heavy clay soils as recommended for these soil types (Greppa, 2013).

b. The modified scenario

The oat crop in the present four-year rotation on the farm was assumed to be replaced by one year of grass ley undersown in wheat (see Appendix, Table A.1). The impact of this change on SOC was then calculated. Only one year of grass ley was chosen, so as to limit the impact on the food production system, and the oat crop was chosen to be replaced because it is the least productive crop in the rotation.

The LCA was based on the assumptions that the grass was cut, swathed, field-dried to 35% dry matter (DM) content, chopped, ensiled, pre-treated (extrusion) and fed to the biogas plant (together with the currently added pig manure). The digestate of both pig manure and grass silage was assumed to be stored in a covered storage tank and subsequently recycled to the farm as biofertiliser. The biogas produced was handled and used as in the current scenario. Additional modified scenarios were also tested, but are presented elsewhere (Björnsson et al., 2013).

c. Cultivation

Cultivation inputs for the current and modified scenario per hectare and annum are presented in Table 1. Further details about these inputs are provided in the appendix (Tables B.1–B.4; C.1).

The grass ley crop was assumed to be established undersown in wheat and to be harvested once the same year (Prade, Svensson, Hörndahl, Kreuger, & Mattsson, 2015). Break-up of the ley was assumed to be carried out on 1 August the following year, in order to allow time for establishment of winter oilseed rape (Prade et al., 2015). The resulting growing season allowed that the ley was harvested twice in the year when it was terminated. Average harvested yield of the food crops was estimated based on annual measurements on the case farm. Yield of the grass ley was based on manual sampling in recent field experiments (Prade et al., 2015) and was assumed to be 20% lower to account for field losses during harvest (Table 2).

Crop-specific fixed factors and mass ratios based on Nordic data were used to calculate aboveground (stubble, straw) and belowground (root and extra-root biomass) residue inputs to the soil based on the harvested yield data, i.e., grain, oilseeds and grass ley biomass (Table 2). For grass leys, the amount of aboveground residues (stubble) was assumed to be 25% of the harvested biomass. Below-ground crop residues were calculated in two steps: (a) root biomass inputs were calculated using shoot-to-root ratio and (b) exudate inputs (extra-root material) were assumed to be 65% of root input (Bolinder, Janzen, Gregorich, Angers, & VandenBygaart, 2007). In the base case this Nordic dataset was used, which included the regionally adapted data as described in this paragraph.

In a sensitivity analysis the same calculations were repeated with fixed factors and mass ratio data from IPCC (2006). The IPCC dataset was originally prepared for global application, but was assumed to give less reliable simulated changes in SOC content here.

d. Biogas and biofertiliser production

To improve the cause/effect relations in this study, food industry residues currently added to the on-farm biogas plant were excluded from the present calculation, which only included pig manure and grass silage. The inputs and outputs from the biogas plant are shown in Table 3. The amount of

Table 1 – Crop cultivation inputs (kg ha^{-1} a^{-1}), including fertiliser demand in terms of nitrogen (N), phosphorus (P) and potassium (K), and supply by biofertiliser or mineral fertiliser in the current and modified scenario.

Scenario	Crop fertiliser demand			Diesel	Materials	Machinery	Added as mineral fertiliser[a]		
	N	P	K	CO_2-eq[b]	CO_2-eq[b]	CO_2-eq[b]	N	P	K
Current	196	28	42	266	192	99	169	18	27
Modified	192	28	87	341	184	102	138	10	30

[a] The difference between demand and mineral fertiliser application was applied as biofertiliser (Table 3). P, K and the mineralised share of N in the biofertiliser (NH_4-N) were assumed to replace mineral fertiliser after subtraction of loss of NH_3 at application, and mineral fertiliser addition was decreased accordingly.

[b] Values represent CO_2-equivalents. For background data, see appendix (Tables B.1–B.4 and C.1).

Table 2 – Dry matter (DM) yield data for harvested crop parts (wheat and oat grain, oilseeds, grass biomass) and coefficients used for calculation of crop residues contributing to soil organic carbon (SOC).

Crop	Yield [t DM ha^{-1} a^{-1}]	Nordic dataset		IPCC[a] dataset		
		Aboveground[b]	B/A ratio[c]	Aboveground[b]	Intercept[d]	B/A ratio[c]
Winter oilseed rape	2.5	0.92	0.20	1.09	0.88	0.22
Winter wheat	6.5	0.57	0.33	1.61	0.40	0.23
Oats	4.0	0.50	0.47	0.91	0.89	0.25
Grass crop, year of establishment in wheat	2.5	0.25	0.58[e,f]	0.30	0.00	0.00
Grass crop, production year	4.3 + 4.7	0.25	0.88	0.30	0.00	0.80

[a] IPCC (2006) methodology does not specifically include exudates.

[b] Factors for aboveground residues for cereals were based on Nilsson and Bernesson (2009). Aboveground residues = Yield * Aboveground factor + Intercept (IPCC only).

[c] Ratio of belowground residues/aboveground biomass (B/A). Aboveground biomass included stubble and harvested biomass; belowground residues in the Nordic dataset were based on literature data (Akhtar & Mashkoor Alam, 1992; Becka, Vasák, Kroutil, & Stranc, 2004; Kätterer et al., 2011; Koga et al., 2011; Pietola & Alakukku, 2005) and included extra-root material as 65% of other belowground biomass (Bolinder et al., 2007).

[d] t DM ha^{-1} a^{-1}.

[e] Only extra-root biomass was accounted for.

[f] IPCC data suggest unlimited increase of root biomass with grass yield. In the present study, root biomass was assumed to increase proportional with grass yield up to a ceiling value of 6 t DM ha^{-1} which was derived from a study using data from Swedish long-term field experiments (Bertilsson, 2006).

Table 3 – Input and outputs from biogas production, as an average for the whole crop rotation.

	Amount biogas feedstock [t ha^{-1} a^{-1}]		Biogas production[b] [GJ ha^{-1} a^{-1}]	Digestate production [t ha^{-1} a^{-1}]	Content in digestate when applied to field as biofertiliser[c] [kg ha^{-1} a^{-1}]				
Scenario	Manure	Silage[a]			C	N-tot	NH_4-N	P	K
Current	8.5	–	5.0	8.1	109	33	27	10	15
Modified	8.5	8.1	28.1	14.7	718	105	62	18	57

[a] The amount of grass silage was calculated based on yields given in Table 2, assuming field drying to 35% DM, and a loss of 5% DM during ensiling.

[b] Based on DM-based methane yield of 210, 261 and 221 m^3 t^{-1} for pig manure, 1st cut grass silage and 2nd cut grass silage, respectively (Björnsson et al., 2013), model calculations based on biodegradability as presented by Lantz et al. (2013), and after losses during production and upgrading as described in the appendix (Table C.3). All gas volumes are given as dry gas at 0 °C and 101 kPa.

[c] Losses of nitrogen as ammonia nitrogen (NH_3-N) corresponding to 1% of total nitrogen (N-tot) during digestate storage under roof cover were subtracted (Karlsson & Rodhe, 2002). For calculations on the loss of organic material as methane during storage, see appendix (Table C.4). Only the mineralised share of N in the biofertiliser (NH_4-N) was assumed to replace mineral N, and after subtraction of losses of NH_3 at field application, which was assumed to be 0.9% of added N for mineral fertiliser (SEPA, 2015). For the biofertiliser, 15% of added N was assumed to be lost as NH_3 when applied in cereals, 30% when applied in grass crops (Karlsson & Rodhe, 2002). P and K in the biofertiliser were assumed to replace P and K in mineral fertiliser in a 1:1 ratio.

biogas produced from pig manure is the same in both scenarios, in the modified scenario the biogas production from ley grass was added to the biogas produced from pig manure.

3. Methods

a. Soil carbon modelling

Changes in SOC content were calculated employing the ICBM model (Andrén & Kätterer, 1997; Kätterer & Andrén, 2001), which is used for e.g. Swedish GHG emission inventory calculation (SEPA, 2015). The model was applied to calculate the annual SOC content according to carbon inputs and mineralisation rates. For this purpose, the model was adjusted to account for different input types (aboveground and belowground crop residues and manure/digestate amendments; Fig. 1) with specific humification coefficients. Humification coefficients for carbon added as grass (0.12), other crops (0.15), crop roots (0.35) and biofertiliser (0.41; assumed same as for sewage sludge) were taken from Kätterer et al. (2011). Carbon content of crop DM was assumed to be 45% (Kätterer et al., 2011). A starting value of 2% SOC content was assumed, which is in line with the latest measurements on the farm and corresponds to the mean SOC content in agricultural soils of southern Sweden (Carlgren & Mattsson, 2001).

The model was calibrated with data derived from a long-term SOC field experiment located in Ekebo, southern Sweden (55°59′N; 12°52′E; 17.8% clay, 1.43 t m^{-3} bulk density) (KSLA, 2007; Petersen et al., 2008), close to the case farm (Kirchmann, Eriksson, & Snäll, 1999). From this experiment, data on annual crop yield and SOC content determined regularly were available for two different crop rotations, each with 16 different fertilisation regimes, for the period 1962–2014, i.e. 32 time series datasets. The model was calibrated using the first-order decomposition rate of the old carbon pool (k_O) as a variable to fit the modelled to the measured SOC data by maximising the average coefficient of determination (R^2) of all 32 datasets. This resulted in k_O values of 0.0098 and 0.0100 a^{-1} for when the Nordic and the IPCC dataset were used for calculating the amounts of crop residues, respectively. The impact of SOC change was calculated as mean annual SOC change (kg ha^{-1} a^{-1}) by averaging SOC changes over 40 and 20 years for the Nordic and IPCC methodology, respectively.

b. Yield impact

Food crop grain and seed yields have been shown to increase with increasing SOC content (Brady et al., 2015). In the present study, a yield increase was predicted for wheat grain yield and was assumed to be between 0.4 and 0.8 t wheat grain DM ha^{-1} for each 1%-unit increase in SOC (Lal, 2004). Both the upper and the lower value were used to calculate the range of wheat yield change due to SOC change. In the case farm soils (0–20 cm depth), each 1%-unit of SOC corresponds to 20.4 t C ha^{-1}. The yield impact was analysed separately from the GHG emission assessment and was not considered in the LCA assessment.

c. Greenhouse gas emissions

The calculation of GHG emissions was based on the methodology for LCA outlined in the ISO standards (ISO, 2006). Emissions were quantified as global warming potential (GWP) in a 100-year perspective, expressed as carbon dioxide equivalents (CO_2-eq) (IPCC, 2006). The functional unit was the average hectare over the crop rotation per year. The results are also presented per MJ vehicle fuel produced in the modified scenario, to enable assessment of indirect land use change (iLUC) impact (Valin et al., 2015). Data for emissions, emission factors (EF) and GWP are summarised in Tables C.1 and C.2 in the appendix. The assessment included:

(1) Direct and indirect emissions from cultivation (including field application of biofertiliser), harvest, transport and storage of feedstock. Indirect emissions include emissions derived from the manufacture of production means such mineral fertiliser, machinery seeds etc.
(2) Production, upgrading and compression of biogas and emissions from digestate storage. Related energy use and emissions are presented in the appendix (Table C.3). The methane emissions during digestate storage were calculated based on the IPCC model for manure

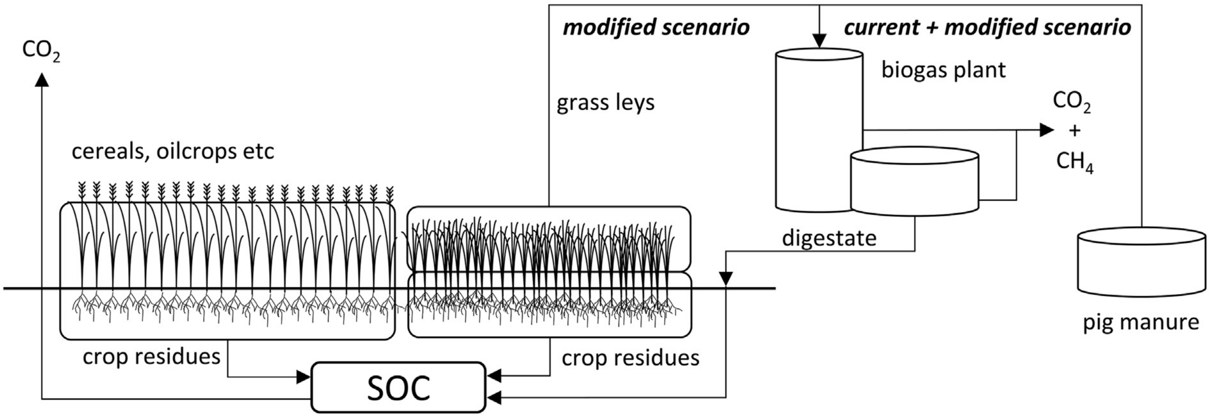

Fig. 1 – Flows of carbon investigated in the soil organic carbon (SOC) modelling.

(IPCC, 2006). Details and complementary input data for calculations are presented in Table C.2 in the appendix.

(3) Changes in SOC were recalculated to mean annual CO_2 uptake. SOM was assumed to contain 50% C and 5% N, i.e. a C:N ratio of 10:1 (Pribyl, 2010). N incorporated in SOM was assumed to be unavailable for biogenic N_2O formation.

For the product outputs from the current and modified scenario, respectively, a systems expansion approach was applied in accordance with the recommendation in the ISO standard (ISO, 2006). In the systems expansion, the total output of grain, oilseeds and biogas was assumed to be equal in the different scenarios, and the lack of oats in the modified scenario was compensated for by additional production outside the farm that was assumed to take place within the region on excess farmland. In the base case, this was assumed not to cause any iLUC due to displacement effects (see Appendix, Table C.1). In the absence of land use change (LUC) impact data for ley as an annual crop, an LUC emissions figure calculated for biogas produced from maize silage (Valin et al., 2015) was used to illustrate the LUC-induced GHG emissions for the modified scenario (Appendix, Table C.1). In the systems expansion, the higher output of upgraded biogas delivered to the natural gas grid in the modified scenario was assumed to replace fossil vehicle fuel (see Appendix, Table C.1), as was the case with 88% of the biogas produced in Swedish co-digestion plants in 2015 (SEA, 2016).

The sensitivity of the results was tested for input data with greater uncertainty or where different input data or emissions factors were given in different standards or references (Table 4). For the SOC calculations, the effects of digestate vs. no digestate application (A; Table 4) and straw incorporation into the soil vs. straw recovery (B) were tested to clarify their contribution to the SOC change. The impact of using the IPCC instead of the Nordic dataset on the mean annual SOC change was also tested (C1-4). For GHG calculations, the sensitivity of important emission factors and process parameters was tested using alternative assumptions (D–J), as was the impact of using the IPCC instead of the Nordic dataset for calculating the mean annual SOC change (K).

4. Results and discussion

a. SOC changes

The two scenarios investigated differed substantially as regards changes in SOC content (Fig. 2). Integration of grass ley into the crop rotation and recycling of biofertiliser increased the SOC content from 2% to 3% within 20–30 years with no straw removed and within 30–40 years with wheat straw removed.

The current scenario was based on the conventional cereal-dominated four-year crop rotation, where all straw was left in the field and where digested pig manure was used to cover part of the fertiliser requirement. The addition of pig manure digestate in combination with relatively high crop residue yields explained the SOC increase in the current scenario even with all straw removed.

In the modified scenario, where a year of grass was introduced into the crop rotation, the amount of digestate produced from pig manure and grass was large enough to cover most of the fertiliser requirement on the farm (Table 1). Accordingly, a much higher increase in SOC was found in the modified scenario compared with the current scenario (Fig. 2). After approximately 140 years, SOC approached steady state at 3.0 and 5.1% SOC in the current and modified scenario with no straw removal, respectively (results not shown). The sensitivity results for the modified scenario where the digestate was excluded (Fig. 2; dashed grey line) demonstrated that a large proportion of the SOC increase originated from applying the digestate as organic fertiliser.

The effect of the grass ley on SOC was similar in both the Nordic and IPCC approach (Fig. 3) and it is clear that the grass had a substantial positive effect on SOC content. A similar strong positive effect of grass ley is recognised in the German SOM contribution guidelines (VDLUFA, 2014). In comparison, the contribution of oats and of winter oilseed rape to SOC was much lower. Winter wheat had a more positive effect on SOC content, but the effect was more than 2.5-fold higher for the IPCC method than with the Nordic approach (Fig. 3). This effect is likely to be attributable to the substantially lower harvest index used in the IPCC methodology, which resulted in higher straw input per unit of grain. While such high straw/grain ratios exist elsewhere, e.g. in the USA (Dai et al., 2016), the trend in cereals, specifically wheat, in Northern Europe (including the study region) has been towards varieties with shorter straw and larger ears (Bertholdsson & Kolodinska Brantestam, 2009; Nilsson & Bernesson, 2009). This harvest index difference was also reflected in the mean annual SOC change for the whole crop rotation, where IPCC methodology clearly resulted in considerably higher soil carbon inputs than the Nordic approach (Fig. 3).

Thus the results showed that introduction of one year of grass into a cereal-dominated crop rotation can substantially improve SOC content, given that the change is a medium to long-term commitment. In fact, the case farm currently operates a second crop rotation that includes three years of meadow fescue for seed production on a smaller fraction of the farm, 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 market for meadow fescue seed. In a region characterised by crop production and lack of organic fertiliser, a biogas plant could help to create a potential market for grass leys and in return deliver digestate for use as organic fertiliser.

Another strategy for improving SOC content would be to implement grass leys as in the modified scenario in order to boost the SOC content to the steady state level of the current scenario within approx. 25 years. This way, the SOC content would be close to the steady state of the current crop rotation if a return to a crop rotation without grass ley is desired.

Direct measurements of SOC changes for a crop rotation is preferable to SOC modelling, but impractical for LCA studies due to the relevant changes being long-term. Estimation of SOC changes in models is an acceptable approach if a well-documented model is locally adjusted (Smith, 2004), as in this study. The applied SOC model is used to estimate GHG emissions from cropland for the Swedish GHG inventory, but

Table 4 – Input data used in the base case and sensitivity analysis. Variables with identical letters were changed simultaneously.

Parameter		Base case	Sensitivity analysis
SOC calculations			
Effect of digestate	(A)	Digestate added to soil[a]	No digestate added to soil
Straw removal	(B)	No straw removal[b]	Straw removal according to typical recovery coefficients[c]
Belowground crop residues (Table 3)	(C1)	Exudates (extra-root residues) correspond to 65% of root residues[d]	Exudates not implicitly included[e]
	(C2)	Root residues proportional to aboveground residues, but limited to 6 t ha^{-1} of DM[f]	Root residues proportional to aboveground residues[e]
Aboveground crop residues (Table 3)	(C3)	Nordic mass ratios	IPCC mass ratios[e]
Time span for calculation of average annual carbon changes	(C4)	40 years	20 years[e]
GHG calculations			
Emissions factor for N_2O emissions at biofertiliser field application	(D)	1%[e]	0.2%[g]
GHG emissions in mineral N production	(E)	6.6 kg CO_2-eq (kg N)$^{-1}$[h]	3.1 kg CO_2-eq (kg N)$^{-1}$[i]
Process energy in biogas production	(F)	Heat from natural gas	Heat from wood chips
	(G)	Swedish average electricity[j]	Nordic average electricity[k]
Direct N_2O emissions in digestate storage	(H)	Roof covered, 0% of N[l]	Floating crust, 0.5% of N[l]
Methane conversion factor for digestate storage	(I)	3.5%[m]	10%[e]
GWP for methane	(J)	25[e]	34[n]
Mean annual SOC change	(K)	Nordic data (C1-4 as outlined above)	IPCC data (C1-4 as outlined above)

[a] This includes digestate from pig manure in the current scenario and digestate from both pig manure and grass ley in the modified scenario.
[b] As practised on the case farm.
[c] Nilsson and Bernesson (2009).
[d] Bolinder et al. (2007).
[e] IPCC (2006).
[f] Bertilsson (2006).
[g] Experimental value from national field experiments with cattle manure digestate (Rodhe et al., 2013).
[h] Current production (Börjesson, Tufvesson, & Lantz, 2010).
[i] Best available technology (BAT) for fertiliser delivered to Sweden (Fossum, 2014).
[j] Gode et al. (2011).
[k] Martinsson, Gode, Arnell, and Höglund (2012).
[l] Direct N_2O emission factors for manure from IPCC (2006) are applied.
[m] Value used in the Swedish GHG inventory (SEPA, 2015).
[n] New value suggested by IPCC (2013).

predicted results are likely to have a higher uncertainty. As presented above, this uncertainty of mean annual SOC change was addressed using a set of sensitivity analyses.

b. Wheat yield changes

Under Nordic conditions, the changes in SOC after 50 years as presented above would lead to an estimated 8–16% net increase in yield of wheat grain in the modified scenario compared with yield in the current scenario (Fig. 4). When approaching steady state, the initial decrease in arable land used for food crop production of 25% for the modified scenario could be offset to a major extent by the yield increase. If oats were replaced by wheat grain on a 1:1 ratio, the loss of oat production of 4 t DM ha^{-1} a^{-1} would be compensated for by a 31% increase in wheat yield, from 6.5 to 8.5 DM ha^{-1} a^{-1}, considering that wheat is grown in two of the four years in the crop rotation.

The predicted food crop yield increase due to increased SOC is in line with that reported in some previous studies (Lal, 2010a; Quiroga, Funaro, Noellemeyer, & Peinemann, 2006), but higher than that reported in others, e.g. Bauer and Black (1994) suggested that potential yield increases due to SOC increases may be as low as 30 kg ha^{-1} for each 1% increase in SOC. This was confirmed by a recent study stating that if no nutrient limitation exists, a SOC content of 1% may already be sufficient to reach maximum productivity and that a further increase in SOC would not affect cereal yield (Oelofse et al., 2015). Indeed, in the yield/SOC feedback loop (increased yields that increase SOC content which again supports higher yields) it is unclear what is cause and what is effect and variables other than SOC content may explain the yield increases found in some studies (Hijbeek et al., 2017). On the other side, our calculations neglected two other potential positive effects of the grass ley on crop yields, namely pre-crop effects due to nutrient transfer and soil structural improvements due to better infiltration, which lowers the risk of standing water and soil compaction (Tidåker, Sundberg, Öborn, Kätterer, & Bergkvist, 2014). This positive pre-crop effect resulted in 1000 kg higher wheat yields according to a compilation of numerous Swedish field experiments (Tidåker et al., 2014). Although the yield/SOC feedback is highly uncertain, the

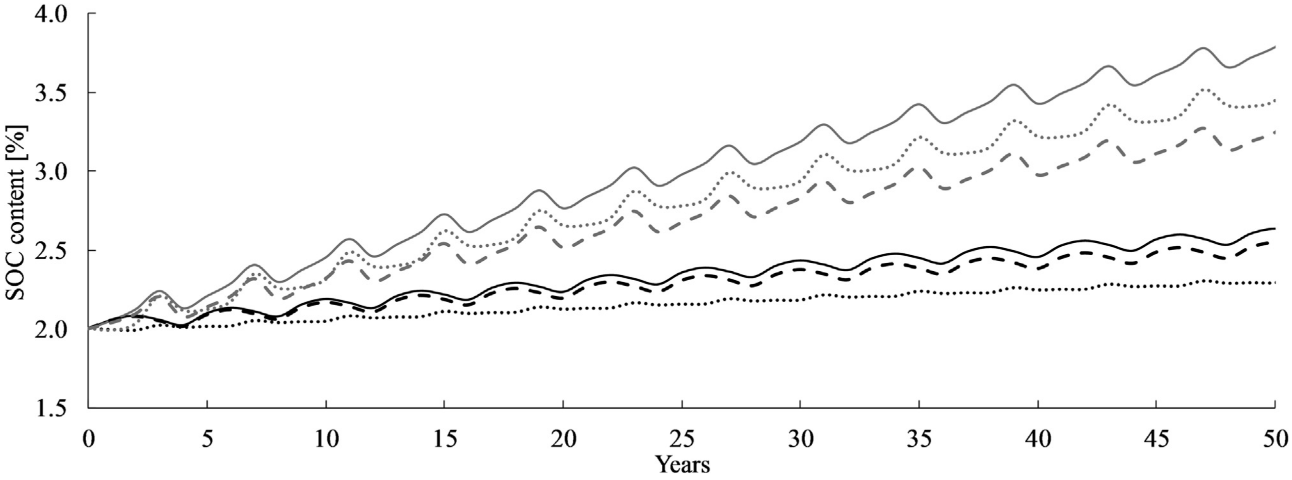

Fig. 2 – Simulated change in soil organic carbon (SOC) content in the current (solid black line) and modified (solid grey line) scenario over a 50-year period under base case conditions. Two sensitivity analyses were tested for both scenarios: (i) the SOC change based on crop residues including straw, but without the effect of digestate spreading (A; Table 4; dashed lines); and (ii) changes in SOC with digestate added but straw removed according to typical recovery coefficients (B; Table 4; dotted lines).

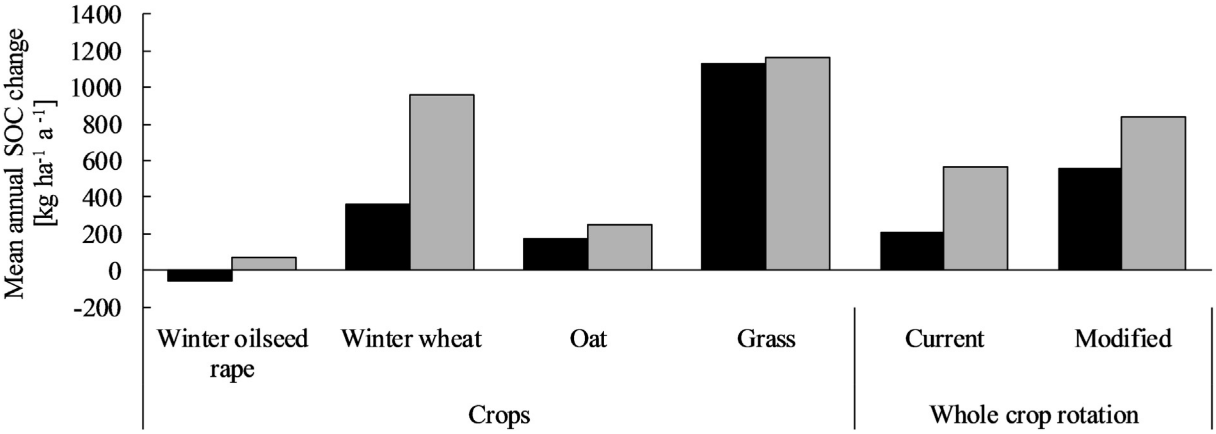

Fig. 3 – Change in mean annual soil organic carbon (SOC, kg ha^{-1} a^{-1}) brought about by single crops and whole crop rotations according to the Nordic (black columns) and IPCC dataset (grey columns) used to calculate the amount of crop residues. Crop rotations represent mean annual SOC changes from both crop residues and digestate application.

wheat yield response assumed in this study was lower than the above pre-crop effect which was not considered in this study and can rather be considered a conservative estimate.

c. Greenhouse gas emissions

The overall greenhouse gas (GHG) emissions in the modified scenario were considerably lower than in current conditions (Table 5).

Emissions related to cultivation were slightly higher in the modified compared with the current scenario. This was mainly due to the increase in biogenic N_2O formation when approximately one-third of the crop N demand was provided through biofertiliser, and also due to the higher amount of N-containing crop residues when grass was included in the crop rotation. However, these emissions were partly compensated for by the decreased N_2O emissions deriving from production and application of mineral fertiliser. Emissions from the production of biogas increased for the modified scenario in proportion to the higher amounts of feedstock processed. The current scenario, with a smaller amount of organic fertiliser applied and with all straw assumed to be left in the field, led to carbon sequestration. Replacing oats with grass in the modified scenario had a profound impact on carbon sequestration.

The impact of the different product outputs in the modified scenario was integrated in the assessment as corresponding GHG emissions through systems expansion. The net GHG emissions from cultivation and biogas production (Table 5) are shown together with the impact of systems expansion, where emissions from additional crop cultivation and emission benefits of biogas replacing fossil fuels were considered. The total net emissions of the current system amounted to 2.1 t CO_2-eq ha^{-1} a^{-1}, while the modified scenario resulted in avoided emissions of 0.9 t CO_2-eq ha^{-1} a^{-1} (Fig. 5).

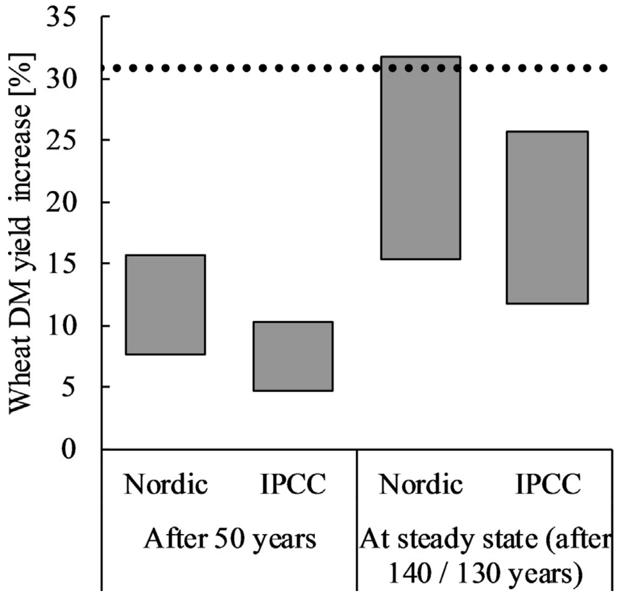

Fig. 4 – Predicted wheat yield increase in the modified scenario relative to the current scenario after 50 years and close to steady state (SS). The dashed line corresponds to the wheat yield increase required if wheat were to replace oats on a 1:1 mass ratio basis.

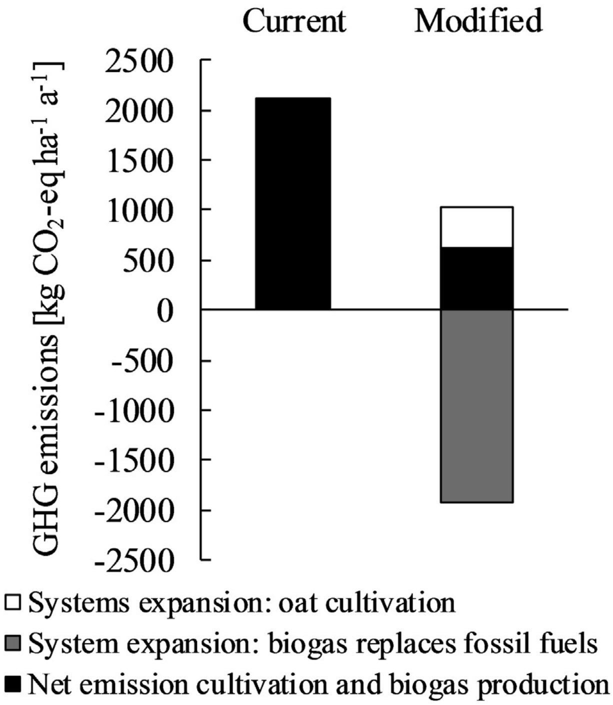

Fig. 5 – Total emissions of greenhouse gases (GHG) in the current and modified scenario after systems expansion, i.e. where emissions or avoided emissions are included to achieve equal crop product output in the current and modified scenario.

The avoided emissions were to a large extent an effect of the SOC changes that occurred when grass ley was introduced in the crop rotation. The impact of replacing fossil fuels with the biogas produced was equally important.

Figure 6 shows the GHG emissions as the difference between the modified and current scenario, and per MJ biogas produced from grass silage. The emissions from cultivation and biogas production were small compared with the large benefit of the SOC increase and the impact of cultivation of the lost oats production, including the LUC impact.

Even on including the LUC impact, the net emissions for the biofuel were negative, giving avoided emissions of 26 g CO_2-eq MJ^{-1} even without the benefit of replacing fossil fuels being considered. This is in line with other regional studies on grass as biofuel feedstock, where a GHG reduction of over 100% has been reported compared with the reference GHG emissions value for fossil fuels of 84 g CO_2-eq MJ^{-1} (Börjesson, Prade, Lantz, & Björnsson, 2015).

The sensitivity analyses showed that both scenarios were sensitive to some aspects, e.g. reducing the field emissions of N_2O (D, Table 6), a shift to best available technology (BAT) in the production of mineral nitrogen fertiliser (E, Table 6) and how the amounts of crop residues and SOC impacts were calculated (K, Table 6). However, since these aspects influenced both scenarios, the impact of a change from the current to the modified system was low. Irrespective of components evaluated in the sensitivity analysis, the change to the modified scenario including grass resulted in a large reduction in GHG emissions in the order of 3 t CO_2-eq ha^{-1} a^{-1} compared with the current conventional four-year cereal-based crop rotation. The parameters tested in sensitivity analysis led to an acceptable variation in the base case result of 2–9%.

The use of crops or the removal of crop residues from farm land for biofuel production is often regarded as controversial and has been identified as having a negative impact on soil quality and food crop productivity (Lal, 2010b; Möller, Schulz, & Müller, 2011). Moreover, biogas production from grass has

Table 5 – Greenhouse gas (GHG) emissions per emissions category for the current and modified scenarios. Negative values indicate avoided emissions.

Emission category	Current	Modified
	[kg CO_2-eq ha^{-1} a^{-1}]	
Cultivation – diesel	229	304
Cultivation – materials/machinery	291	287
Cultivation – fertiliser production	1179	903
Biogenic N_2O – mineral fertiliser	632	515
Biogenic N_2O – biofertiliser	155	489
Biogenic N_2O – crop residues	179	349
Biogenic N_2O – indirect	175	212
Subtotal cultivation	2838	3059
Biogas – process and pre-treatment energy	75	151
Biogas – upgrading energy and propane	9	49
Biogas – process methane leakage	7	41
Biogas – upgrading methane leakage	25	141
Emissions digestate storage	57	102
Subtotal biogas process	174	484
SOC change	−803	−2592
SOM nitrogen uptake	−103	−331
Subtotal SOM change	−905	−2923
Net emissions before systems expansion	**2107**	**620**

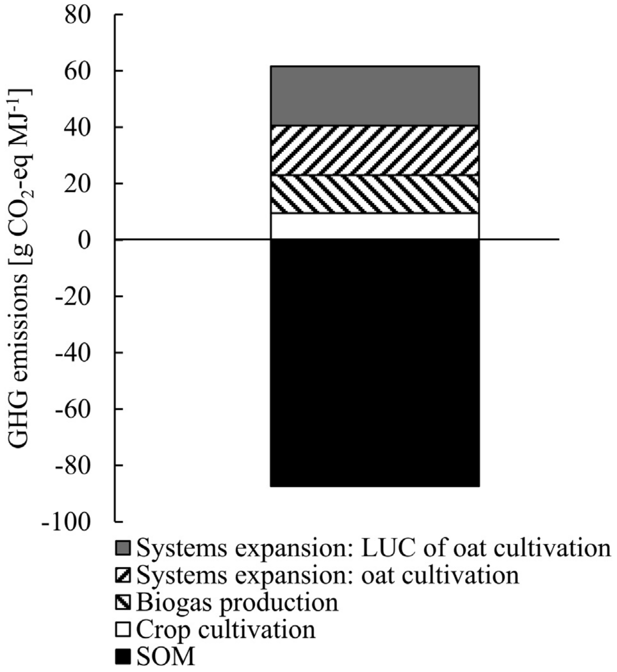

Fig. 6 – Greenhouse gas (GHG) emissions impact including systems expansion of a change from the current to the modified scenario, shown as the emissions per MJ fuel produced.

Table 6 – Impact on total greenhouse gas (GHG) emissions (kg CO_2-eq ha^{-1} a^{-1}) in the current and modified scenario for the components investigated in the sensitivity analysis. The results are presented as the net impact on the total emissions for the current and the modified scenario after systems expansion, and as the resulting impact of a change from the current to the modified system. Letters refer to the parameters listed in Table 4.

	Current	Modified	Impact of change
Base case	2107	−908	−3015
(D) Emissions factor N_2O biofertiliser	1983	−1299	−3282
(E) Best available technology (BAT) for mineral N production	1515	−1363	−2878
(F) Heat source	2040	−1041	−3081
(G) Electricity source	2125	−837	−2963
(H) N_2O digestate storage	2185	−661	−2846
(I) Methane conversion factor (MCF) digestate storage[a]	2210	−727	−2937
(I + J) I + GWP methane	2267	−627	−2894
(K) IPCC dataset for mean SOC change calculation	917	−1890	−2806

[a] The result includes only the impact of increased methane emissions from storage, not the impact on SOC. The higher methane loss from digestate storage also decreased the residual amount of C applied as biofertiliser. In the modified scenario this impact was very small (only 1% of the C in the base case was lost), but in the current scenario 14% of the C in the digestate was lost at the assumed higher methane leakage in the sensitivity analysis.

been shown to have low profitability from a biogas plant perspective at present biofuel market prices (Lantz et al., 2013), which might hinder the introduction of such systems in spite of the positive impact on the agricultural GHG balance. The present study has therefore been followed up with a study encompassing several Swedish regions, including economic evaluations of grass crops as biogas feedstock and other aspects that are important from the farm perspective (Björnsson et al., 2016).

Overall, a large range of crops can be used for biofuel production and their potential impact on the cultivation system varies, so it can be counterproductive to generalise suitability of a specific crop based on negative or positive examples. Instead, the main interactions of the crop within the applied crop rotation need to be highlighted. Combining food production with renewable energy production has been suggested as one possible approach to achieve food systems with lower GHG emissions and to combine food security with energy security (Bogdanski, Dubois, Jamieson, & Krell, 2010). The present study provides an example of a dual benefit, where the GHG reduction is large both during cultivation and due to the production and use of a renewable fuel. Securing future food production will also require sustained or even increased SOC content, which will require the predicted SOC decline in European soils (Smith et al., 2005) to be reversed. Still, only few studies considered simulated SOC changes in GHG balance assessments (e.g. Brandão et al., 2011; Goglio et al., 2015). The importance of SOC changes for both crop-specific and crop rotation-wide GHG balances demonstrated here underlines the need to include SOC change assessment in crop production LCA studies. This includes governing documents such as the EU sustainability criteria for biofuels from crops, which currently do not include the direct SOC changes in arable land (EC, 2015). Furthermore, the LUC impacts suggested and implemented in the EU Renewable Energy Directive for 2021–2030 (EC, 2016) include indirect SOC impacts, but do not consider the direct SOC impacts of changed crops/crop rotations. In some cases, this may cause a bias against energy crop production on arable land if based on incomplete assessments. The present study exemplified the impact of such an approach.

5. Conclusions

In the novel systems approach of simulating SOC changes employed in this case study, a change from a cereal-dominated food crop rotation to a system with integrated production of food crops and grass for biogas production gave indications to:

- Be an efficient measure to increase the SOC content while diversifying the crop rotation. Use as biofertiliser of digestate from biogas production from the grass biomass led to additional SOC build up.
- Result in a direct decline in food crop production. However, potential crop yield improvements due to long-term SOC increases may partly counterbalance these initial production losses.

- Strongly reduce GHG emissions from the whole crop rotation. The GHG benefit due to SOC sequestration was shown to be substantial and we strongly suggest that it be included in crop production LCAs.

Thus, the novel approach of setting simulated SOC changes in agricultural energy crop production in a crop rotation perspective demonstrated that integration of energy and food crop production can reduce GHG emissions and improve cultivation conditions for the overall agricultural production system. Sensitivity analyses showed that uncertainties regarding SOC simulation were acceptable for the tested parameters.

The study also highlighted the need to include SOC change assessment in crop production LCA studies and in regulations at EU level. LUC impacts are covered in the EU Renewable Energy Directive for 2021–2030 and include indirect SOC impacts, but direct SOC impacts of changes in crops/crop rotations are not considered, which may cause substantial bias in assessments of energy crop production on arable land.

Author contribution

Thomas Prade (TP) and Lovisa Björnsson (LB) planned and designed the study and wrote the majority of the paper. TP calculated inputs and emissions of the crop production systems and modelled SOC changes. LB calculated inputs and emissions from biogas production, SOC changes and performed the LCA. Thomas Kätterer (TK) contributed data from long-term cultivation experiments and general help in SOC model calibration. All authors read and commented on the manuscript.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.biosystemseng.2017.10.016.

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