Introduction of grass-clover crops as biogas feedstock in cereal-dominated crop rotations. Part II: Effects on greenhouse gas emissions

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ABSTRACT

In an analysis of climate effects, increased soil organic carbon will have a dual effect due to both increased soil fertility and carbon sequestration. Even so, soil carbon changes are neglected in many crop production LCAs. In the present study, the introduction of grass-clover crops in cereal-dominated crop production was evaluated. The grass-clover crops were used for biogas production, and the digested residue was recycled to the farm as biofertilizer. A shift from the cereal-dominated crop rotation to integrated production of food crops and one or two years of grass-clover crops used as biogas feedstock would result in avoided emissions of 2-3 t CO_2-eq. ha^{-1} a^{-1}. Integrated food and energy crop production would in this case improve soil organic carbon content at the same time as resulting in considerably decreased greenhouse gas emissions from the cultivation system.

Keywords: soil organic carbon, energy crop, biogas, integrated production

1. Introduction

The use of crops or the removal of crop residues from farm land for biofuel production is often controversial, and has been identified as having negative impact on soil quality and food crop productivity (Lal 2010). The range of crops that can be used for biofuel production is, however, large, and it can be contra productive to generalize since the impact of crop choice on the cultivation system is complex and variable. An important aspect in the evaluation of changed land use is the impact on soil organic carbon (SOC) content. In an analysis of climate effects, increased SOC will have a dual effect due to increased soil fertility and crop yields and due to the carbon sequestration (Lal 2004). Even so, changes in SOC are neglected in many crop production life cycle assessments (LCAs) (Brandao et al. 2011). Loss of SOC, erosion and compaction are some of the degradation processes that are threatening soil fertility throughout the EU (EEA 2002; Soilservice 2012). Restoration of SOC content can be achieved by e.g. application of biofertilizers containing organic matter and by including green manuring, catch and cover crops in the crop rotation (FAO 2002). However, intensive agriculture is often niched to either crop production or animal husbandry. In Sweden, farms with animal husbandry cultivate grass-clover crops for forage, and have access to animal manure as biofertilizer, both which positively impacts soil SOC content (Jordbruksverket 2014). In regions with intensive food crop production on the other hand, there is no market for forage crops and the biofertilizer availability is low.

In the present study, which is presented in two parts, the purpose was to evaluate the introduction of grass-clover crops in a cereal-dominated crop rotation in a region with stockless farming and intensively cultivated clay rich soils. The calculations were performed as a farm based case study. At the case farm, the low input of carbon in the intensive food crop production the last decades has been identified as problematic with regards to the high clay content in the soils. Problems with soil compaction and crop losses due to standing water are common, and the grain yield is lower on the farm than in the region in general due to soil compaction in combination with low soil carbon content. Thus, the conventional food crop production maintained for decades was no longer seen as sustainable. The approach investigated in the present study was to integrate 1-2 years of grass-clover crops in the food crop rotation and use this as feedstock for biogas production. The purpose was to evaluate a scenario where a biogas plant has been integrated in an agricultural region with mainly stockless farming, where the biogas plant takes on the role of the absent ruminants. The presence of the biogas plant could create a market for the grass-clover forage as energy crop, and the biogas process also produces a digestate (the liquid residue after the biogas production), which can be used as biofertilizer. The overall objective of the project was to analyse how an integrated production of food crops and energy crops for biogas production impacts SOC and food crop production, which is presented in Part I of the study (Prade et al. 2014), and greenhouse gas emissions per land area, which is presented in the present paper, compared to the presently used food crop rotation.

2. Scenarios for crop production

The case farm (56°N, 12°E) includes 650 hectare (ha, 10 000 m^2) of medium to very heavy clay soils with soil clay content up to 65%, with a 4-year cereal based crop rotation typical for the region, including winter oil seed rape, winter wheat, winter wheat and oats. The reference scenario in the present study is based on data on yields measured at the farm for this crop rotation. In two scenarios, the crop rotation is extended to also include one year of grass-clover crops following oats (Scenario GC1), or two consecutive years of grass-clover crops following oats (Scenario GC2). This reduces the land used for production of food crops within the farm by 20% (GC1) and 33% (GC2).

The information on cultivation inputs for each investigated crop rotation is given as average per ha and year (a, annum) in Table 1. Operations include crop cultivation, fertilization with mineral fertilizer or biofertilizer, harvest, and for the biogas feedstock grass-clover also ensiling, transport to biogas plant and feed-in at biogas plant. Use of machinery and materials in different production operations was analyzed in order to calculate direct and indirect greenhouse gas (GHG) emissions, and include emissions from a large range of inputs as seeds, pesticides, concrete and plastics for ensiling etc and are summarized as corresponding GHG emissions as carbon dioxide equivalents (CO_2-eq) (Table 1). For details on these inputs, please refer to Björnsson et al. (2013). The main contributors to GHG emissions in cultivation (fertilizer production and diesel consumption) are given separately as amounts (kg fertilizer or liter of diesel) (Table 1). The fertilizer demand is the average demand of nitrogen (N), phosphorous (P) and potassium (K) in the crop rotations.

Table 1. Crop cultivation inputs

Scenario			**Reference**	**GC1**	**GC2**
		N	196	183	179
Crop fertilizer demand	[kg ha^{-1} a^{-1}]	P	28	27	28
		K	42	76	103
Diesel	[l ha^{-1} a^{-1}]		69	84	87
Materials	[kg ha^{-1} a^{-1}]	CO_2-eq	192	197	176
Machinery	[kg ha^{-1} a^{-1}]	CO_2-eq	92	107	94

Crop yield data and coefficients used for calculation of crop residues and SOC are presented in Part I of this study (Prade et al. 2014). Amounts of crop residues are calculated based on Nordic data in the base case, and in the sensitivity analysis the methodology presented by IPCC is applied (IPCC 2006). The amounts of crop residues are important for calculations of SOC, and in addition give rise to biogenic nitrous oxide (N_2O) emissions. The N content of the crop residues as presented by IPCC are used (IPCC 2006) for these calculations.

3. Biogas production

The problems with soil compaction and the declining grain yields at the case farm were the main reasons for constructing a biogas plant within the farm boundaries in 2006. Biogas is there produced from mainly food industrial waste. The digestate is used as biofertilizer on all land within the farm since 2007. Life cycle inventory data from a LCA performed for the biogas plant within the boundaries of the investigated case farm was used as input for the biogas part of the present study (Lantz and Börjesson 2014).

For the grass-clover as biogas feedstock, the emissions from cultivation inputs given in Table 1 include cultivation and harvest, field drying (to 35% dry matter, DM), transport to biogas plant, ensiling in bunker silos (assuming a DM loss of 5%) and feed-in at the biogas plant. The amounts of grass-clover silage available as biogas feedstock after losses are shown as average per ha of the crop rotation in Table 2. After feed-in, the grass-clover silage is assumed to be pretreated by extrusion to improve the properties as biogas feedstock, where after it is kept at 37°C under oxygen free conditions in the stirred tank biogas digester. The digestate is stored in a covered digestate storage tank and subsequently recycled to the farm as biofertilizer. Loading, transport to field and spreading of the digestate as biofertilizer is included in the cultivation inputs shown for GC1 and GC2 in Table 1. The biogas produced is upgraded, compressed, spiked with propane (a requirement to compensate for the lower energy value of the upgraded biogas compared to the gas in the Swedish natural gas grid) and delivered to the natural gas grid. The compression to 200 bar required at the vehicle filling station is also included.

GHG emissions were calculated based on mass of biogas feedstock, mass of digestate or the biogas produced for each scenario as presented in Table 2. Background information on emissions or primary energy demands are given as footnotes below the table. Emissions in biogas production are calculated to represent only the emissions related to the grass-clover, even if in practice this feedstock will be co-digested with other biogas feedstock. Similarly, the amount of biofertilizer in the form of digestate is calculated to correspond only to the product from grass-clover digestion. Thus, the emissions or benefits from digestate originating from other organic feedstock (food industrial waste etc.) are excluded.

Table 2 shows the amount of digestate and the content of N as total nitrogen (N-tot) and ammonium nitrogen (NH_4-N), P and K. These calculated concentrations are based on measured content in the grass-clover feedstock (Björnsson et al. 2013) and a calculation model for nitrogen mineralization during biogas production based on methane yields as presented by Lantz et al. (Lantz et al. submitted). This digestate is used as biofertilizer in the GC1 and GC2 scenarios, and then partly replaces the mineral fertilizers needed to fulfil the crop fertilizer demand (Table 1), while in the reference scenario, mineral fertilizers only are used.

Table 2. Input and outputs from biogas production in the grass-clover scenarios

Scenario			**GC1**	**GC2**
Amount biogas feedstock [a]	[t ha^{-1} a^{-1}]		5.9	10.5
Biogas production [b]	[GJ ha^{-1} a^{-1}]		17.3	30.9
Amount of digestate [c, d]	[t ha^{-1} a^{-1}]		4.8	8.5
Applied to field as digestate [e]	[kg ha^{-1} a^{-1}]	N-tot	54	87
		NH_4-N	28	42
		P	6	10
		K	32	52

[a] Primary energy input per t feedstock: electricity for extrusion 50 MJ t^{-1}, electricity for pumping and stirring 54 MJ t^{-1}, natural gas for process heat 121 MJ t^{-1} (Lantz and Börjesson 2014).
[b] Based on methane yields of 261 m^3 t^{-1} DM and 221 m^3 t^{-1} DM for 1st and 2nd cut grass-clover (Björnsson et al. 2013) and after methane losses in production (0.29%) and upgrading (1%) (Lantz and Börjesson 2014). Primary energy input in gas handling: upgrading 3.0% of energy in upgraded gas, compression 2.6% of energy in upgraded gas. Propane addition; energy corresponding to 25% of the energy in the upgraded biogas.
[c] Calculated as average for the crop rotation (as if the amount is distributed evenly spread evenly on the farm).
[d] Losses of nitrogen and organic material during digestate storage under roof cover are subtracted: 1% of total nitrogen (N-tot) is lost as ammonia nitrogen (NH_3-N). Methane emissions are calculated based on the IPCC model for manure (IPCC 2006) with a scenario specific calculated maximum methane potential (B_0) and a methane conversion factor of 3.5% (Naturvårdsverket 2013), resulting in methane emissions during digestate storage of 0.4% (GC1) and 0.5% (GC2) of the produced methane (Björnsson et al. 2013).
[e] Only the N present as NH_4-N is assumed to replace mineral N. P and K are assumed to replace mineral fertilizer without losses.

4. Method

The LCA was performed according to the ISO standard (ISO 2006), with focus on quantifying emissions of greenhouse gasses (GHG). The functional unit was set to 1 ha of arable land. The assessment included cultivation, harvest and storage of crops, biogas production, upgrading and compressing, digestate storage and application and soil carbon changes. The majority of the LCI data are summarized in Tables 1 and 2. Additional emission and characterization factors are summarized in Table 3. Data on harvest yields, SOC modelling and SOC changes are presented in Part I of the study (Prade et al. 2014). A systems expansion approach, in accordance with the recommendation in the ISO standard, was applied. In the systems expansion, the total output of grains (wheat and oats) and oil seed (rape seed) was equivalent in the different scenarios. Thus, a reduced output of grains and oil seeds per ha in the crop rotation as a whole, due to the introduction of grass-clover crop cultivation, was compensated for by additional grain and oil seed production outside the farm. The potential benefit of improved food crop yields due to SOC increases as outlined in Part I of this study was thus not taken into account here (Prade et al. 2014). The required additional cultivation was assumed to take place within the region on excess farmland, not leading to any indirect land use changes due to displacement effects. Regional data for GHG emissions in cultivation (Börjesson et al. 2010) were used, and recalculated per kg DM of crop grain or seed (Table 4). The output of upgraded biogas delivered to vehicle filling stations via the natural gas grid was assumed to replace fossil vehicle fuels (EU 2009) (Table 4).

Table 3. GHG emission and characterization factors

Characterisation factors in aggregation of emissions		**Reference**
CH_4	23 g CO_2-eq (g CH_4)$^{-1}$	(IPCC 2006)
N_2O	296 g CO_2-eq (g N_2O)$^{-1}$	(IPCC 2006)
Life cycle emissions from input energy or materials		
Diesel	84 g CO_2-eq MJ^{-1}	(EU 2009)
Swedish electricity mix [a]	10 g CO_2-eq MJ^{-1}	(Gode et al. 2011)
Nordic electricity mix [b]	69 g CO_2-eq MJ^{-1}	(Gode et al. 2011)
Wood chips [b]	2 g CO_2-eq MJ^{-1}	(Gode et al. 2011)
Propane [c]	74 g CO_2-eq MJ^{-1}	(JRC 2011)
Natural gas [a]	69 g CO_2-eq MJ^{-1}	(JRC 2011)
Fertilizer production – N	6.6 g CO_2-eq g^{-1}	(Börjesson et al. 2010)
Fertilizer production – P	2.9 g CO_2-eq g^{-1}	(Börjesson et al. 2010)
Fertilizer production – K	0.4 g CO_2-eq g^{-1}	(Börjesson et al. 2010)

[a] Used in base case calculations.
[b] Used in sensitivity analysis for electricity or heat demand in biogas production.
[c] Propane required for spiking the biogas replaces natural gas in the grid.

Table 4. Product GHG emissions used in systems expansion

Emissions from replacing crops or fossil fuels	
Oats grain	407 kg CO_2-eq (t DM)$^{-1}$
Rape seed	829 kg CO_2-eq (t DM)$^{-1}$
Wheat grain	407 kg CO_2-eq (t DM)$^{-1}$
Fossil fuels	84 kg CO_2-eq MJ^{-1}

Direct biogenic emissions of N_2O were calculated based on the IPCC model, where 1% of the N contained in crop residues is assumed to be converted to N_2O-N (IPCC 2006). This IPCC N_2O emission factor (EF) of 1% was also applied for the N added through biofertilizer, while a national EF of 0.8% (Naturvårdsverket 2013) was used for mineral fertilizer in the base case, and the IPCC EF in the sensitivity analysis.

Nitrogen losses to air after field application were calculated as corresponding to 15% of digestate content of NH_4-N when applied in cereals/rape and 30% when applied in grass-clover (Naturvårdsverket 2013). The corresponding loss at mineral fertilizer application was 0.9% (Naturvårdsverket 2013). Nitrogen leakage to water was calculated based on regional data to 42, 43 and 35 kg N ha^{-1} a^{-1} for the crop rotations in the reference, GC1 and GC2 scenarios respectively (Johnsson et al. 2008). For indirect N_2O emissions, 1% of nitrogen emitted to air or water was assumed to be converted to N_2O-N (IPCC 2006).

The increases in SOC for all scenarios as presented in Part I (Prade et al. 2014) are in the present study given as average annual CO_2-uptake. In addition, N in a mass ratio of 1:10 to accumulated SOC is assumed to be made unavailable for biogenic N_2O formation in the soil due to the integration in soil organic matter.

Sensitivity analyses were performed for a range of the input assumptions as summarized in Table 5. For details on these assessments and the selection of data, please refer to Björnsson et al. (2013).

Table 5. Background data and assumptions in base case and sensitivity analyses

Variable	**Base case**	**Sensitivity analysis**
Time span	40 years [a]	20 years [b]
Amounts of crop residues	Nordic data [a]	IPCC method [b]
N_2O EF mineral fertilizer	0.8%, National [c]	1%, IPCC [b]
Digestate storage methane leakage	National MCF 3.5% [c]	Experimental for digestate [d]
Biogas production – electricity [e]	Swedish mix	Nordic mix
Biogas production – heat [e]	Natural gas	Wood chips

[a] (Björnsson et al. 2013)
[b] (IPCC 2006)
[c] (Naturvårdsverket 2013)
[d] (Rodhe et al. 2013)
[e] See Table 3

5. Results and discussion

The GHG emissions are shown in Table 6 together with the product outputs of crops and biogas given as average per ha for the crop rotations in the three analysed scenarios.

Table 6. GHG emissions per category and product outputs for the three analysed scenarios

SCENARIO:	**Reference**	**GC1**	**GC2**
GHG EMISSIONS [kg CO_2-eq ha^{-1} a^{-1}]			
CULTIVATION			
Fertilizer	1 393	1 103	980
Diesel	208	252	263
Materials	192	197	176
Machinery	92	107	94
BIOGENIC N_2O			
Mineral fertilizer	729	577	509
Biofertilizer	-	252	405
Crop residues	179	298	320
Indirect	155	179	170
Soil organic matter	-98	-271	-307
BIOGAS PRODUCTION			
Process and pre-treatment energy	-	55	99
Upgrading energy and propane	-	30	54
Process methane leakage	-	25	45
Upgrading methane leakage	-	87	155
Digestate storage	-	34	79
SOIL ORGANIC CARBON (SOC)	-769	-2 124	-2 401
NET EMISSION	**2 081**	**801**	**643**
PRODUCT OUTPUTS			
Oats [t DM ha^{-1} a^{-1}]	1.00	0.80	0.67
Winter oil seed rape [t DM ha^{-1} a^{-1}]	0.63	0.50	0.42
Winter wheat [t DM ha^{-1} a^{-1}]	3.25	2.60	2.17
Biogas [GJ ha^{-1} a^{-1}]	-	17.3	30.9

The avoided GHG emission due to carbon sequestration by SOC incorporation has a strong impact on total GHG emissions in all scenarios, but especially in the GC scenarios, where grass-clover root biomass and biofertilizer give additional SOC contributions. In the reference scenario, the crop residues left in the field give a low and slow build-up of SOC content to 2.9% after 145 years, while in the GC scenarios, 3% SOC is reached already after 30 years, with a steady state level after 125 years of 4.1-4.4% (Prade et al. 2014). Emissions related to inputs in cultivation (diesel, fertilizers, materials, machinery) decrease in the GC scenarios due to the decreased fertilizer demand when biofertilizer is used. Biogenic N_2O emissions, however, increase due to larger emissions from biofertilizer and from the nitrogen in crop residues from grass-clover. At the same time, the SOC build-up in the GC scenarios also gives a large incorporation of N into soil organic matter, which decreases the N_2O emissions, giving a similar net emission of biogenic N_2O in all scenarios. Emissions related to the production of biogas in the GC scenarios give a relatively small contribution. All in all, the conventional food crop rotation gives an average GHG emission of 2.1 t CO_2-eq ha^{-1} a^{-1}. The emissions from the GC scenarios with integrated food crop and grass-clover production are much lower, 0.6 to 0.8 t CO_2-eq ha^{-1} a^{-1}.

In the systems expansion, the 20-33% lower production of food crops in the GC scenarios (Table 6) is included as an added climate impact from cultivation of these crops elsewhere in the region, while the avoided GHG emission when the upgraded biogas (Table 6) replaces fossil vehicle fuels is subtracted. The resulting total GHG emissions after systems expansion are shown in Figure 1, where the striped bars show the emissions summarized per category from Table 6, and the dotted bars show the impact of systems expansion. The resulting net GHG emission is negative for both GC scenarios; -0.2 t CO_2-eq ha^{-1} a^{-1} when one year (GC1), and -1.2 t CO_2-eq ha^{-1} a^{-1} when two years of grass-clover crops is integrated in the food crop rotation (GC2).

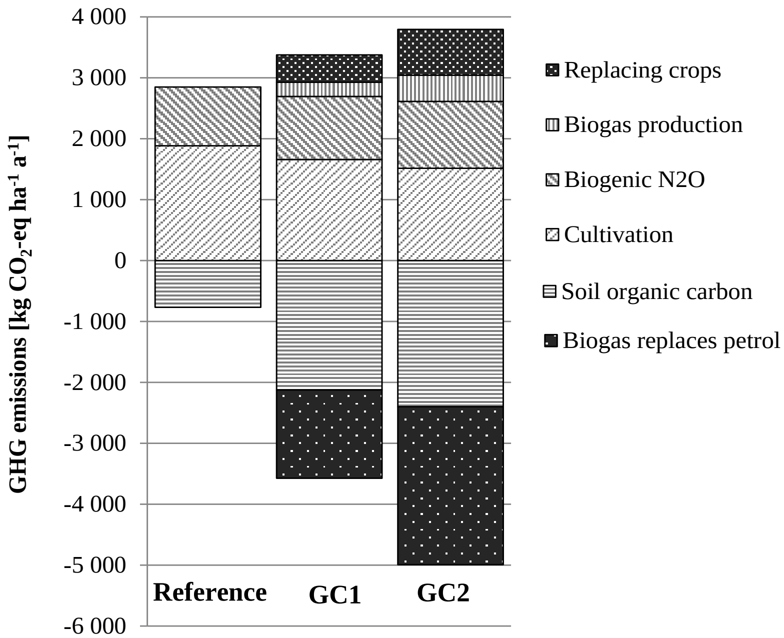

Figure 1. GHG emissions summarized per category in Table 6 (striped bars), and after systems expansion (dotted bars).

The net GHG emissions per scenario from Figure 1 are shown as the base case in Figure 2, together with the impact of changing input parameters in SOC modelling, cultivation and biogas production in the sensitivity analysis. In the base case, the annual SOC change was calculated over a time span of 40 years, to reflect the slow process (125-145 years) of achieving steady state SOC levels. IPCC suggest a 20 year timespan, which is applied in the sensitivity analysis and give lower annual GHG emissions for all scenarios. In the base case calculations, amounts of crop residues are calculated based on Nordic data on ratios between harvested crop and crop residues (Björnsson et al. 2013; Prade et al. 2014). The IPCC methodology evaluated in the sensitivity analysis differs mainly in suggesting much higher cereal straw yields (IPCC 2006). IPCC data thus give higher SOC accumulation and lower GHG emissions for all the investigated scenarios, but with larger impact on the reference scenario with 75% cereals in the crop rotation. The straw yields suggested in the IPCC calculation model are, however, unrealistically high compared to actual straw yields in cereal cultivation in Sweden (Nilsson and Bernesson 2009). The only other aspect in the sensitivity analysis with a noticeable impact on the net result is the assumption about increased methane emissions from digestate storage, which is based on an experimental study on digested cattle manure (Digestate storage CH_4, Figure 2). The risk of methane leakage is an important aspect to consider, since digestate from grass-clover digestion will contain quite a high residual amount of undigested organic material. This makes the digestate interesting as biofertilizer, but also increases the risk of methane leakage during storage. Since 99% of the digestate methane leakage has been shown to occur during the warmer months of the year, (Rodhe et al. 2013), a way of minimizing leakage is to make sure the storage is emptied in spring, which is what is assumed in the base case in the present study.

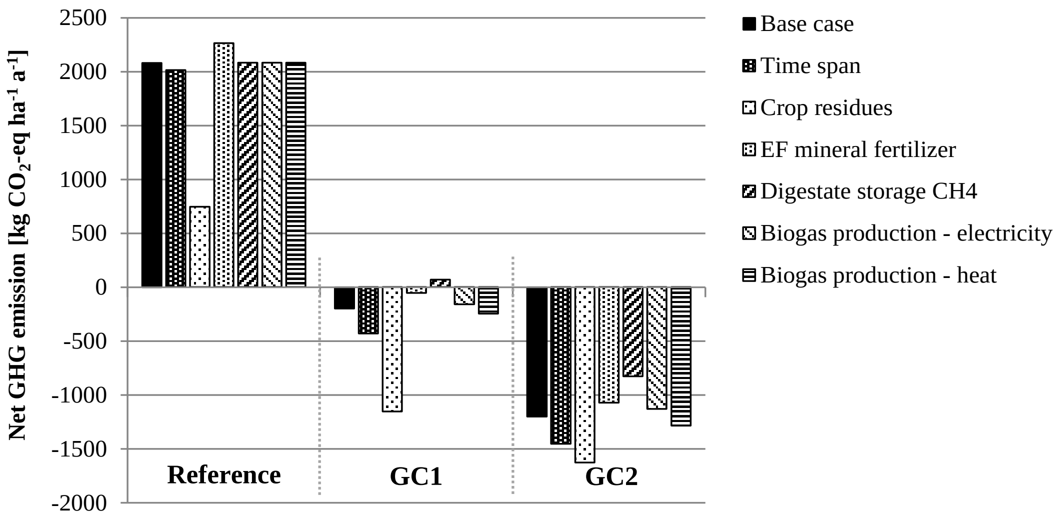

Figure 2. Net GHG emissions for the three analysed scenarios in the base case (black bars) and after varying a range of input parameters in the sensitivity analysis.

Looking at the difference between emissions in the reference scenario and the investigated GC scenarios, the shift from the 4-year cereal dominated food crop rotation to a 5-year crop rotation that includes one year of grass-clover as an energy crop for biogas production would result in avoided emissions of 2.3 t CO_2-eq ha^{-1} a^{-1} (ranging from 1.9 to 2.4 t CO_2-eq ha^{-1} a^{-1} based on the variation shown in the sensitivity analysis, Figure 2). Shifting to a 6-year crop-rotation with two years of grass-clover would give avoided emissions of 3.3 t CO_2-eq ha^{-1} a^{-1} (ranging from 2.4 to 3.5 t CO_2-eq ha^{-1} a^{-1}, Figure 2).

6. Conclusions

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 (FAO, 2011). The studied change from a cereal dominated food crop rotation to a system with integrated production of food and energy crops was shown to strongly reduce GHG emissions from the cultivation system. Since production of energy crops on farm land is sometimes seen as conflicting with sustainable food crop production, it is important to also highlight cases where an integrated approach can have multiple benefits. The possibility of using grass-clover crops for biogas production opens up for a possibility of integrating grass-clover in the crop rotation in regions with no demand for cattle feed. Grass-clover crops will diversify the crop rotation and have a strong impact on the build-up of SOC. Such a change in cultivation practice could in turn improve long term soil fertility at the same time as giving significantly decreased GHG emissions, in the range of 2-3 t CO_2-eq ha^{-1} a^{-1}, for the investigated cultivation system.

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