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Towards Sustainable Rye Cultivation
– Soil Carbon and Yield Modelling for Crop Rotations with Rye

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Abstract
Using the Introductory Carbon Balance Model, ICBM, five different crop rotations with rye

1. Rye-Ley-Ley-Rye-Beans-Rye
2. Rye-Rye-Rapeseed-Rapeseed
3. Rye-Ley-Ley-Rye-Potatoes-Rye
4. Rye-Rye-Potatoes-Wheat
5. Rye-Rye-Potatoes-Beans-Wheat-Rye-Potatoes-Rapeseed

were tested theoretically in four different cultivation scenarios

- Straw left on the field, biogas digestate added as fertilizer. Labelled "+straw+BD".
- Straw left on the field, only synthetic fertilizer. Labelled "+straw-BD".
- Straw harvested, biogas digestate added as fertilizer. Labelled "-straw+BD".
- Straw harvested, only synthetic fertilizer. Labelled "-straw-BD".

on clay soil with 1 %, 2 % or 2.5 % carbon in top soil at start of the simulation. The term biogas digestate refers (in this case) to the slurry that remains after organic material, primarily food waste or animal manure, has been used for biogas production. For rotations with ley, a case where ley was used for biogas production and the resulting digestate was spread on the fields was also tested with all scenarios.

Simulations were run over 48 years, and the results compared with respect to soil carbon effects and crop yield (by mass of total solids, energy and protein yield, as well as straw and bio fuel potential to replace fossil fuels), weighted to find the best performing crop rotation with rye, and the best cultivation methods.

As expected, use of biogas digestate had a strong positive effect on soil carbon. Crop rotations with ley could not be shown to be more beneficial than those without in this study, especially not when crop yield was considered, unless the ley was used for biogas production and the digestate spread on the field. Straw harvest did, as expected, lower soil carbon stocks but given the potential reduction of

greenhouse gas emissions when straw replaces oil as a fuel for heating, harvesting straw can still be recommended. The emission reduction is approximately five times larger than the potential carbon sink effect of the soil when straw is tilled back into the field, due to rapid degradation of fresh plant material in soil.

The best rotation, in terms of yield relative to carbon effects, was found to be Rye-Rye-Potatoes-Wheat, highly productive (high yield of total solids, energy and protein, low yield of straw, no biofuels) and with a mostly neutral carbon effect on normal, healthy soils. The best rotation from a soil carbon perspective was found to be Rye-Ley-Ley-Rye-Potatoes-Rye with ley used for biogas production. The yield of food crops from this rotation was relatively low.

The spreadsheet model used for simulations in this study is described in the report and can easily be modified and used for other studies, or for getting a rough idea of the yield and carbon effects of other crop rotations.

Sammanfattning

Med hjälp av en modell för markkolsmodellering, ICBM, The Introductory Carbon Balance Model, testades fem olika växtföljder

1. Råg-Vall-Vall-Råg-Bönor-Råg
2. Råg-Råg-Raps-Raps
3. Råg-Vall-Vall-Råg-Potatis-Råg
4. Råg-Råg-Potatis-Vete 5.
5. Råg-Råg-Potatis-Bönor-Vete-Råg-Potatis-Raps

teoretiskt med fyra olika odlingsmetoder

- Halmen skördas ej, rötrest används som gödselmedel. Märkt med ”+straw+BD”.
- Halmen skördas ej, endast mineralgödsel används. Märkt med ”+straw-BD”.
- Halmen skördas, rötrest används som gödselmedel. Märkt med ”-straw+BD”.
- Halmen skördas, endast mineralgödsel används. Märkt med ”-straw-BD”.

på lerjord med 1 %, 2 % eller 2,5 % kol i matjorden i början av simuleringen. Med rötrest avses, om inget annat anges, i första hand rest från rötning av matavfall eller gödsel från djur. För växtföljder med vall testades även ett alternativ där vallen rötades och rötresten spreds på fälten tillsammans med alla fyra odlingsmetoder.

Alla scenarier simulerades i 48 år, och resultaten jämfördes med avseende på markkoleffekter och avkastning (massa torrsubstans, energiinnehåll och proteinavkastning, samt möjligheterna att ersätta fossila bränslen med producerad halm och biobränslen) för att hitta den sammantaget bästa växtföljden och odlingsmetoden.

Som väntat hade användning av rötrest en kraftigt positiv effekt på markens kolinnehåll. Fördelar med växtföljder med vall jämfört med växtföljder utan vall kunde inte påvisas i denna studie, framförallt inte när skördens storlek (avkastningen) vägdes in, förutsatt att inte vallen rötades och rötresten spreds på åkern. Att skörda halm bidrog som väntat till en sänkning av markens kolförråd, men med tanke på den potentiella minskningen av växthusgasutsläpp när olja för till exempel

uppvärmning ersätts med halm kan halmskörd ändå rekommenderas. Minskningen av utsläpp är ungefär fem gånger så stor som den potentiella kolsänkan när halmen plöjs ned, eftersom färskt växtmaterial snabbt bryts ned i marken.

Den bästa växtföljd som testades i denna studie var Råg-Råg-Potatis-Vete, med stora skördar (hög avkastning räknat i torrsubstans, energi och protein, låg avkastning av halm, inga biobränslen) och med huvudsakligen neutral kolbalans på normala, sunda jordar. Den bästa växtföljden ur ett markkolsperspektiv var Råg-Vall-Vall-Råg-Potatis-Råg, om vallen rötades. Denna växtföljd hade dock relativt låg avkastning av för människan ätbara grödor.

Den Excel-modell som användes vid simulering är beskriven i rapporten och kan enkelt modifieras och användas i andra studier, eller för att få en ungefärlig bild av vad man kan förvänta sig i termer av skörd och kolbalans för andra växtföljder.

Introduction

Background

Crop rotations with rye

This work focuses on rye as a central crop in all tested crop rotations, even though it is currently only grown on about 1% of all arable land in Sweden, or 2% of the grain crop area (Jordbruksverket, 2011). Increasing the amount of rye on our fields and in our diet could be beneficial both from an environmental point of view, and for our health, for several reasons (see below). This makes rye well worth a study like this.

Environment

Unlike the more common cereal crops, such as wheat and barley, rye can be successfully grown on marginal soils. It is hardy to drought, and has a small need for pesticides in the spring compares to wheat (Hammar, p. 52). The need for fertilizer is also smaller than for wheat (Hammar, p. 51). Since it is a less grown crop, increasing the amount of rye in areas otherwise dominated by wheat and barley can add to biodiversity.

On the other hand, rye grows higher than other cereal crops and the long, weak straw easily bends, causing the crop to lie down on the field. The tall varieties build larger root systems, making them less sensitive to drought but when they lie down, the risk for germination on the field increases remarkably. Field germination, in turn, lowers the quality of the crop. To prevent this, chemical straw shorteners are often used for rye in Sweden. (Hammar, 1990, p. 48-51)

Health

While rye contains less protein than wheat (8.2% compared to 10% in whole grain flour with 14% moisture content (Livsmedelsverket), more in certain types of wheat), it contains more dietary fibre (13.6%, compared to 11.3% in wheat) and according to Hammar (1990, p. 54) the protein in rye has a higher nutritional value. Wheat contains more iron (5 mg/100g compared to 3.3 mg/100g rye) and zinc (2.3 mg/100g compared to 2.1 mg/100g rye) than rye, but all wholegrain products contain phytic acid, which limits the uptake of iron and zinc. When soaked in tepid water, the enzyme phytase is activated, and destroys the phytic acid, making it easier for the body to absorb the minerals. This process is more effective in rye than in wheat (Egli, 2002), and is further enhanced by the sour environment in a sourdough. Since the chemical structure of rye makes it almost necessary to use sourdough in rye bread, the phytase process is typically much more complete in wholegrain rye bread than in wholegrain wheat products. This makes rye a good source of iron and zinc, which is particularly important in a more sustainable diet with less meat. Adding rye, for example rye bread, to a diet may also help increase the intake of dietary fibre, which would be beneficial to the health of the population (Livsmedelsverket, 2014).

Soil carbon

The soil is one of the major carbon pools on the Earth, larger than the atmosphere and the biosphere combined, though still small compared to the oceans. Carbon is found in the soil both as living biomass, such as fungi and bacteria, and as dead organic matter in different states of degradation. The decomposers feed on the dead biomass, releasing carbon dioxide to the atmosphere while new substrate is added, creating a cycle that is at equilibrium in a natural system.

However, a monoculture field of annual crops is not a natural system. When crops are removed every year, less organic matter is returned to the soil, which can cause a gradual decrease in the soil carbon pool – more so if the soil is poorly managed. This, in turn, makes the soil less fertile, as well as increasing the atmospheric carbon pool, and thus adding to global warming.

According to a summary of existing research done by Emma Eriksson (2010), carbon content below 2% in agricultural soil has a negative impact on the harvest, and on those soils, increased carbon content will increase crop harvests. She also states that about 40% of the soils in the agriculture-intense areas in Sweden (94 000 ha) fall into this category, and would need measures to increase the carbon content in order to increase the harvests.

Increasing the carbon content of a soil can be done by increasing input (organic material) or decreasing carbon loss. Sources of carbon can be straw (tilled into the soil after the crop is harvested), manure, biogas digestate, ley or green fallow crops, as well as the roots left in the ground from each year's crops. Depending on how easily the organic material is degraded in the soil, and how available it is to decomposers, the same absolute input of carbon can vary in terms of long-term positive effects on the soil. Carbon input can also be increased with fertilizer and other methods to increase the harvest, since a larger crop harvest also means a larger amount of residues.

Humus (old carbon, reformed by microorganisms) in the soil helps keep minerals such as calcium, magnesium and potassium available to plants, and prevent them from leaking when water drains from the soil. Humus also helps in holding plant available water. The reason is that humus, like clay, consists of very small particles with a charged surface, where ions can be adsorbed. While a clay surface has an overall negative charge, the surface of a humus particle has both negative and positive charges, making it able to attract both cations (positive) and anions (negative). (Astera, 2007)

Many plant nutrients are found as cations in the soil. When water drains through the soil, ions are easily dissolved and drained with it, unless they are adsorbed to a charged surface. The more available charged surface, the more cations can be held in the soil in a form that is useful to plants via cation exchange. Humus has a much larger surface per weight unit than clay and like clay, it can also keep water from draining. Thus, higher humus content in the soil will help keep nutrients and water available to plants. (Astera, 2007) Potentially harmful metals, such as aluminium, are also adsorbed to the humus particles, preventing leakage to groundwater (Tan, 1998, p. 172).

Another positive effect of organic matter in the soil is improved soil structure. Organic matter helps clay particles form aggregates, small lumps of clay with pores in between, more effectively. This structure makes water infiltration into the soil easier, so that rainfall becomes useful to plants.

Also fresh organic matter can help improve the structure of the soil. It has a relatively small surface area per weight unit compared to humus or clay and does not improve aggregation or cation exchange, but it acts as food for soil organisms and decreases the bulk density of the soil. If left on the soil as mulch, fresh organic material protects the underlying soil. (Tan, 1998, p. 99)

Another important reason to use crop rotation is to avoid diseases in the crops. Many pathogens stay in the soil for a number of years and if the same crops are grown two years or more in a row, or too often, problems will increase with time. On a conventional farm, pesticides can be used to partly control the pathogens, but preventing the diseases with a well-planned crop rotation is better for the environment.

Purpose

This study aimed to increase the knowledge about how various ways to grow rye, together with other crops, in Sweden affect the environment in terms of soil carbon stock and carbon dioxide emission or sequestration, in relation to their yield. Apart from comparing different crop rotations with beans, potatoes and rapeseed, the effects of ley crops in the rotations, straw harvest and use of biogas digestate were also quantified. Thus, more understanding about different options in agriculture was created, using existing models and data.

An additional purpose was to create a user-friendly spreadsheet for easy calculation of carbon effects in crop rotations in other research projects. Using that spreadsheet, it is a quick task to get at least a rough idea of carbon effects of almost any crop rotation under Swedish conditions.

Goal

The goal of this study was to compare 60 (120 for crop rotations with ley) different alternatives for rye cultivation and their effects on the soil carbon content. Crop yield in all alternatives was also calculated and weighted against carbon effects to compare and rank the different crop rotations, depending on the preferences in the specific area.

Scope

The following alternatives were compared in this study:

Five different crop rotation alternatives, with and without ley, were compared. In reality, there is no standard crop rotation for rye in Sweden, since it is such a marginalised crop.

The effects of biogas digestate were tested in comparison to a conventional case with only synthetic fertilizers for each alternative, on three different soil qualities. It might have been more realistic to test cases with untreated animal manure as fertilizer, but considering the positive effects of anaerobic digestion (methane yield and stabilization of remaining carbon), biogas digestate seemed like a more interesting alternative. The term biogas digestate, or biogas slurry, refers (in this case) to the slurry that remains after anaerobic digestion of a substrate rich in nitrogen, such as food waste or animal manure.

All rotations were also tested with straw either harvested or left on the field, to find out which option is better from an environmental perspective.

Previous studies

Soil carbon dynamics have been studied in several previous publications, both in field experiments and using the so called Introductory Carbon Balance Model, ICBM. Especially Andrén and Kätterer have studied the topic a lot both with the original ICBM article 1997, and in later publications. Other researchers have used the ICBM as part of their studies.

ICBM

In “ICBM: The Introductory Carbon Balance Model for Exploration of soil Carbon Balances” from 1997, results from a 35 year field experiment are used to calibrate the mathematical model. The experimental setup in that study was arable crops in a clay soil in central Sweden, grown with or without N-fertilizer, with or without straw removal, with manure and with sewage sludge, and compared to bare fallow. The results show that manure has a positive effect on the carbon balance, and sewage sludge has a very positive effect. When straw is not harvested, the carbon stock remains about constant, slightly higher when N-fertilizer is used, since that increases the biomass. Straw removal causes long-term carbon depletion, especially when no N-fertilizer is used. Bare fallow causes the strongest carbon depletion, since present organic material is degraded, but none is added. These data were used to calibrate a two-component model, simple enough to solve analytically for a steady state situation. (Andrén & Kätterer, 1997)

A later publication (Andrén & Kätterer, 2004) introduces a version of the model that can be used for crop rotations, since calculations are performed to find the changes from one year to another rather than the steady state situation. The later version was used in this study.

Materials & Method

The carbon effects of each crop was estimated per year, using the Introductory Carbon Balance Model (ICBM) by Andrén and Kätterer.

The model

ICBM, the Introductory Carbon Balance Model, was developed by Olof Andrén and Thomas Kätterer in 1997. It is a minimum model for describing how the carbon stock in the top soil depends on what is grown, and how. To account for the difference between carbon in fresh organic matter and in old, degraded matter (humus), two carbon pools are used in the model: “Young”, which is the easily degraded matter that was added that year, and “Old”, which consists of relatively stable humus, older than a year. “Old” is by far the bigger part in reasonably healthy agriculture soil, and degrades slowly. In other models, there can be several different pools but ICBM uses only two, in order to stay simple.

The following parameters are used:

Y = the amount of carbon in fresh material, in kg/m^2 (to be calculated each year)

O = the amount of carbon in degraded, stable organic material (humus), in kg/m^2 (to be calculated each year)

Y_0 = starting value for Y

O_0 = starting value for O

i = the input of carbon in fresh organic material each year, for example roots and straw tilled down when the crops are harvested. With increasing i, the carbon balance gets increasingly positive and the unit is kg/m^2.

h = humification coefficient. This dimensionless parameter shows how well the carbon in a certain substrate is turned into humus, rather than carbon dioxide. For example, manure has a higher h-value (around 0,3) than fresh straw (around 0,12). A higher h-value is positive for the soil carbon balance.

k_Y = a parameter for the degradation rate of the young carbon pool. To keep the model sufficiently simple, it is kept constant at 0,8, with the unit "per year".

k_O = degradation rate of the old carbon pool, kept constant at 0,006 with the unit "per year". If K_Y and K_O would increase, that would have a negative impact on the carbon balance.

r = a dimensionless climate parameter, that shows how K_Y and K_O are affected by the climate, cultivation methods et cetera. In a normal scenario, with a climate similar to the Uppsala area in Sweden, r is 1 or close to 1 and an increase in r is negative for the carbon balance.

Details on how the parameters have been calculated can be found in ICBM (Andrén & Kätterer, 2007).

In their differential form, the equations to determine Y and O look like this:

$$\frac{dY}{dt} = i - k_Y rY$$

$$\frac{dO}{dt} = hk_Y rY - k_O rO$$

Excel application

To calculate the carbon balance in the scenarios I've been testing, I put the integrated ICBM into an Excel spreadsheet running for 48 years. For every year, Y and O values from the previous years were used as Y_0 and O_0. Below is a guide over the parameters that are entered as input values into the spreadsheet model and the ones calculated by the model. This guide can also be seen as instructions for use for anyone, who wants to use the spreadsheet model for another research project. Please note, however, that the spreadsheet was primarily made to be used in this study, and there may be errors and limits to user friendliness.

	A		B	C	D	E	F	G	H	I	J
1											
2	Crop		Winter wheat	Spring wheat	Winter barley	Oats	Rye	Dry bean	Potatoes	Rapeseed	Ley, harvested
3	Yield (kg/ha/year)		6225	4228	5387	3949	5701	2200	30533	3551	5420
4	Yield after ley	1	7225	5228	6387	4949	6701	2200	30533	3250	5420
5	Yield after beans		6925	4928	6087	4649	6401	2200	30533	3250	5420
6	TS (fraction)		0,86	0,86	0,86	0,86	0,86	0,85	0,21	0,91	0,835
7	Above ground residues (fraction)	2	0,4	0,75	0,59	0,89	0,88	0,68	1,06	1,02	0,25
8	Below ground residues (fraction)		0,23	0,28	0,22	0,25	0,22	0,22	0,2	0,22	0,76
9	Carbon content (fraction)		0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46	0,46
10	i-roots (kg/m2/year)	3	0,0793	0,0820	0,0745	0,0738	0,0933	0,0318	0,1215	0,0661	0,1978
11	i-straw (kg/m2/year)		0,0985	0,1254	0,1257	0,1390	0,1985	0,0585	0,3126	0,1516	0,0520
12	i-roots after ley		0,0920	0,1013	0,0884	0,0925	0,1096	0,0318	0,1215	0,0605	0,1978
13	i-straw after ley		0,1143	0,1551	0,1491	0,1742	0,2333	0,0585	0,3126	0,1388	0,0520
14	i-roots after beans		0,0882	0,0955	0,0842	0,0869	0,1047	0,0318	0,1215	0,0605	0,1978
15	i-straw after beans		0,1096	0,1462	0,1421	0,1637	0,2228	0,0585	0,3126	0,1388	0,0520
16	Fraction of straw harvested	4	0,75	0,75	0,75	0,75	0,75	0,75	0	0,75	
17	i-straw (harvested)		0,0246261	0,03136119	0,031433684	0,034759	0,049617	0,014623	0,312646	0,0379044	
18	Harvested carbon (kg C/m2/year)		0,0739	0,0941	0,0943	0,1043	0,1489	0,0439	0,0000	0,1137	
19	i-straw after ley (harvested)		0,0285821	0,03877869	0,037268784	0,043562	0,05832	0,014623	0,312646	0,0346915	
20	Harvested carbon after ley		0,0857	0,1163	0,1118	0,1307	0,1750	0,0439	0,0000	0,1041	
21	i-straw after beans		0,0274	0,0366	0,0355	0,0409	0,0557	0,0146	0,3126	0,0347	
22	Harvested carbon after beans		0,0822	0,1097	0,1066	0,1228	0,1671	0,0439	0,0000	0,1041	

Figure 1: Parameters in the spreadsheet model, "Database"

Figure 1 shows the database of yield data and information for various crops, used in the model.

1. Crop yield, varying depending on where in the rotation the crop is grown. The numbers in this study are based on Swedish averages from SCB (2012). The green numbers can be replaced if for example experimental data from a specific farm is used, and the numbers for yield after ley or beans will follow automatically.
2. Total solids (dry matter fraction) and amount of residues relative to crop yield. Primarily based on IPCC data (2006).
3. Carbon input from crop residues. Calculated based on input numbers above.
4. The fraction that can be collected when straw is harvested. For example, if the plant is 80 cm high and this parameter is set to 0.75, 60 cm will be considered harvested and useful as a fuel, while 20 cm will be left on the field and contribute to the soil carbon input of that year.

Numbers written in red are based on estimations or qualified guesses due to lack of actual data.

25				
26	**Manure**		**Bio**	**Farmyard (cattle)**
27	TS (fraction)		0,038	0,098
28	N (kg/ton)	1	4,5	3,9
29	Carbon content (fraction)		0,48	0,48
30	Max N spreading (kg/ha/year)		100	100
31	Max spreading (kg/m2/year)	3	2,222222222	2,564102564
32	Max C input (kg/m2/year)		0,040533333	0,120615385
33				
34	C input from ley digestate (kg/m2/year)		0,1312453	
35				
36				
37				
38	**Base parameters**		**h**	**r**
39	Roots		0,23	
40	Above ground	2	0,1	
41	Bio manure		0,41	
42	Farm yard manure			
43	Annual crops			1,04
44	Grass			0,76

Figure 2: Parameters in the spreadsheet model, "Database"

Figure 2 shows background data for manure (biogas digestate and fresh animal manure), to be used in the model.

1. Basic data for bio- and farmyard manure. The properties of biogas digestate can of course vary with the substrate, and might be different from these. "Max N spreading" is the highest amount of nitrogen from fertilizer that is allowed on cereal fields.
2. Base parameters for the ICBM model, calibrated to give correct results. It has been suggested that roots decompose slower than above ground residues, because they are embedded into the soil more difficult to access. However, the specific h values have not yet been calibrated for the version of ICBM used here, and Thomas Kätterer did not recommend using them in this case. In this study, the same h value (1,67 for food crops and 1,125 for ley) was used for roots and above ground residues alike. These values are not linked to the simulation sheets.
3. Highest possible spreading of manure, and highest possible carbon input from manure. Calculated by the program, based on manure properties and legal directions.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Year	Crop	Straw option	Fertilizer	i-roots	i-straw	i-manure	i-total	h-roots	h-straw	h-BM	h-total	r	Y	a	O
2					Input of	Input of	Input of C	Total C	Huminic	Humifica	Humificati	Average	Climate co	Carbon in	A part of t	Carbon in "old"
3	0	Rye	Left	Synthetic	0,0933	0,1985	0	0,292	0,167	0,167	0,41	0,167	0,76	0,211922		7,288078
4	1	Ley		Synthetic	0,1978	0,052	0	0,25	0,125	0,125	0,41	0,125	0,76	0,274217	-0,08475	7,29314256
5	2	Ley		Synthetic	0,1978	0,052	0	0,25	0,125	0,125	0,41	0,125	0,76	0,285305	-0,066	7,28972808
6	3	Rye	Left	Synthetic	0,1096	0,2333	0	0,343	0,167	0,167	0,41	0,167	1,04	0,291342	-0,0674	7,28695897
7	4	Field beans	Left	Synthetic	0,0318	0,0585	0	0,09	0,167	0,167	0,41	0,167	1,04	0,276018	-0,10672	7,30124532
8	5	Rye	Left	Synthetic	0,1047	0,2228	0	0,328	0,167	0,167	0,41	0,167	1,04	0,159408	-0,06164	7,29025687
9	6	Rye	Left	Synthetic	0,0933	0,1985	0	0,292	0,167	0,167	0,41	0,167	0,76	0,211922	-0,08194	7,29067901
10	7	Ley		Synthetic	0,1978	0,052	0	0,25	0,125	0,125	0,41	0,125	0,76	0,274217	-0,08475	7,29573174
11	8	Ley		Synthetic	0,1978	0,052	0	0,25	0,125	0,125	0,41	0,125	0,76	0,285305	-0,066	7,29230548
12	9	Rye	Left	Synthetic	0,1096	0,2333	0	0,343	0,167	0,167	0,41	0,167	1,04	0,291342	-0,0674	7,28952464
13	10	Field beans	Left	Synthetic	0,0318	0,0585	0	0,09	0,167	0,167	0,41	0,167	1,04	0,276018	-0,10672	7,30379503
14	11	Rye	Left	Synthetic	0,1047	0,2228	0	0,328	0,167	0,167	0,41	0,167	1,04	0,159408	-0,06164	7,29279072
15	12	Rye	Left	Synthetic	0,0933	0,1985	0	0,292	0,167	0,167	0,41	0,167	0,76	0,211922	-0,08194	7,2931971
16	13	Ley		Synthetic	0,1978	0,052	0	0,25	0,125	0,125	0,41	0,125	0,76	0,274217	-0,08475	7,29823837
17	14	Ley		Synthetic	0,1978	0,052	0	0,25	0,125	0,125	0,41	0,125	0,76	0,285305	-0,066	7,29480071

Figure 3: Parameters in the spreadsheet model, simulation sheets

Figure 3 shows the actual simulation sheet, where the background data and ICBM equations are used. One such sheet was created for each combination of scenario, crop rotation and soil carbon start value.

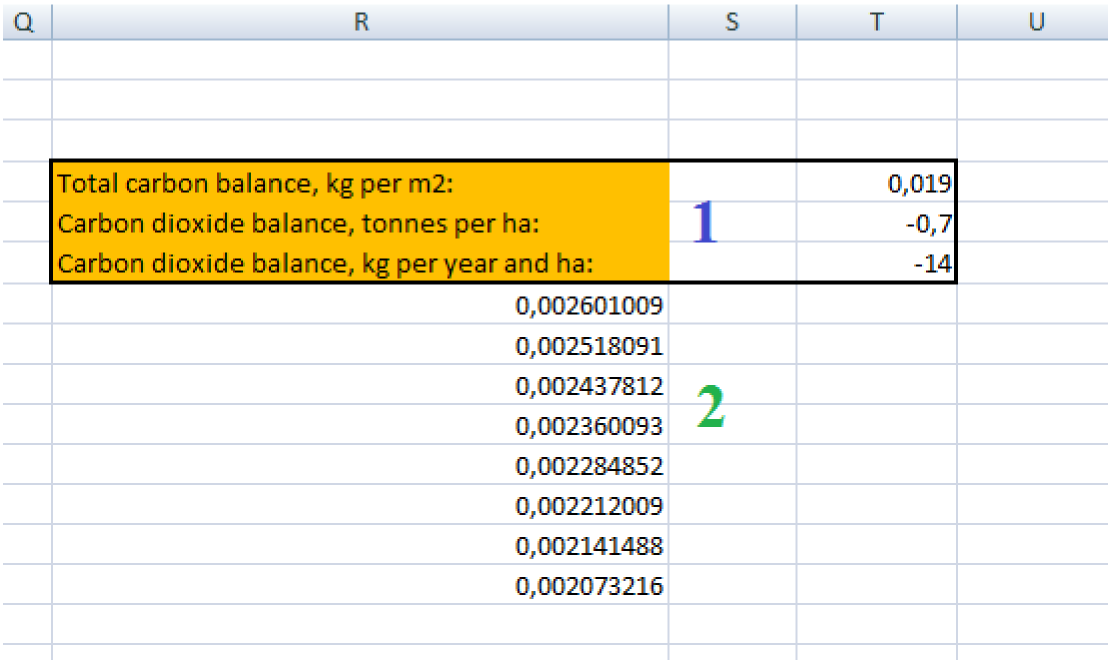
1. Notes for memory, not used by the program. List your crop rotation and cultivation methods here.
2. Carbon input values. Can be linked to the values in the database sheet.
3. h values for different materials.
4. r values for different crop categories (grass or annual crops)
5. Young carbon, calculated for every year based on input data. The young carbon pool adjusts quickly, so it makes sense to set the start value to the same as the end value. This has to be done manually, actually typing in the number, otherwise the program complains.
6. Since the calculation of the old carbon pool is rather complicated, a help parameter is created and used in the equation. This column holds the help parameter, but no information that is useful for the results in itself.
7. Calculation of the old carbon pool each year. The start value is decided by the total carbon percentage at the start of the simulation.

Q	R	S	T
	Constants		
d" m	aterial, kg/m2	Year0	Year48
	kY	0,8	
	kO	0,006	
	Top soil, depth (m)	0,25	
	Soil density (kg/m3)	1,5	
	Carbon year 0 (% by weight)	2	2,005
	Total carbon per m2 year 0 (kg)	7,5	7,519
	Fraction of C in Y	0,028256	0,02818626
	Fraction of C in O	0,971744	0,97181374

Figure 4: Parameters in the spreadsheet model, simulation sheets, far right

Figure 4 shows parameters for the type of soil used, and the constants in the model, as well as the end result after 48 years of simulation.

1. The constants k_Y and k_O.
2. Properties of the soil. All simulations in this study were done with the settings in this picture, representing a clay soil with 25 cm top soil. It is assumed that all soil carbon is found in the top soil.
3. The carbon content in percent by weight of the top soil, and the absolute amount of carbon per square meter. The column to the left shows the start value, while the column to the right shows the calculated value after a 48 year simulation.
4. The fraction of carbon that is found in the young and the old carbon pool, respectively. This is decided by the end value for the new carbon pool, since it adjusts faster. Old carbon is all carbon that is not in the young carbon pool.



Q	R	S	T	U
	Total carbon balance, kg per m2:		0,019	
	Carbon dioxide balance, tonnes per ha:	1	-0,7	
	Carbon dioxide balance, kg per year and ha:		-14	
	0,002601009			
	0,002518091			
	0,002437812	2		
	0,002360093			
	0,002284852			
	0,002212009			
	0,002141488			
	0,002073216			

Figure 5: Parameters in the spreadsheet model, simulation sheets, far right

Figure 5 shows the changes in old carbon and carbon dioxide over the simulation period.

1. Different ways of measuring carbon balance – either by the amount of carbon that is lost or accumulated over 48 years, or net carbon dioxide emitted or absorbed over 48 years, or net carbon dioxide per year. Positive carbon values and negative carbon dioxide values indicate an increase in soil carbon.
2. Carbon balance for each full crop rotation (for example, six years if the crop rotation is rye-ley-ley-rye-beans-rye). This has to be adjusted manually, since the program does not know the length of the crop rotations. Each number is the old carbon pool for the first year of one rotation minus the old carbon pool for the first year of the previous rotation. The numbers are used in diagrams that illustrate the carbon effects.

Crop	TS (%)	Energy (MJ/kg)	Protein (%)	Yield (tons/ha/y)	Yield after ley	Yield after beans
Rye	86	15,5	11,8	5,701	6,701	6,401
Beans	85	15	20	2,2		
Rapeseed	91	25	10	3,551		
Winter wheat	86	16,4	15,9	6,225	7,225	6,925
Barley	86	15,5	12,7	5,387	6,387	6,087
Oats	86	14,3	11,6	3,949	4,949	4,649
Potatoes	22	15	10	30,533		
Ley	83,5			5,42		

Figure 6: Parameters in the spreadsheet model, yield sheet, right side. Basic yield properties for various crops.

Figure 6 shows properties of harvested crops.

1. List of crops in the database. Other crops can be added if needed for a future study.
2. Basic properties for crops: Dry matter percentage (total solids), energy content per kg of dry matter and protein percentage in dry matter. Red numbers are estimated. The estimated protein content is too low in this screenshot. A more realistic estimate would be 30 %.
3. Yield, with modified columns for crops grown in the year after ley or beans. Linked to the "Database" sheet.

Fuel	MJ/kg	MJ/litre
Diesel	46,2	37,3
Biodiesel	42,2	33
Gasolene	46,4	34,2
Ethanol	30	24
Methanol	19,7	15,6
Biogas		
Methane (1.013 bar, 15°C)	55,6	0,0378

Source: Wikipedia, Energy density

Crop	Ley	
%TS	83,5	
%VS of TS	88	Substrathandboken
Methane yield, m3/kg VS	0,3	
% of max yield reached	70	
% of gas needed in plant	18	
Net methane yield, m3/kg VS	0,1722	
Net methane yield, m3/ton wet crop	126,5326	

Figure 7: Parameters in the spreadsheet model, yield sheet, right side. Properties of vehicle fuels and biogas potential for ley.

Figure 7 shows properties of fuels, and calculations for the biogas process.

1. List of fuels in the database
2. Energy content in fuels, per mass and volume. (The difference is particularly large for biogas.)
3. Calculation of methane yield when ley is anaerobically digested. VS is short for volatile solids, and is the fraction of total solids that is digestable. The percentage of maximum yield reached reflects the fact that in order to use the capacity of the biogas plant efficiently, substrate is not kept in the reactor for as long as it would take to get the theoretical maximum yield. Some of the gas is needed in the plant, mostly to keep the reactor at the desired temperature since anaerobic digestion produces very little heat in itself.

Rotation 1	Rye-Ley-Ley-Rye-Beans-Rye			
Crop harvest				
Crop	Yield (tons/ha/48 years)	TS (tons/ha/48 years)	Energy(MJ/ha/48 years)	Protein (tons/ha/48 years)
Rye	150,424	129,4	2005152	15,3
Beans	17,6	15,0	224400	3,0
Ley	86,72	77,2		
Total	254,744	221,5	2229552	18,3
Total minus ley	168,024	144,3	2229552	18,3
Straw harvest				
Crop	Straw (tons/ha/48 years)	TS (tons/ha/48 years)	C (kg/m2/48 years)	Energy(MJ/ha/48 years)
Rye	104,12	85,38	3,93	1561841,4
Beans	9,30	7,63	0,35	139565,9
Total	113,43	93,01	4,28	1701407,24
Ley harvest				
Ley (tons/ha/48 years)	TS (tons/ha/48 years)	Biogas(m3/ha/48 years)	Methane (m3/ha/48 years)	Energy(MJ/ha/48 years)
86,72	77,2			
Biofuel potential				
Crop	Yield (tons/ha/48 years)	Biofuel produced	Fuel yield (m3/ha/48 years)	Fuel yield (MJ/ha/48 years)
Ley	87	Methane	10973	414775,76
Total fossil fuels replaced:		11	m3 diesel/ha/48 years	

Figure 8: Calculation of results for crop rotations. Parameters in the spreadsheet model, yield sheet, left side.

Figure 8 shows calculations of biofuel potential.

1. List of crops in the studied rotation.
2. Total yield of each crop over a 48 year period. Calculated by multiplying the yield per year with the number of years the crop is grown, adjusted for higher yields in years directly after ley or beans.
3. Dry matter yield per crop. Calculated by multiplying the yield with dry matter fraction.
4. Energy yield per crop. Calculated by multiplying dry matter yield with energy content.
5. Protein yield per crop. Calculated by multiplying dry matter yield with protein fraction.

6. Total yield, all crops combined, with or without ley. Ley is not always included, since humans cannot eat it. When this screenshot was taken, the energy content of ley was not yet entered into the model.
7. Data for straw harvest – total yield, dry matter yield, carbon content and energy yield, divided by crop and in total. Only applies when straw is actually harvested, and then calculated on 75 % of the total above ground residues, in accordance with the Database sheet.
8. Ley yield, total and as dry matter.
9. Biofuel potential. If a crop rotation contains ley or rapeseed, it is a possible option to process it to biofuel. Ley can be used for biogas production, and biogas can be used as a vehicle fuel, replacing fossil diesel. Rapeseed can be used to produce RME, Rapeseed Methyl Ester (more generally known as FAME, Fatty Acid Methyl Esters), also replacing fossil diesel. Please note that this is only one possible use for these crops. Ley can also be used as animal feed, while rapeseed can be processed into rapeseed oil for human consumption. No matter how the rapeseed oil is used, the byproducts can be used as animal feed.

Choice of crop rotations

Rye is a rather marginalised crop in Sweden. It is currently only grown on 2.5 % of all arable land, and often on the soils that are less productive, because it is not very demanding. Most of the rye fields in Sweden can be found in the southeast of Götaland and on light soils in Scania, because rye is hardy to drought but sensitive to frost nights late in spring (Hammar, 1990, s. 49). There are no established crop rotations that focus on rye, since the crop is not priority. Therefore, I have had to improvise to some extent in the choice of crop rotations to test.

Rye-ley-ley-rye-field beans-rye:

This is a modified version of a suggestion from Jordbruksverket, for organic farming. The original rotation is 5 years, and one year of rye is added at the end to fit in the 48 year model. While this probably makes the option less suitable for organic farming, it is still feasible for the study.

In reality, field beans are sensitive to drought and not very well suited to the soils that are usually chosen for rye. However, if crop rotations are to be used, one cannot expect the area to be perfect for every crop in the rotation.

Rye-rye-rapeseed-rapeseed:

Strange as it may seem, since this crop rotation grows both rye and rapeseed too often to safely avoid diseases, it is actually used and therefore it is suitable for this work. However, according to Hammar (1990, s 96), oil crops are more commonly grown after ley or fallow.

Rye-ley-ley-rye-potatoes-rye:

Another modified crop rotation for organic farming, this time with potatoes, a crop that is suitable for the same type of soil that rye is often grown on. Potatoes do need a lot more water than rye, but that can be handled with irrigation (Hammar, 1990, s. 211)

Rye-Rye-Potatoes-Wheat:

This is a short rotation with rye and potatoes, where the frequency of potatoes follows the recommendations.

Rye-Rye-Potatoes-Beans-Wheat-Rye-Potatoes-Rapeseed

This is an eight year rotation, with many different crops. Potatoes are grown in four year intervals, which is enough to avoid diseases according to recommendations. Beans and rapeseed have eight year intervals, which is more than enough to avoid diseases, and potatoes are not grown directly after rapeseed, which could cause a chemical taste in the potatoes (Hammar, 1990, s. 212). Rye is grown two years in a row, which is a risk, of course, but in a study that focuses on rye, there has to be more rye in the rotations.

The scenarios

For each crop rotation, four different scenarios were tested: with or without straw removal and with synthetic mineral fertilizer or biogas digestate (residues from biogas production). For crop rotations with ley, an additional scenario where the ley crops were digested for biogas and the digestate from that process was added to the soil.

Straw

When straw was harvested, 75 % of the above ground residue biomass was calculated as removed. This corresponds to cutting about 15-20 cm off the ground and harvesting the cut off part, including chaff. The harvested straw was burnt for energy, see ”System expansion” below.

The remaining stubble, as well as all above ground residues in the scenarios without straw removal, was ploughed into the soil.

Biogas digestate

When biogas digestate was used, it was assumed that 100 kg of nitrogen was added per year and hectare. The recommendations for nitrogen fertilizer for most crops are slightly higher than 100 kg per year and hectare (Jordbruksverket, 2012, p. 34). However, given the variation in nutrient content for biogas digestate from different substrates (See Salomon & Wivstad, 2013, p. 13 for examples with animal manure and food waste as substrate), and for the sake of simplicity in this study, it is reasonable to keep the biogas digestate levels somewhat below recommendations, and the same for all crops. With the properties for biogas digestate used in this study (4.5 kg N/ton and a dry matter fraction of 0.038), 2.2 kg/m^2 can be spread each year. With 48 % carbon in dry matter, this means a carbon input of 0.04 kg/m^2/year.

Also phosphorous spreading is limited, to 22 kg per year and hectare on average over a five year period (Jordbruksverket, 2014). Assuming a phosphorous content of 0,7 kg/tonne (well in accordance with the figures presented Salomon & Wivstad), the amount spread in this simulation is well within that limit.

Fresh farmyard manure contains more carbon, and can contribute three times as much to soil carbon input. However, a larger fraction of the carbon in fresh manure is lost as carbon dioxide during the first year, giving it a lower h value. Since biogas can be a valuable fuel for vehicles or for heat and electricity, replacing fossil fuels, anaerobic digestion can be seen as a better way to use the more volatile carbon in manure than to add it to fields.

In the scenarios where mineral fertilizer was used, no carbon was added to the soil from the manure. Fertilizer was applied every year, also when the crop was ley.

Biogas from ley

When the ley crops in rotations 1 and 3 were digested to produce biogas, the resulting digestate was returned to the soil. In the model, all of this extra biogas digestate was added in the year after the ley was grown. In reality, it would probably rather be spread over the entire area, which would be seen as an even spread over all six years but the end result on the soil carbon stock would be the same.

Parameter values

Values for the constants k_Y and k_O (0.8 and 0.006 respectively) can be found in Andrén and Kätterer 2004.

Start values for the carbon pools were based on 25 cm topsoil, with a bulk density of 1.5 kg/m^3 (clay soil). The levels 1%, 2% and 2.5% C by weight were based on telephone communication with Thomas Kätterer in September 2011.

Values for carbon input are based on data from IPCC, 2006. With an assumption that the amount of residues is proportional to the crop yield, the amount of residues can be estimated from crop yield, and an experimentally derived parameter that gives the specific fraction for each crop.

Crop	Dry matter fraction	Above ground	Below ground
Spring wheat	0.86	0.40	0.23
Winter wheat	0.86	0.75	0.28
Barley	0.86	0.59	0.22
Oats	0.86	0.89	0.25
Rye	0.86	0.88	0.22 (Not from IPCC)
Potatoes	0.22	1.06	0.20
Beans	0.85	0.85	0.19

Table 1: Residues as a fraction of crop yield, and try matter fraction in harvested product, for a number of crops, based on IPCC data (2006). Dry matter fraction based on SCB data (2012).

Data for rapeseed was based on qualified guesses, with measurements for other crops taken into account.

Ley crops are different from annual crops, in the way that they grow on the field for more than one season. The seeds are sown together with the annual crop. When the annual crop is harvested in the fall, the soil is not tilled, and the ley crops are left to grow. The perennial ley crops are then harvested two or three times per season, but the roots are not removed and the soil is not tilled until the end of the last ley crop season. Thus, the root biomass increases with time, and becomes much larger than for annual crops. At the same time, since the soil is not tilled, less carbon is emitted to the atmosphere. This and other factors are weighted together, and shown as a lower r-value for ley crops than for annual crops.

According to Bolinder et al (2001), it is difficult to measure root biomass, and the results may vary a lot, depending on things such as time when the sample was taken, nutrient status of the soil, separation methods etc. Therefore, root contribution to the soil carbon balance is often either neglected, or just estimated. In their study, Bolinder et al (2001) made an attempt to measure root biomass of seven perennial grass species and two perennial legume species in Canadian soil, in the intervals 0-15 cm, 15-30 cm and 30-45 cm. The root biomass increased with time, and was about twice as big in the second year, as it was in the first year. In my study, I used an average value for the first year in the interval 0-30 cm to estimate root biomass from ley, assuming that about 50% of the crop was legumes and 50% grasses. The reason that I used the first year value is that the growth is cumulative and if I would double the value in the second year, I would be counting the same carbon twice. I also assumed that 80% of the above ground biomass could be counted as harvested yield. This gave me a root to yield fraction of 0.76, which is significantly higher than the values that are given for annual crops (about 0.23).

When straw was harvested, it was estimated that 75% of the above ground residues were taken, which corresponds to approximately 20 cm stubble for most cereal crops.

Carbon content of plant residues was set to 46% of DM, and for biogas digestate, C-content was set to 48% of DM.

Estimated spreading of biogas digestate was based on a yearly spreading of 100 kg nitrogen per year and hectare, assuming that all nitrogen was provided as biogas digestate. Data from JTI (2006) (Rötrest från biogasanläggningar) was used to estimate TS and nitrogen content in biogas digestate.

Yield data was taken from Swedish SCB, Statistiska Centralbyrån (2012). Estimated normal yields for all of Sweden, based on data collected over a long time, were used. For potatoes, data for food potatoes rather than starch potatoes was used. For beans and ley, the yields were based on a five year average, also from SCB.

According to my data, wheat yields are considerably higher than rye yields. This is not at all necessarily the case when wheat and rye are grown on the same field. Instead, it is most likely a result of the fact that rye is often grown on marginal land, where wheat would not grow well at all. Thus, the yield data at hand is not a good comparison for rye and wheat within the same crop rotation. The data was used anyway, but with the reservation that wheat probably looks better than what it actually is. There may be similar problems with data for other crops as well.

h values are set to 0.12 for crop residues and 0.31 for biogas digestate in older ICBM data sets. However, in a study from 2011, Kätterer et al suggest that roots should be assigned a considerably higher h value than above ground residues, namely 0.15 for above ground material and 0.35 for roots. The same paper suggests 0.27 as h value for farmyard manure, and 0.41 for sewage sludge. Those values for manure and biogas digestate were used here, but on suggestion from Thomas Kätterer, I did not use separate h-values for roots and shoots. Instead, I used a weighted average (0.167 for cereal crops and 0.125 for ley), while keeping in mind that it may affect the impact of straw harvest in the model compared to reality. See Discussion for more on this topic.

The climate constant r was set to 1.04 for annual crops (Kätterer et al), and multiplied with 0.73 to 0.76 for years with ley.

The total amount of C at the start of each simulation was constant (decided by the percentage, 1, 2 or 2.5%), but the ratio between Y_0 and O_0 was set so that Y_0 matched Y after the last year.

System expansion

In some of the studied crop rotations, non-food crops such as ley were produced, as well as straw harvested. To be able to compare the different crop rotation alternatives, these crops had to be given a value, which could be used for all of them.

One way of calculating is to simply compare the lower heating value of all crops, whether it is beans, wheat or straw. This method makes comparison easy, but it is also very crude. A high-protein food is, in reality, much more valuable than a by-product that can practically only be used for heat production, and when the lower heating value is used to compare the two, this aspect is lost. On the other hand, it can be useful to get a crude measurement, which does not have to be weighted with respect to several parameters, such as protein content, or what the crop can be used for.

Another way is system expansion, where the crops are processed into products, which replace other products. The harvested straw can be burnt for power and district heating. When burning the straw, other fuel, such as oil, is replaced. In the same way, ley can be used to produce biogas and rapeseed to produce biodiesel, both of which replace fossil diesel. The crops could also be used as feed for animals, to replace for example imported soy.

A third way would be to allocate all environmental effects to the food crops, or just to the rye. However, that would be unfair since the non-food crops most definitely have a value.

In this work, two main methods were chosen to compare the different scenarios: Lower heating value, and system expansion. For system expansion, biofuels were chosen rather than animal feed, because of the controversies regarding meat production in a sustainable society. In addition to this, protein yield was calculated and compared.

Rapeseed

Biodiesel, or FAME (Fatty Acid Methyl Ester) can be made from any biological fat, for example rapeseed oil. In the natural oil, the fatty acids form triglycerides, esters with glycerol as the alcohol and three fatty acids. In FAME, each ester molecule consists of one fatty acid, and methanol. Other alcohols can also be used. When the rapeseed oil is mixed with methanol and a strong base or acid as a catalyst, it changes into methyl esters and glycerol. The glycerol sinks to the bottom of the tank, and the biodiesel is ready for use. (European Biofuels, 2011)

In the system expansion, I assumed that 3 kg of rapeseed is needed for 1 litre of biodiesel. Considering the difference in energy content, 1 litre of biodiesel replaces about 0.9 litres of fossil diesel.

Ley

Ley crops can either be ploughed back into the soil, used as animal feed or anaerobically digested to produce biogas. In this paper, I assumed that the ley was used for biogas production, and the digestate was returned to the soil, even in the scenarios where other biogas digestate was not used. That way, most of the nutrients and some of the stable carbon in the ley crops are returned to the soil. At the same time, the energy in the crops is made available as a biofuel for vehicles, replacing fossil diesel. (It is more common that biogas from farm scale plants is used for heat and electricity, because the gas is difficult to handle as a vehicle fuel, but I still assumed that it was used for vehicles, to make the comparison more transparent.)

Prior to digestion, the ley crops have to be stored as silage, because they are harvested two or three times per year, and the digester needs an even load, spread out over the year, to function.

When calculating the methane yield from the ley, data from Nordberg et al (2006) was used. It was assumed that the digester was run continuously, with a retention time that allowed for about 70 % of the maximum gas yield to be reached. Out of the gas produced, 15% was needed for heating the plant, and 3 % was needed for electricity within the plant. The remaining gas was considered net yield for biogas from ley.

However, when calculating the yield for any biogas plant or process, many aspects have to be taken into account. Not only the substrate and retention time affect the amount of gas produced, but also the mix of substrates, and mechanical factors such as stirring. (Carlson & Uldal, 2009) A mix of more than one substrate usually gives a higher yield than if each substrate would be digested separately. For example, it could be a good idea to mix the ley with waste from food industry, and/or with manure, and the numbers presented here are merely estimations, not absolute truth.

To calculate the amount of carbon in the digestate, I simply subtracted the carbon in the gas from the total amount of carbon in the ley crops before digesting. Theoretical methane yield from ley crops is 0.3 m^3/kg VS, and the gas consists of 56% methane and 44% carbon dioxide (Carlson & Uldal, 2009). With a carbon content of 46% of TS in the ley crop, the maximum theoretical amount of carbon to leave as gas was calculated, and then 70% of that was subtracted from the total carbon in the crops. If this is true, then the digestate contains 0.29 kg of carbon per kg TS from ley added to the digester. With a ley harvest of 5 420 tons/year/ha (wet mass), 0.13 kg C/m^2 is added in the years after ley when no other biogas digestate is used. In the scenarios where biogas digestate is already used, the maximum limit for nitrogen fertilizer makes it impossible to add the digested ley to previously calculated biogas digestate for extra carbon input. Note, however, that ley digestate has higher carbon content than the biogas digestate that previous calculations have been based on, and can replace it.

Analyzing a number of different cover crops, Ketterings et al (2011) found their C:N ratio to vary from 11 to 32, with most of the ratios close to 20. While the C:N ratio varies depending on time of harvest, access to nitrogen in the soil and other factors, 20 can be seen as a good enough estimation for the C:N ratio of the assumed ley crop mix in this study. Assuming no nitrogen losses in the biogas process, spreading the digestate from all harvested ley would add 104 kg N/year/hectare to the soil, along with a very healthy carbon input.

The reason why more carbon can be added as biogas digestate when ley is digested is that the C:N ratio is considerably higher in ley crops than in substrates such as food waste or animal manure, on which the general data for biogas digestate is based.

In the scenarios where ley is grown and digested and the digestate is returned to the soil, ley digestate replaces other biogas digestate also in the scenarios where biogas digestate was already used.

Parameters compared

Effects on young carbon

The young carbon pool describes the material that has recently been added to the soil. Over time, most of the carbon in this material is lost as CO_2, and a smaller fraction of it is turned into more stable humus, assuming that decomposing microorganisms are available in the soil. Humus makes up the old carbon pool. The young carbon pool adjusts quickly to the amount of organic material added each year. Therefore, it is not a good way to measure the overall carbon status of a soil, but on the short term, it still matters. The fresh organic material is food for organisms in the soil, such as worms, which help improve the structure of the soil. The material as such can also give structure, and protect the underlying soil when covering it as mulch (Tan, 1998, s. 99). However, to get a picture of the long term status of the soil, it is better to look at the old carbon pool.

Effects on old carbon

The old carbon pool changes much slower, and is built up over time from material, that is not easily degraded. While most of the fresh material that is added to the new carbon pool is degraded and the carbon lost as CO_2, a small portion is turned into stable molecules, humus, and becomes part of the old carbon pool. How big this portion is differs depending on the substrate, and that is illustrated by the h-value in the model.

When illustrating change in the old carbon pool over a time period of 48 years, with annual crops and realistic scenarios, the differences are small. But even if it doesn't look very dramatic, these are the most relevant changes studied in this work, since they affect the long term health and quality of the soil.

Carbon dioxide

When carbon is lost from the soil, it ends up in the atmosphere as CO_2, and the soil acts like a carbon source. When the soil carbon pool increases, the soil instead acts like a carbon sink. These flows of CO_2 must be quantified and compared to the emissions, or prevented emissions, of other activities, such as burning straw for heat.

Total carbon percentage

This is another way to illustrate the long term changes in the soil, which closely follows the changes in the old carbon pool.

Yield

In order to make sense, the environmental effects of each scenario have to be compared to the yield of food crops and other useful products. There are different ways to quantify the yield. In this paper, total solids, energy yield, straw and protein yield are considered. Calculations are performed with and without the ley harvest.

Results

Overall results

Effects on young carbon

In all scenarios, the young carbon pool changed a lot from one year to another. It was generally higher when biogas digestate was used as fertilizer (17-27 % higher on average), and when straw was not harvested (39-125%). The highest average amount of young carbon was found in Rotation 3 (0.28 kg/m^2 when biogas digestate was used and straw not harvested), and the lowest average amount was found in Rotation 2 (0.065 kg/m^2 with straw harvest, and no biogas digestate).

When biogas digestate from digested ley crops was added to the soil in Rotations 1 and 3, the average young carbon pool became considerably larger. The highest value, 0.36 kg/m^2, was found in

Rotation 3. On average, the young carbon pool was 14 % larger in Rotation 1 and 12 % larger in Rotation 3 when the ley crops were used in this way.

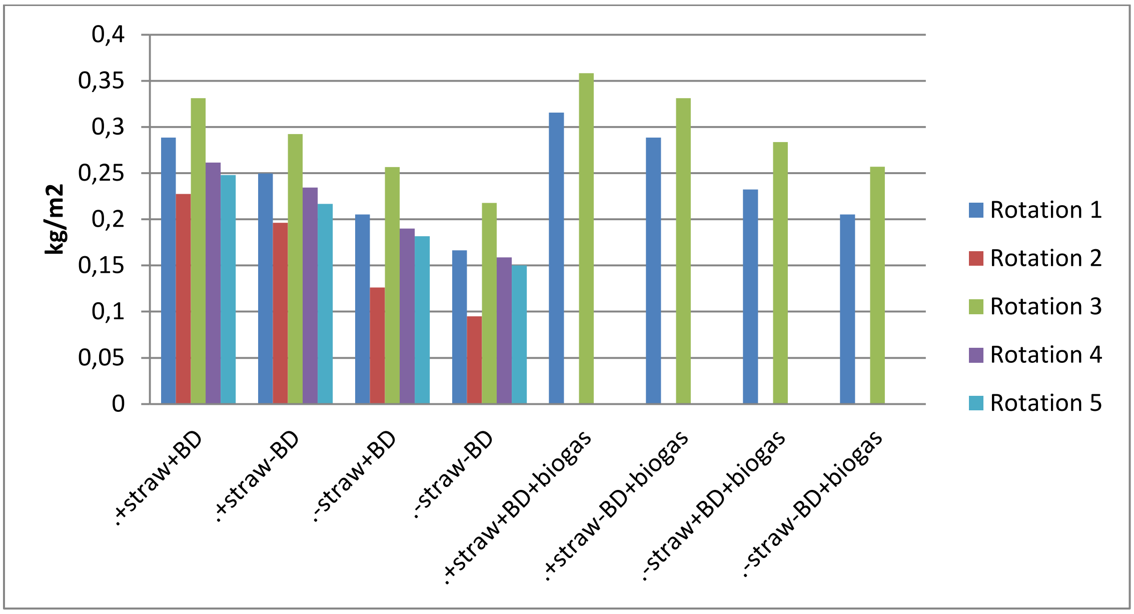


Figure 9: Average young carbon pool for each crop rotation and scenario.

The figure above shows the average amount of young carbon for each scenario and crop rotation. In reality, there is a rather big variation from one year to another, because the C input varies a lot between different crops. For rotation 2 (rye-rye-rapeseed-rapeseed), where the young carbon pool is smallest on average, the variation looks like this:

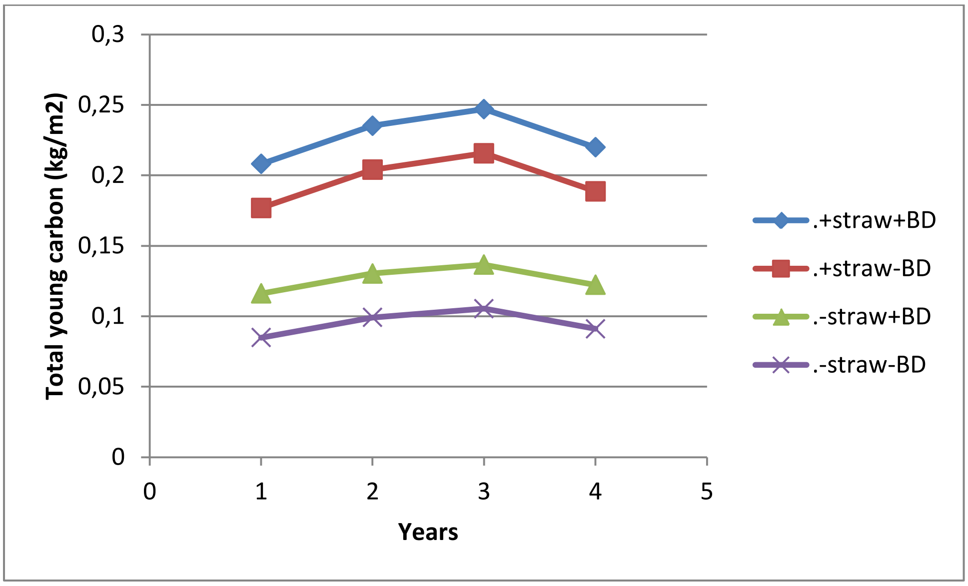


Figure 10: Year to year variation in the young carbon pool for rotation 2, rye-rye-rapeseed-rapeseed.

As shown in Figure 10, rye leaves more residues than rapeseed, meaning that the young carbon pool increases in years with rye, and decreases in years with rapeseed. This trend is more visible when straw is left on the field.

The highest average carbon pools are found in rotation 3 (rye-ley-ley-rye-potatoes-rye), where the variation looks like this:

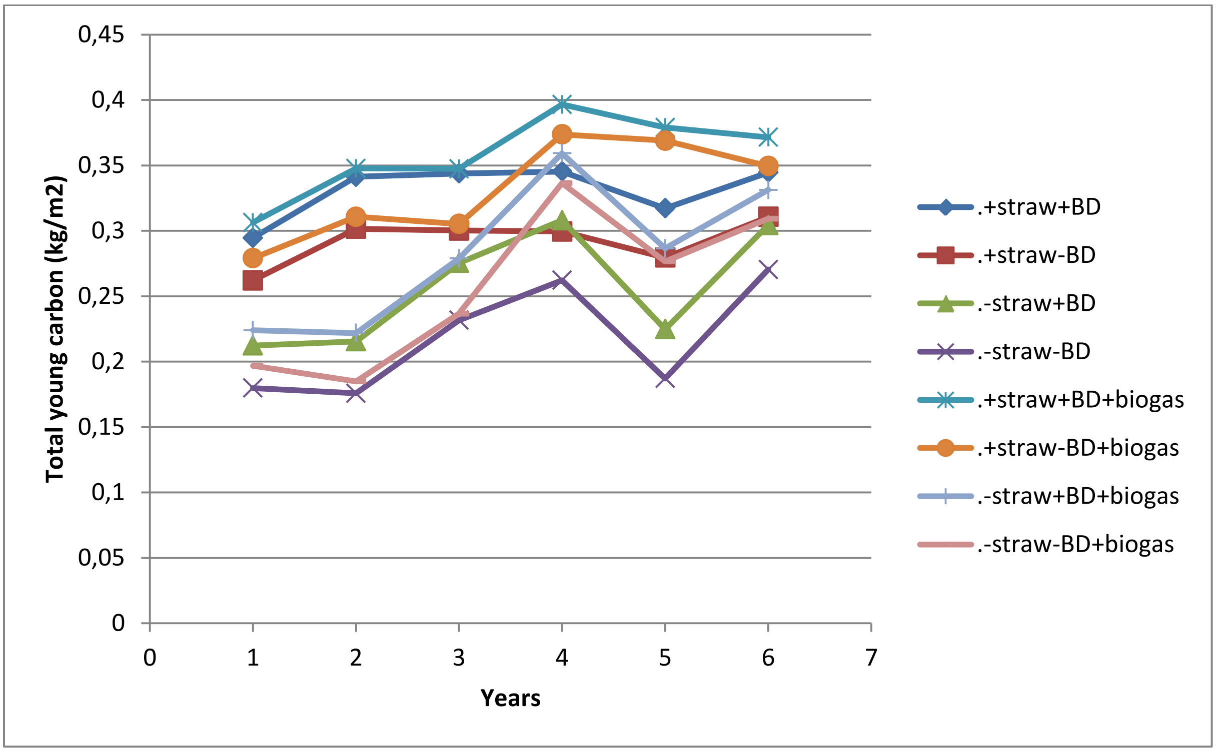


Figure 11: Year to year variation in the young carbon pool for rotation 3, rye-ley-ley-rye-potatoes-rye.

Figure 11 shows that potatoes and ley give a large increase in young carbon in the scenarios where straw is harvested, because straw harvest does not affect them. The effect of ley digestate is also shown.

Effects on old carbon

Since changes in the old carbon stock are slow, the differences between scenarios don't look dramatic at all. But as slowly as the soil carbon reserves are destroyed, as slowly they have to be rebuilt and agriculture is not a 50 year project. Agriculture continues for as long as humanity does. So seen in that light, it definitely matters if the soil carbon stock decreases with 10% over 50 years.

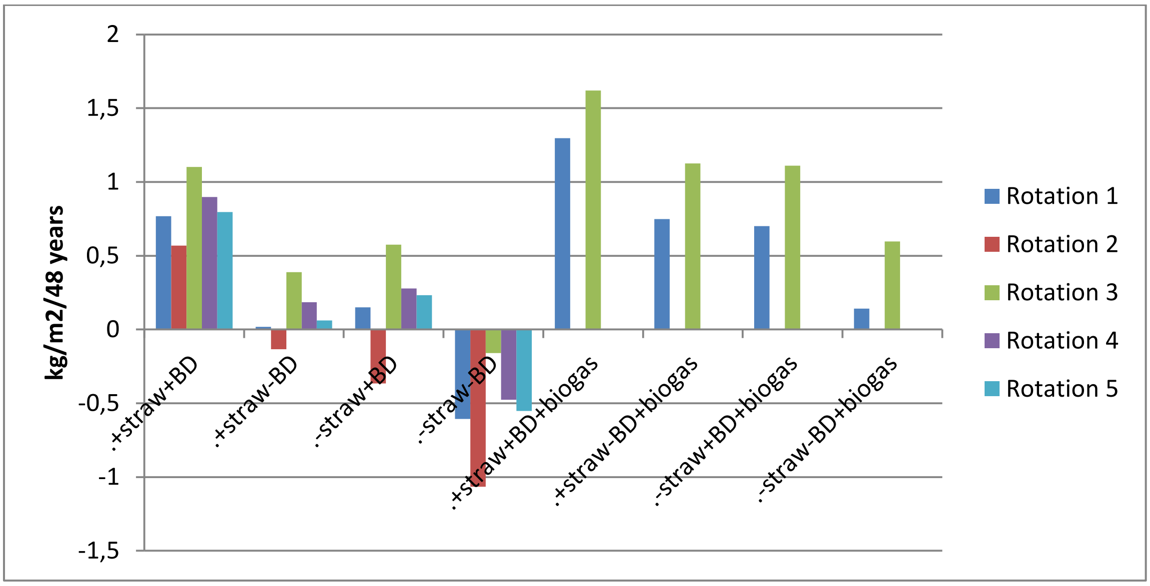


Figure 12: Change in old carbon stock over a 48 year period, kg/m^2 , starting at 2 % carbon.

Figure 12 shows the change in old carbon (kg/m^2) over a 48 year simulation, starting at 2 % or 7.5 kg/m^2 of which almost 7.3 kg is old carbon. As seen in the figure, Rotation 3 (Rye-Ley-Ley-Rye-Potatoes-Rye) is the most beneficial in terms of old carbon stock in all scenarios (especially when ley digestate is returned to the soil), while Rotation 2 (Rye-Rye-Rapeseed-Rapeseed) is the least beneficial. This, as well as the differences between scenarios, matches well with changes in total carbon, and more on the results can be found under "Total carbon percentage".

However, change in carbon stock is not linear. For each combination of crop rotation and cultivation scenario, a steady state exists, at least in theory. If the soil currently holds more old carbon than it would at steady state, there will be a gradual leak. If the soil holds less old carbon than at steady state, the stock will instead increase. The larger the difference, the faster the change and as the soil approaches its specific steady state, the change will slow down. This is shown in figures 13, 14 and 15 for Rotation 5, with three different start values.

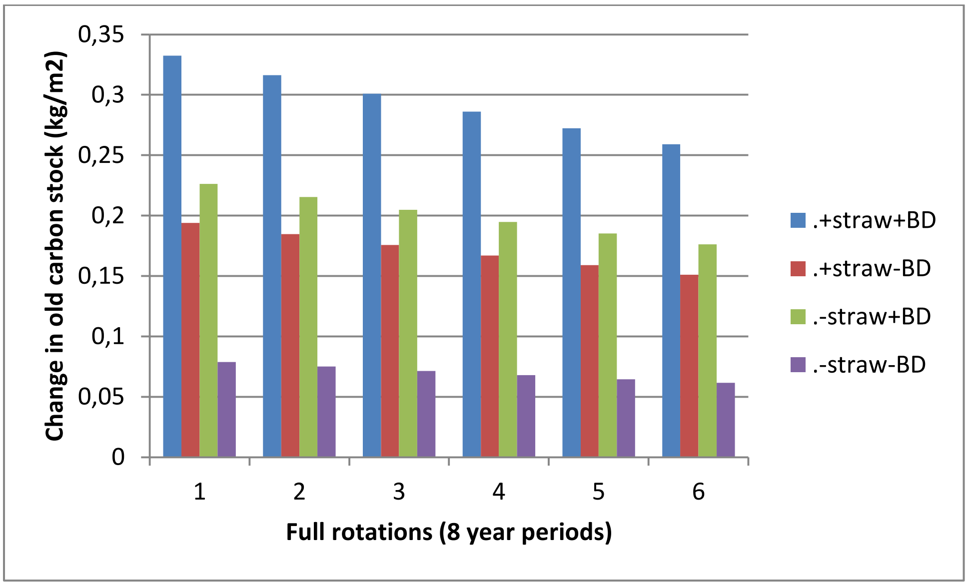


Figure 13: Change in old carbon stock for rotation 5, starting at 1 % carbon, divided into full rotations.

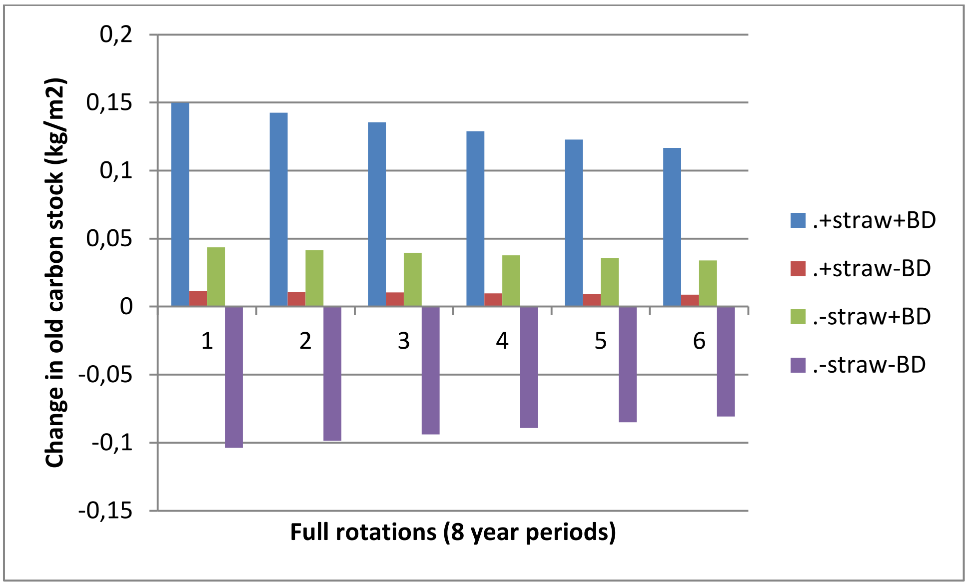


Figure 14: Change in old carbon stock for rotation 5, starting at 2 % carbon, divided into full rotations.

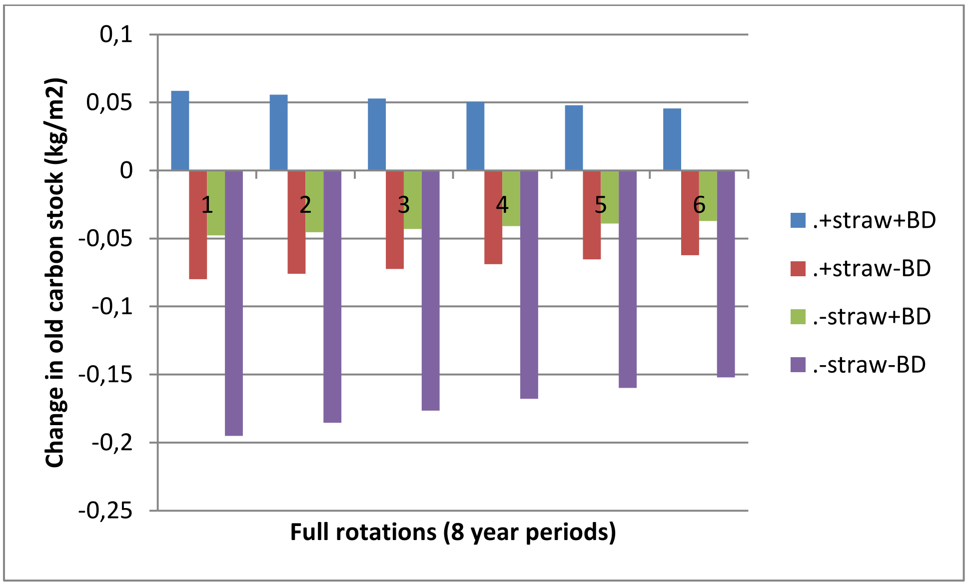


Figure 15: Change in old carbon stock for rotation 5, starting at 2.5 % carbon, divided into full rotations.

Carbon dioxide

The carbon dioxide balance is really just another way to calculate the change in the total carbon stock, and the results when comparing crop rotations are similar. The relevance lies in the easy comparison to other sinks and sources of carbon dioxide.

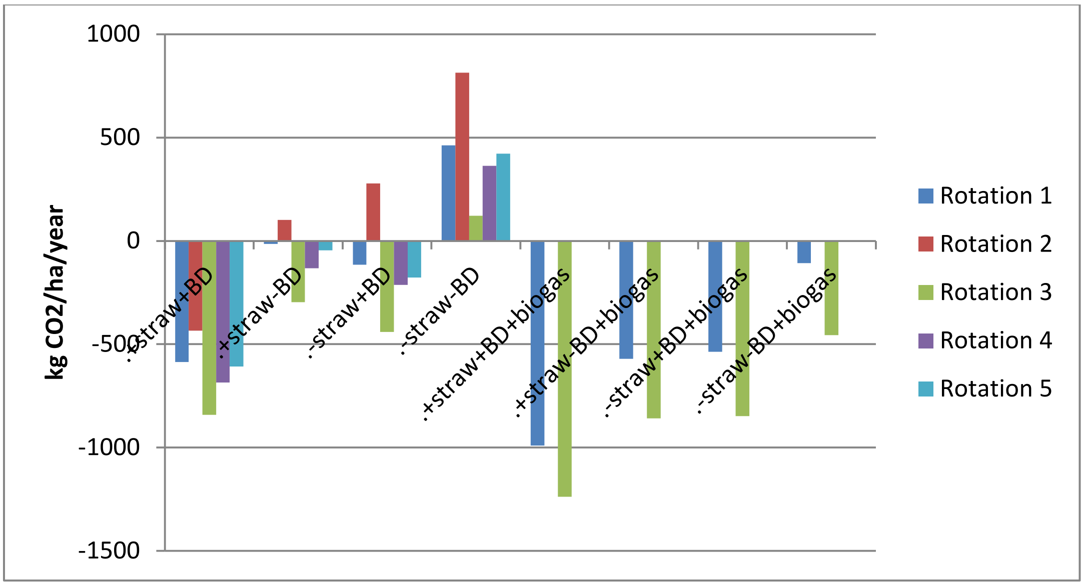


Figure 16: CO_2 balance for all rotations and scenarios, kg per year and ha (average over 48 years). Numbers are positive when carbon is leaked to the atmosphere, negative when the field acts as a carbon sink.

As seen in figure 16, where start value for soil carbon was set to 2 %, Rotation 2 (Rye-Rye-Rapeseed-Rapeseed) releases about 800 kg of CO_2 to the atmosphere (on average over 48 years, the annual value is larger at the start of the simulation for reasons stated earlier, and varies depending on the crop of the year) when straw is harvested and biogas digestate not used. The same amount is sunk in the field when biogas digestate is used and straw not harvested in Rotation 3 (Rye-Ley-Ley-Rye-Potatoes-Rye). If, on top of that, ley is used for biogas production and digestate returned, 1 200 kg CO_2/year is sequestered by Rotation 3.

To get a bit of perspective, 800 kg of CO_2 equals the emissions from burning 320 l of petrol in a car, calculated based on the atomic mass of carbon and oxygen, a 70 % carbon content in petrol (Wolfram Alpha) and a petrol density of about 750 kg/m^3 (The Engineering Toolbox).

In the "standard" scenario, where straw is left on the field and only synthetic fertilizer is used, the balance varies from 101 kg/year/ha emitted in Rotation 2 and 297 kg/year/ha sequestered in Rotation 3.

Total carbon percentage

This measurement is very similar to those of old carbon stock and CO_2 balance, because the old carbon stock makes up the vast majority of the total soil carbon.

Figure 17 shows a comparison of all crop rotations and cultivation scenarios in average soils (2 % carbon at the start of the simulation).

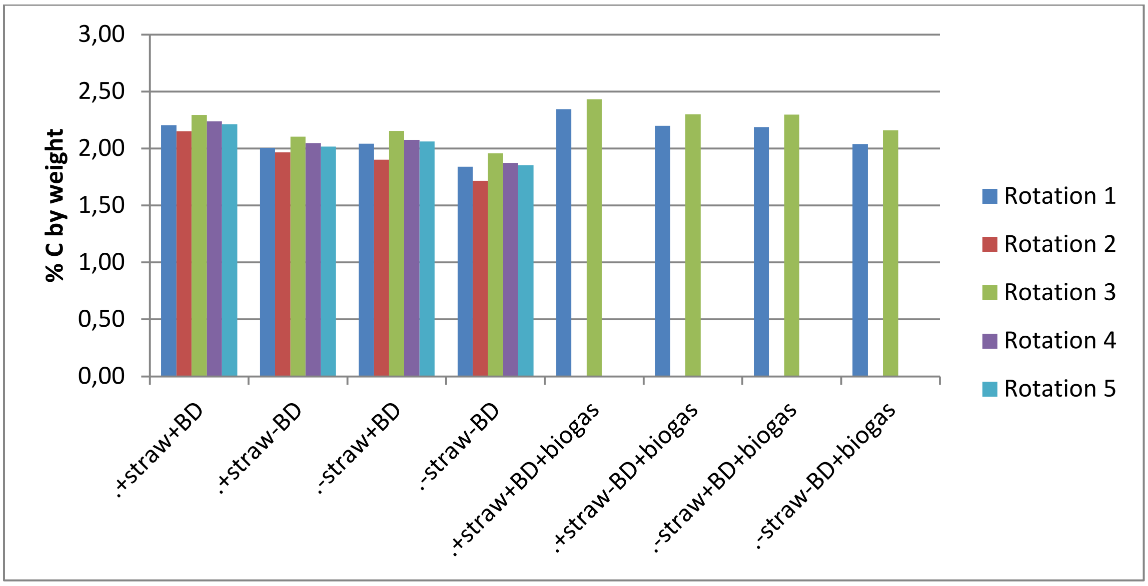


Figure 17: Carbon percentage in the soil after 48 years of simulation. Start value: 2 %.

As shown in the figure, cultivation methods have a large impact on the effect on the carbon stock. When straw is harvested and no biogas digestate is used, the carbon stock decreases for all rotations, except for Rotation 1 and 3 in the biogas scenario. In the opposite case, all rotations instead manage to increase the carbon stock. This is hardly surprising, considering that the input of carbon from straw and biogas digestate is larger than the differences between the crops.

The effects of biogas digestate and leaving straw in the field seem to be approximately equal, with some differences between the rotations.

Comparing the rotations, however, rotation 2 (Rye-Rye-Rapeseed-Rapeseed) seems to be considerably less beneficial to the soil than the others, regardless of the cultivation scenario. Rotation 3 (Rye-Ley-Ley-Rye-Potatoes-Rye) seems to be the one to increase the carbon stock the most in all scenarios, with rotation 1 (Rye-Ley-Ley-Rye-Beans-Rye), 4 (Rye-Rye-Potatoes-Wheat) and 5 (Rye-Rye-Potatoes-Beans-Wheat-Rye-Potatoes-Rapeseed) ending up somewhere in-between. In the scenario where ley is used for biogas production, Rotations 1 and 3, especially Rotation 3, perform a lot better than the others.

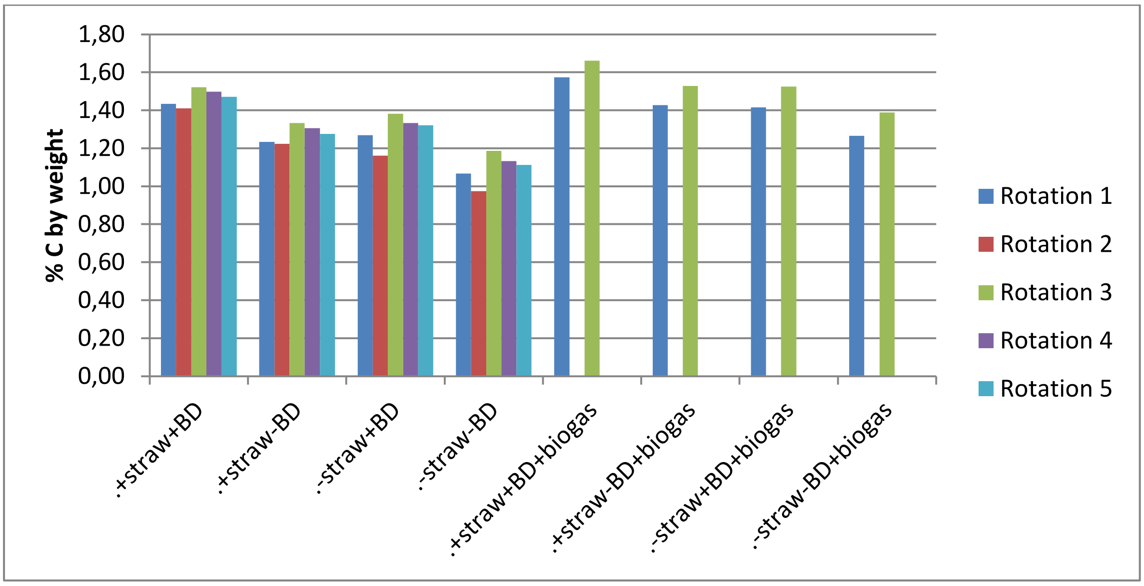


Figure 18: Carbon percentage in the soil after 48 years of simulation. Start value: 1 %.

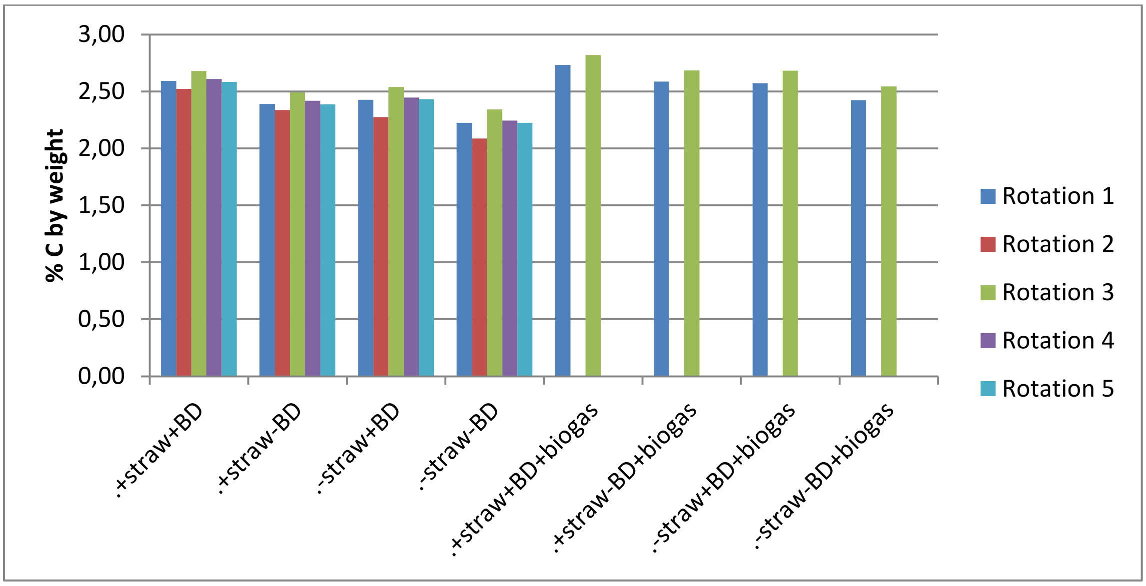


Figure 19: Carbon percentage in the soil after 48 years of simulation. Start value: 2.5 %.

Figures 18 and 19 show carbon percentage at the end of simulation, when the start value is 1 % or 2.5 % rather than 2 %. As seen in the figures, the system tends to aim for a steady state, meaning that a low-carbon soil easily increases in carbon content, whereas a soil, that is rich in carbon, more easily leaks to the atmosphere. The average steady state is close to 2 %, which is also a normal value for average agricultural soils. It is worth noting, however, that Rotation 3 manages the soil carbon stock even from the highest tested value when ley digestate is returned, regardless of the chosen straw option and whether or not other biogas digestate is added.

Yield

The yields were estimated over the whole 48 year period and different parameters compared. When it comes to overall crop yield (total solids) including ley, Rotation 4 (Rye-Rye-Potatoes-Wheat) is the most productive one, closely followed by Rotation 3 (Rye-Ley-Ley-Rye-Potatoes-Rye). The least productive tested crop rotation in terms of total solids is Rye-Rye-Rapeseed-Rapeseed (Rotation 2), but comparing total solids may not be fair since rapeseed is an energy-rich crop. The differences are significant – Rotation 4 has a 34 % higher yield than Rotation 2.

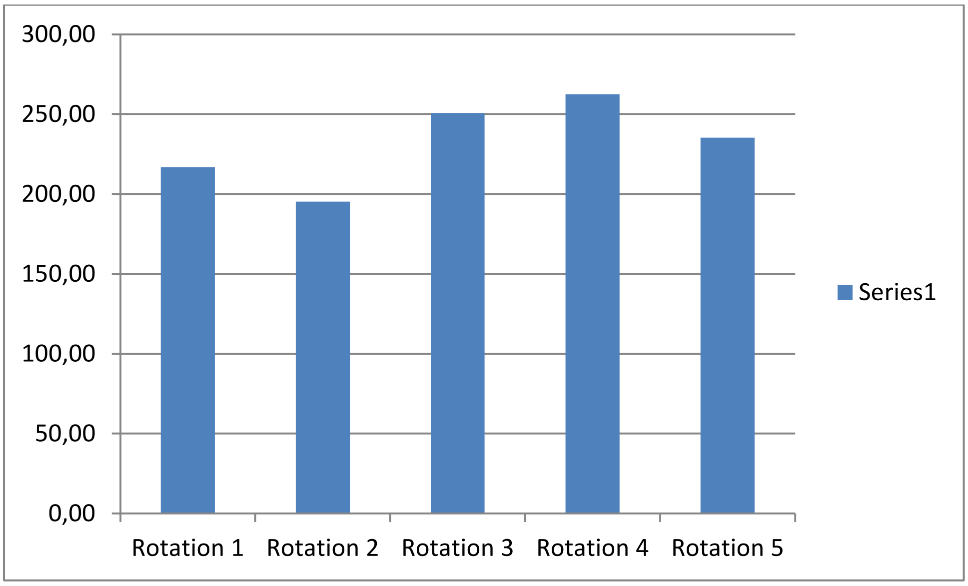


Figure 20: Overall crop yield, tons/ha/48 years, including ley. Total solids.

When ley is not included in the comparison, Rotation 4 is by far the most productive one in terms of total solids, with a 82 % higher productivity than Rotation 1.

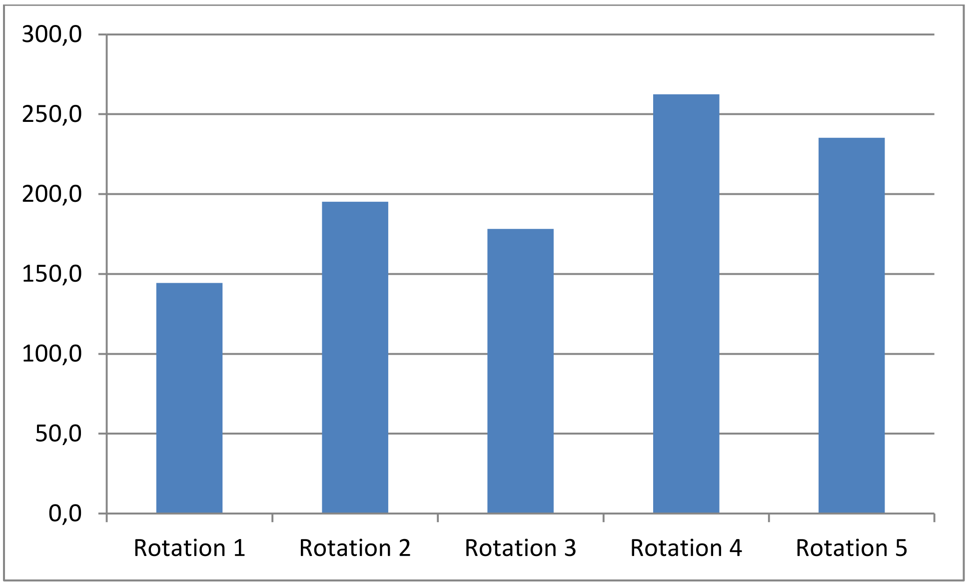


Figure 21: Overall crop yield, tons/ha/48 years, not including ley. Total solids.

However, as mentioned above about rapeseed, some crops have a higher energy value than others, making comparison by weight alone unfair. A comparison by energy content (lower heating value) gives a different ranking.

As seen in the figure, rotation 4 (Rye-Rye-Potatoes-Wheat) is the most productive one, also in terms of energy yield (when ley is not included). However, the energy yield of rotation 4 is only 9 % higher than that of Rotation 2 (Rye-Rye-Rapeseed-Rapeseed), even though Rotation 2 has a relatively low mass yield. At the same time, the energy yield of Rotation 4 is 83% higher than that of Rotation 1 (Rye-Ley-Ley-Rye-Beans-Rye), the least productive option in terms of energy.

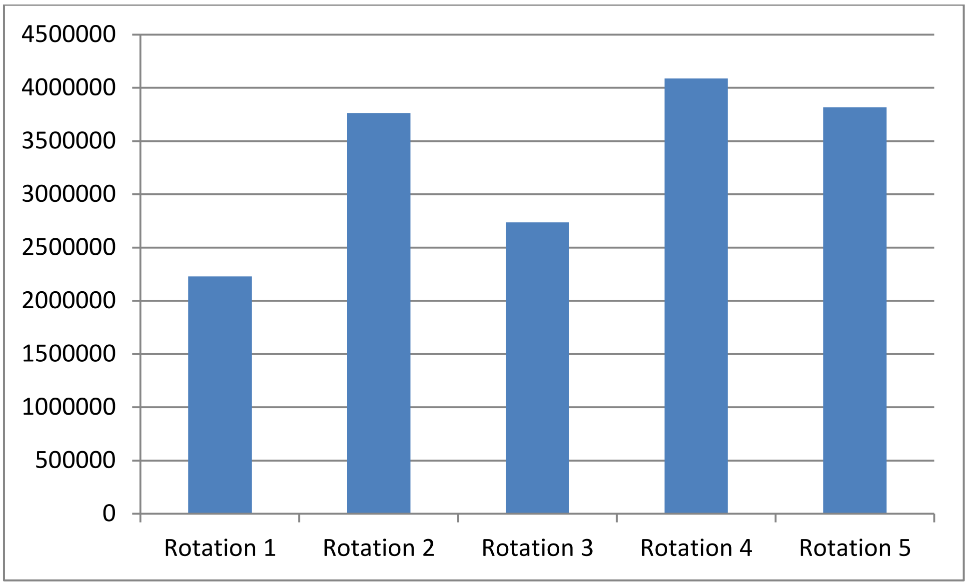


Figure 22: Total energy yield from crops, not including ley. MJ/ha/48 years.

When the ley is included, the energy yield as well as the mass yield looks different. The energy yield is much more similar between rotations when ley is included. However, the energy in ley is not available to humans as food. It becomes useful either as animal feed, or as a substrate for biogas production.

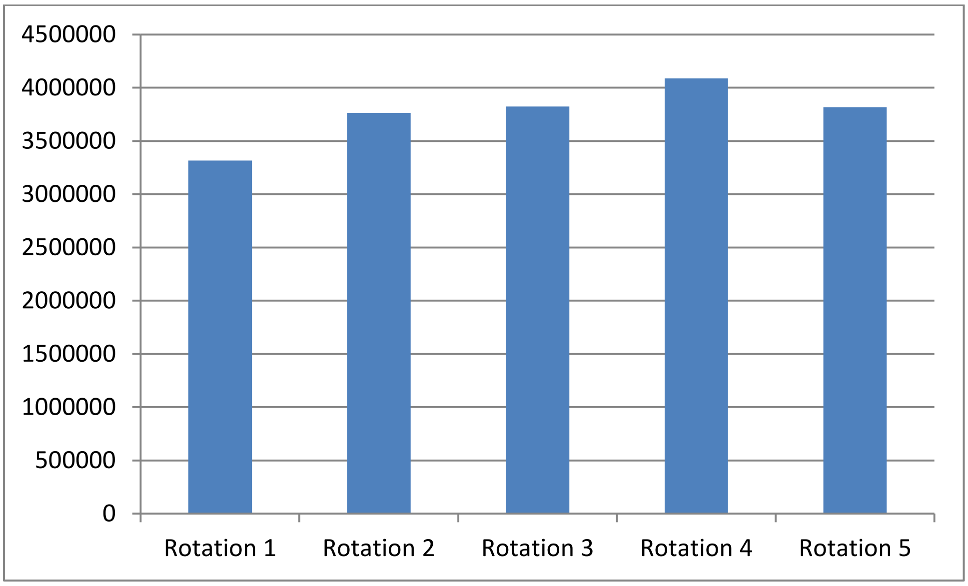


Figure 23: Total energy yield from crops, including ley. MJ/ha/48 years.

Another way to compare the crop rotations is by protein yield. Protein is a valuable nutrient, especially in a diet with less animal products than the current consumption level. In this comparison, ley is not included since its protein is not available for human digestion.

It seems logical to assume that a crop rotation with beans would give a relatively high protein yield, but that is not necessarily the case. Instead, the most productive choice from a protein perspective is Rotation 4 (Rye-Rye-Potatoes-Wheat), with no legumes at all. This is partly due to a high listed protein content for winter wheat, more on that in the Discussion part. Rotation 5 (Rye-Rye-Potatoes-Beans-Wheat-Rye-Potatoes-Rapeseed) is not far behind, but due to low yields, beans contribute less than the other crops. However, the protein in beans might have a higher value than protein in cereals because of its amino acid profile. Using a similar logic, rapeseed protein (about 7% of the protein yield from Rotation 5) may have a lower value because it is only used as animal feed.

The least productive alternative in this comparison is Rotation 1 (Rye-Ley-Ley-Rye-Beans-Rye). Similar outputs are seen from Rotations 2 (Rye-Rye-Rapeseed-Rapeseed) and 3 (Rye-Ley-Ley-Rye-Potatoes-Rye). The lower output from rotations with ley is of course because the years with ley do not contribute at all in this comparison. The protein yield from Rotation 4 is 63 % higher than that from Rotation 1.

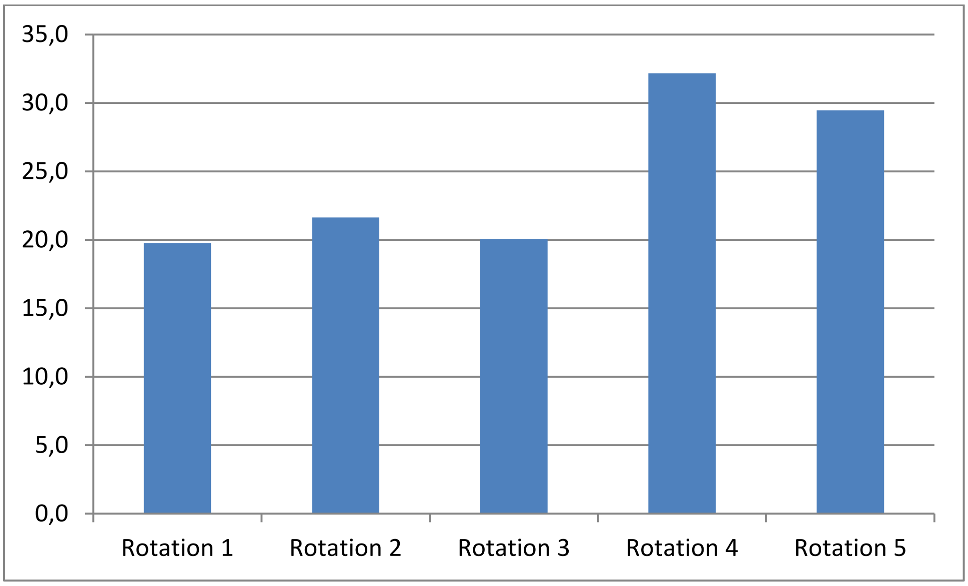


Figure 24: Total protein yield from crops, not including ley. MJ/ha/48 years.

When straw is harvested, that, too, is a resource. Straw can be used for heating, either in homes or as district heating, potentially with electricity production too. 90 % more straw can be harvested with Rotation 5 (Rye-Rye-Potatoes-Beans-Wheat-Rye-Potatoes-Rapeseed), the most productive rotation, compared to Rotation 3 (Rye-Ley-Ley-Rye-Potatoes-Rye), the least productive one.

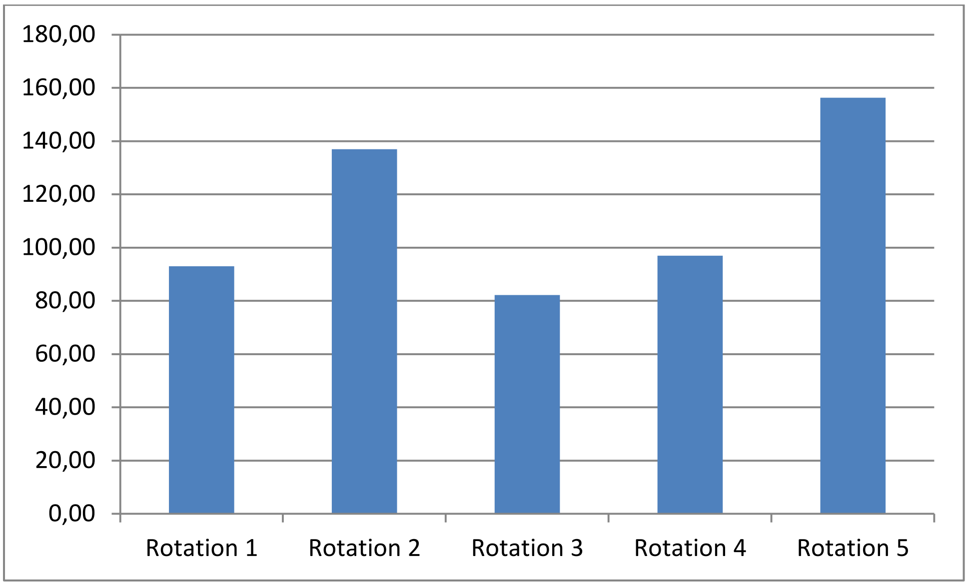


Figure 25: Straw yield, tonnes/ha/48 years. Total solids.

The heat content of straw is 4.389 kWh/tonne, or 12.560 MJ/tonne (Carbontrust, 2013). The direct emissions from fuel oil burning, including CO_2-equivalents of CH_2 and N_2O but not including the emissions from extracting and refining the oil, equal 0.26876 kg/kWh (Carbontrust, 2013). In other words, when one tonne of straw is burnt instead of getting the same amount of energy from fuel oil, 1 180 kg of CO_2 emissions (or the equivalent greenhouse gas potential) is avoided.

156 tonnes/ha of straw can be harvested from Rotation 5 (Rye-Rye-Potatoes-Beans-Wheat-Rye-Potatoes-Rapeseed) over 48 years, replacing oil burning that emits 184 tonnes of CO_2 per hectare, or

3830 kg CO_2/year/ha. The same numbers for Rotation 3 (Rye-Ley-Ley-Rye-Potatoes-Rye), the least productive one in terms of straw yield, are 82 tonnes straw/ha over 48 years, 96.7 tonnes CO_2-emissions avoided per hectare over 48 years and 2 015 kg CO_2/year/ha.

Some crops can be used for biofuel production. In this study, I've considered biodiesel from rapeseed oil and biogas from ley.

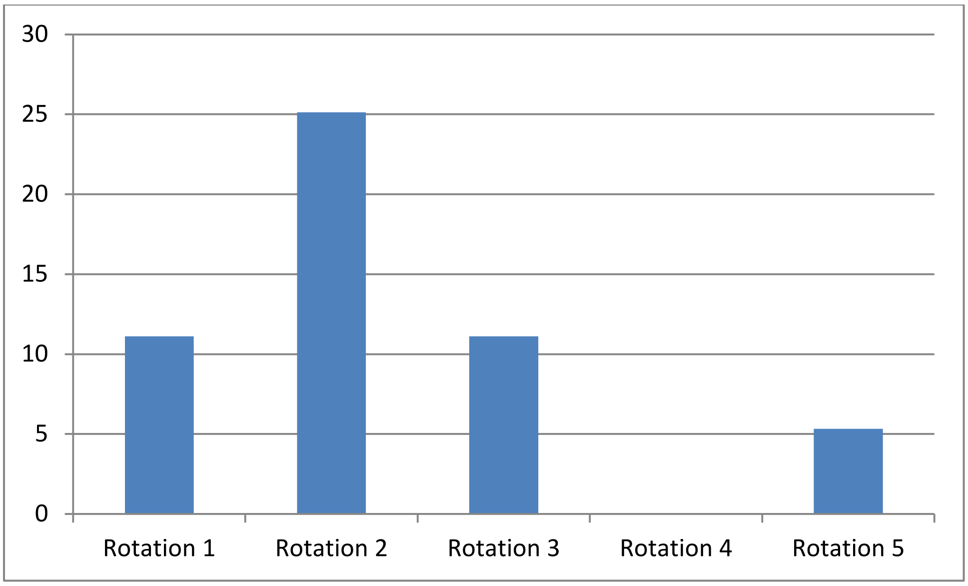


Figure 26: Biofuel potential. Volume of fossil diesel that can be replaced per hectare in 48 years in m^3.

As seen in figure 26, Rotation 2 (Rye-Rye-Rapeseed-Rapeseed) has the biggest biofuel potential by far, if all rapeseed is processed into RME. To do so would, however, lower the energy value of Rotation 2 as food for humans, since rapeseed oil can also be eaten. The same thing is true for the biofuel potential f Rotation 5 (Rye-Rye-Potatoes-Beans-Wheat-Rye-Potatoes-Rapeseed).

Rotations 1 and 3 do not require the same kind of choice, since the ley crops that can be digested to produce biogas are not edible for humans. Rotations 1 and 3 can both replace 11 m^3 of fossil diesel per hectare in 48 years, if all ley is digested. Rotation 4 does not contain ley or rapeseed, and has no biofuel potential according to the definition in this study. It is, however, possible to create biofuels from other crops too, such as ethanol from wheat, if one would choose to.

Discussion

Yield

Yield data for different crops

In the data for crop yield, that much of this work is based on, the numbers for wheat, especially winter wheat, are relatively high (6 625 kg/ha/year compared to 5 701 kg/ha/year for rye). Since the calculation of carbon input from residues is based on assumptions that residues are proportional to crop yield, a higher crop yield means a higher value as soil carbon source.

However, the yield data is based on statistics from actual harvests in Sweden, not from experiments in a controlled environment. The comparison between crops is only fair if they were grown on equally fertile soil, with equal fertilization and cultivation methods. In reality, wheat is a relatively demanding crop that is often grown on the best soils, whereas rye does well also on marginal land, where the soil is not as fertile. It is possible that the numbers would be different if that was not the case and since this work aims to simulate what would happen if different crop rotations were tried on the same patch of land, the actual data available is a possible source for error.

In a sensitivity analysis, winter wheat yield was changed to the same value as rye yield and comparisons were made with the main results. Effects on CO_2 emissions, old carbon stock and average young carbon were very small, and did not change the ranking of the different scenarios. It seems that the potential flaw in available data does not significantly impact the results.

The sensitivity analysis was performed on the scenarios with 2 % C in the soil at the start of the simulation, just like the main comparisons of crop rotations in Results. Unless stated otherwise, all sensitivity analysis was performed on the 2 % scenarios.

Protein yield and quality

In the comparison of protein yield from different crop rotations, rotations with wheat perform very well. This is, of course, partly due to the assumed protein contents in the database that was used. Protein content for wheat was assumed to be 15.9 % of total solids, compared to 11.8 % for rye and 30 % for beans. While it is true that wheat is relatively high in protein (compared to other cereals), its protein content varies. Different wheat varieties have different protein content, depending on if they are soft (grown as animal feed) or hard (grown for bread) (USA Emergency Supply, 2013). The wheat in this study is assumed to be bread wheat, since animal feed is not considered here. The amount of nitrogen fertilizer also has impact on the protein content, as well as weed control, ley or legumes in previous years and other factors (Gartner, 2005).

Sensitivity analysis was performed, with wheat protein content at 10 % and at 12 %. In neither of these tests did the rating between crop rotations change, even though the difference became smaller. Not even when wheat protein content was set to 10 % and wheat yield equal to rye yield did the rating change.

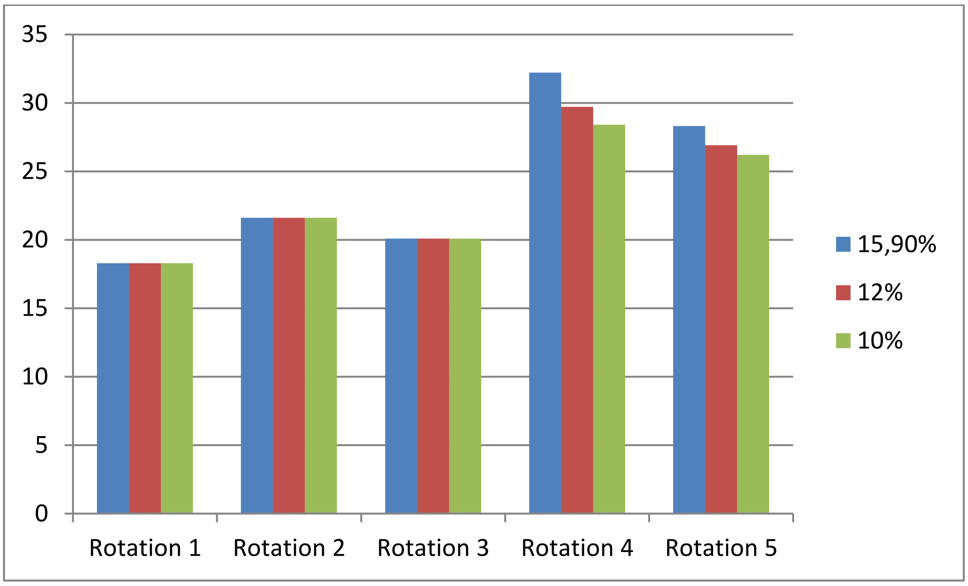


Figure 27: Protein yield in tons/ha/48 years with different protein content in wheat

Explaining effects on the carbon stock

Different h-values

The h-value is a measure of how easily degradable the organic matter is. The higher the h-value, the slower the material will degrade, and the more of it will be left as humus in the "Old" carbon pool. According to more recent research (Kätterer et al, 2011), roots should be given a higher h-value than above ground material, possibly because they are more embedded in the soil, and it's harder for microorganisms to access them. Of course, using different h values for roots and shoots (above ground residues) gives the roots a higher relative value for the carbon balance, and makes the difference between leaving and harvesting straw smaller. However, according to Thomas Kätterer (2012), changing the h-values in the model would change the calibration of the constants k_Y and k_O, and more research is needed before this can be done in a correct way. He did not recommend using different h-values for roots and shoots in this work. Nonetheless, the reader should be aware that there probably is a difference, even though it might not be realistic to model it in a correct way in this study.

A sensitivity analysis, using different h-values for roots and shoots (same approximate average for rye as the value used in the main study, and same approximate proportions as the separate values suggested by Kätterer, namely 0.12 for shoots and 0.27 for roots for grains) was performed on all rotations with the scenario no biogas digestate and 2 % C at the start of the simulation, with and without straw harvest. The results show a much larger difference in the scenarios where straw is harvested. It seems that the ICBM-model was primarily created for scenarios without straw harvest, and that the ratio between the different h-values reflects that. The diagrams below show the CO_2 balance for the different scenarios, and a positive value means that carbon is lost from the soil to the atmosphere as CO_2. When separate h-values are used, the penalty for harvesting straw is much lower and this might affect the decision whether or not straw harvest for fuel is a good idea.

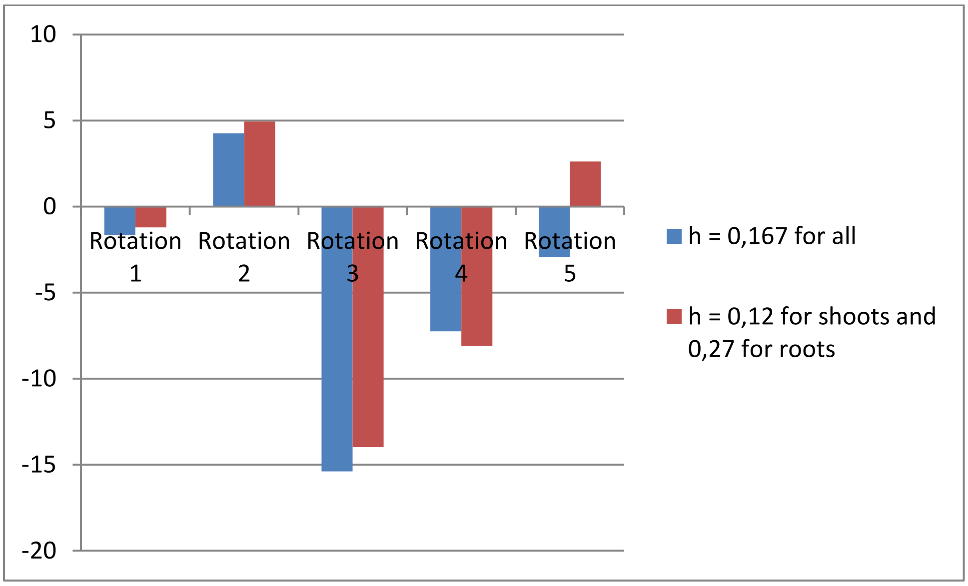


Figure 28: The effect of using different h-values for roots and shoots when straw is not harvested. CO_2 balance, tons/ha/48 years.

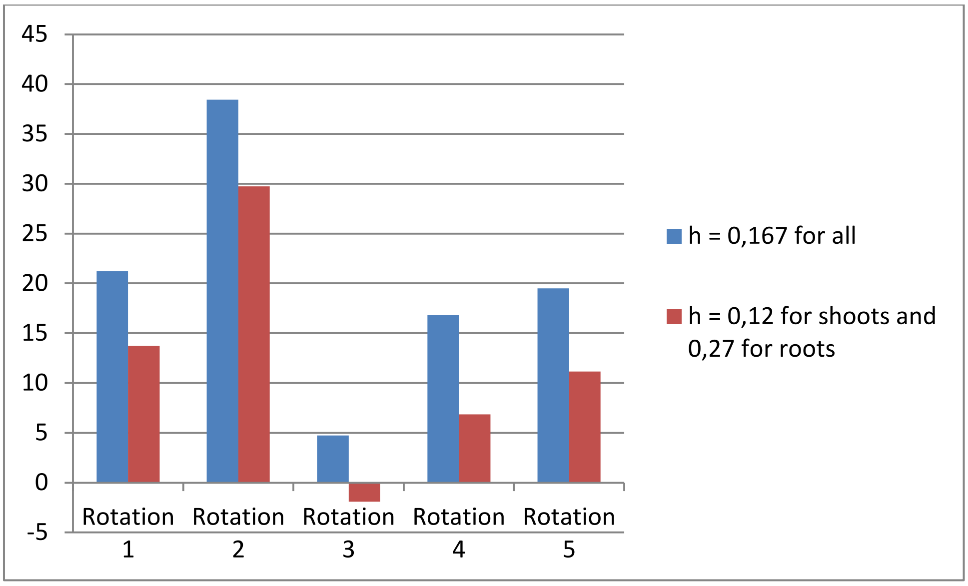


Figure 29: The effect of using different h-values for roots and shoots when straw is harvested. CO_2 balance, tons/ha/48 years.

Data and results

No experiments have been performed for this study. Instead, the simulations were done with existing data from previous studies. If repeated similar experimental studies were to be performed, it is likely that results would vary based on soil properties, measuring methods, weather and other factors. However, since existing data was used in a new way in this study, it's not surprising that my results confirm previous results in the areas that were previously tested. For example, the value of sewage sludge or biogas digestate is already assumed in the dataset behind the Excel model, as well as the effect of leaving or harvesting straw.

What is new, though, is the comparison of different crop rotations, depending on (previously tested) cultivation methods.

Properties of biogas digestate

The properties of biogas digestate differ, depending on the substrate used to produce the gas. If the substrate is mainly protein-rich slaughterhouse waste, the resulting biogas digestate will be rich in nitrogen. As seen earlier, if the substrate is ley crops, the nitrogen content of the biogas digestate will be considerably lower. The more nitrogen the biogas digestate contains, the smaller the volume that can be spread on the field. Of course, from a fuel and time perspective, it is more efficient to spread a smaller quantity of concentrated fertilizer, but the carbon input is larger when a large volume of low-nitrogen biogas digestate is spread.

Due to the variation in biogas digestate properties, the effect of biogas digestate is bound to vary as well. Hence, the numbers given by this simulation should not be seen as an absolute truth. Carbon input from spreading of biogas digestate can be both smaller and larger than the amount assumed in this study.

Soil carbon and harvest

The potential negative effect on the harvest from having less than 2 % carbon in the soil have not been taken into account. It is, however, likely that due to this effect, low carbon soils are more sensitive, due to lower yields and hence also lower input of crop residues.

Comparing the rotations

As seen in the Results section, some of the rotations have a more positive effect on the soil, while others give a higher yield. The yield ranking differs too, depending on which parameter the yield is measured by. It is in the purpose of this paper to put these factors together, in order to find an overall ranking between the rotations.

Comparison by parameter

The best of the tested rotations, when seen purely from a soil carbon perspective, is Rotation 3 (Rye-Ley-Ley-Rye-Potatoes-Rye). Worst from a soil carbon perspective is Rotation 2 (Rye-Rye-Rapeseed-Rapeseed). The other three tested rotations are relatively close to each other in this respect.

When comparing yield by total solids (not including straw), Rotation 4 (Rye-Rye-Potatoes-Wheat) is the most productive one with a 34 % higher yield than Rotation 2 (Rye-Rye-Rapeseed-Rapeseed). Rotation 3 (Rye-Ley-Ley-Rye-Potatoes-Rye) is a close second, while Rotations 1 and 5 are in-between in productivity.

When ley is not included in the total solids, Rotation 1 (Rye-Ley-Ley-Rye-Beans-Rye) is the least productive one. Rotation 4 (Rye-Rye-Potatoes-Wheat) still has the highest yield, 82 % higher than Rotation 3.

When energy content is compared, Rotation 4 (Rye-Rye-Potatoes-Wheat) is still the most productive alternative, with an 83 % higher energy yield than Rotation 1 (Rye-Ley-Ley-Rye-Beans-Rye). Rotation 3 (Rye-Ley-Ley-Rye-Potatoes-Rye) gives a slightly higher yield than Rotation 1, while Rotations 2 and 5 are very close behind Rotation 4.

When ley is included in the energy calculations, the different rotations give more similar results. Rotation 4, being the most productive option, has a 23 % higher yield than Rotation 1, the least productive.

Comparing protein yield also shows Rotation 4 (Rye-Rye-Potatoes-Wheat) in a good light, with a 76 % higher yield than the lowest, Rotation 3 (Rye-Ley-Ley-Rye-Potatoes-Rye). Rotation 5 (Rye-Rye-Potatoes-Beans-Wheat-Rye-Potatoes-Rapeseed) is close behind Rotation 4, while Rotations 1 and 2 only perform slightly better than Rotation 3.

A straw yield comparison gives a somewhat different picture, partly because potatoes is a productive crop in terms of edible parts, but does not produce straw. The rotations with ley also produce less straw than those without. The most productive alternative is Rotation 5 (Rye-Rye-Potatoes-Beans-Wheat-Rye-Potatoes-Rapeseed), with a 90 % higher yield than Rotation 3 (Rye-Ley-Ley-Rye-Potatoes-Rye). Rotation 1 and 4 only produce a little more straw than Rotation 3, while Rotation 2 is not so far from Rotation 5 in performance.

A comparison of biogas potential shows Rotation 2 as a clear winner, but only if rapeseed oil is used as a fuel rather than consumed by humans. Rotations 1 and 3 can potentially replace 11 m^3 of fossil fuel per hectare in a 48 year period, if ley is digested for biogas. Rotation 4 does not contain any biofuel crops as defined by this study, while the rapeseed in Rotation 5 can replace 5 m^3 of fossil diesel per hectare with RME.

Comparison by rotation

In other words, Rotation 1 (Rye-Ley-Ley-Rye-Beans-Rye) is average when it comes to soil carbon effects and yield of total solids (with and without ley), and performs poorly in a comparison of energy-, protein- and straw yield. It has the overall lowest energy yield, but it is among the best in terms of biofuel potential. In the biogas scenario, it is also very beneficial for the soil.

Rotation 2 (Rye-Rye-Rapeseed-Rapeseed) is the worst from a soil perspective, and in terms of total solids yield including ley, and it has a relatively low protein yield. It is, however, the most productive rotation in terms of energy yield, and a close second in terms of potential straw yield. It has the potential to produce more biofuels than the other rotations, but then the rapeseed has to be removed from the calculated energy yield or it would be counted twice.

Rotation 3 (Rye-Ley-Ley-Rye-Potatoes-Rye) is the best tested option for increasing soil carbon, especially when ley is used for biogas and the digestate returned to the soil. It is the second most productive one in terms of total solids when ley is included, but the least productive when ley is not included. It has the lowest protein and straw yield, and the second lowest energy yield. The ley can be used to produce biogas, replacing 11 m^3 of fossil diesel per hectare in 48 years.

Rotation 4 (Rye-Rye-Potatoes-Wheat) is an average performer when studying soil carbon effects, but relatively productive. It has the highest yield of total solids (with and without ley), energy and protein, but among the lowest yields of straw and no biofuel potential.

Rotation 5 (Rye-Rye-Potatoes-Beans-Wheat-Rye-Potatoes-Rapeseed) is average in soil carbon performance and yield of total solids. It is above average in energy and protein yield, and the most productive rotation for straw harvest. Of course, this makes sense for a rotation with a lot of variation, but no ley and mostly crops with straw that can be harvested. The rapeseed can be used to produce RME.

The best rotation

The top performer overall seems to be Rotation 4. While it does not have the most positive effect on the soil, it has at least some positive effects in most scenarios, and on most soils, as seen in figure 30. More importantly, a high yield per hectare means that the same available agricultural land can feed a larger population, or that a constant population can be fed using less land for agriculture.

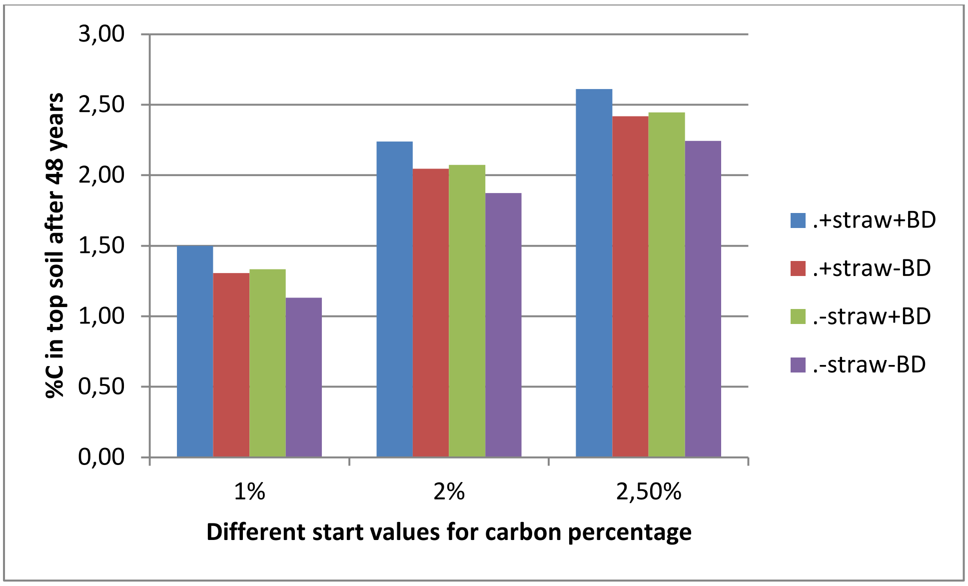


Figure 30: Carbon percentage after a 48 year simulation, depending on start value and cultivation scenario. Rotation 4.

Figure 30 shows that for an average Swedish soil (2 % carbon), Rotation 4 does not make much of a difference on the soil carbon stock. If straw is harvested and only synthetic fertilizers are used, there is a slight decline. If either straw is left on the field or biogas digestate is used, the carbon stock remains intact. With the addition of both straw and biogas digestate, the soil somewhat increases its carbon stock. If the carbon percentage is higher or lower at the start of the simulation, it slowly increases or decreases towards around 2 %, which is enough to not have a negative impact on the harvest.

However, if improving soil health is the main objective, Rotation 3 should be used and the biogas produced from the ley harvest. Rotation 3 gives a relatively low yield of edible crops, somewhat excused by the biofuel potential, but most of all, it has a very positive effect on the soil.

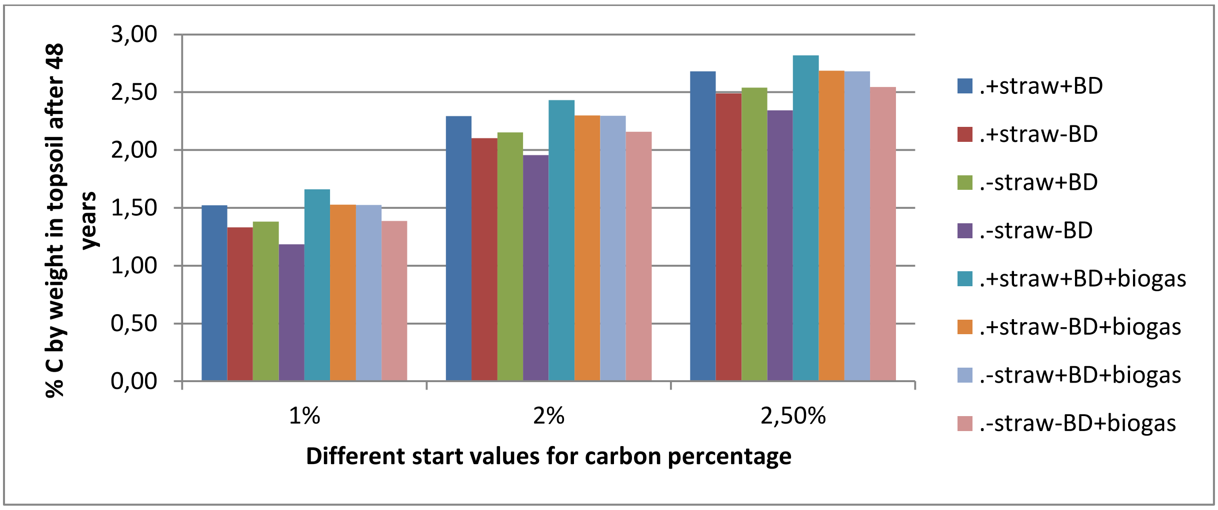


Figure 31: Carbon percentage after a 48 year simulation, depending on start value and cultivation scenario. Rotation 3.

Straw harvest

Straw can be used as fuel, a valuable resource for heat and electricity. At the same time, harvesting straw decreases the carbon input to the soil, adding to potential soil degradation.

One way of comparing the effects is by studying carbon dioxide balance.

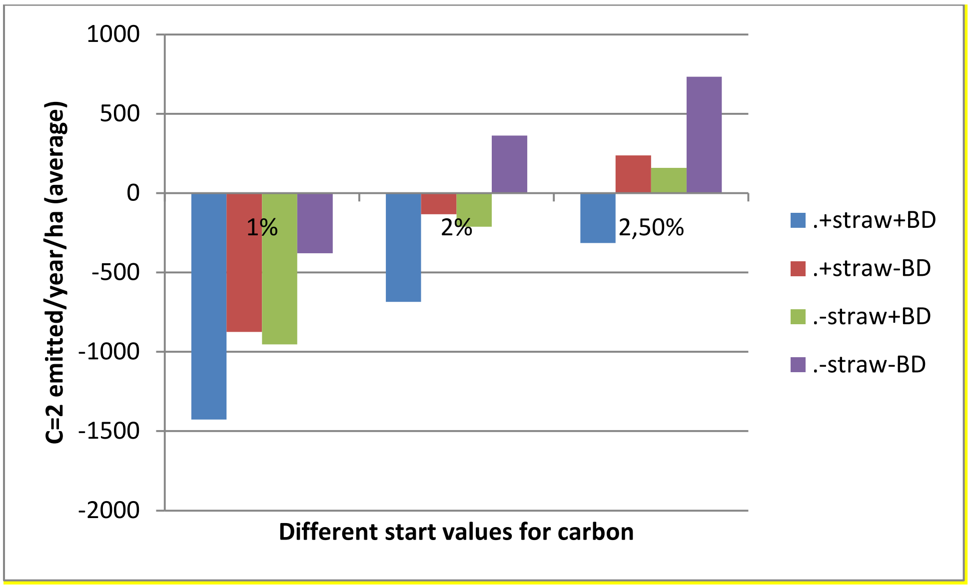


Figure 32: Carbon dioxide balance for all scenarios and start values, average kg/year/ha. Rotation 4.

Looking at the scenarios with only synthetic fertilizers, harvesting straw means that the carbon equivalent of 496 kg CO_2/year/ha leaves the soil, on average. When biogas digestate is used, this figure is 473 kg CO_2.

To compare, it was showed under Results that burning one tonne of straw, rather than fuel oil, for heat or heat and electricity prevents the emission of 1 180 kg CO_2 from fossil sources. The potential straw harvest per hectare from Rotation 4 is 96.9 tonnes/48 years (total solids) or, for comparison, or 2.02 tonnes/year. Harvesting and burning 2.02 tonnes of straw means that the emission of 2 383 kg of CO_2 can be prevented. This is about five times as much as the differences in carbon balance in the soil, resulting from straw harvest.

These numbers are hardly surprising, given the h-value of 0.167 for straw. The h-value is a measurement of how easily degraded the organic matter is and a lower value means that a larger percentage of the organic material will simply degrade and leave the soil as CO_2 during the first year. The portion that is left (about 17 % in this case) is harder to degrade, and stays in the soil as part of the old carbon pool. If separate h-values were used for above- and below ground residues, giving straw a lower h-value, the simulation would show an even smaller portion on the organic material staying in the soil.

Given this, it is probably safe to say straw is a rather inefficient way to keep carbon in the soil, considering its alternative use as fuel.

In a future study, it might be interesting to look into the concept of straw pellet gasification, where the remaining coal pellets are tilled into the soil. That way, most of the energy in the straw can be used, and stable carbon as well as minerals is returned to the soil.

The benefits of ley and legumes

No large benefits from ley and legumes in crop rotations could be shown in this study, as long as the ley was not returned to the soil as biogas digestate. The rotations with ley were generally less productive than those without, because food crops were not grown every year and the increased harvest in the years following ley did not compensate for the missed years. The effects on soil carbon were not very big either in the simulations in this study. Rotation 3, with ley (Rye-Ley-Ley-Rye-Potatoes-Rye) is the best from a soil perspective, when yield is not considered. But the second best rotation (Rotation 4, Rye-Rye-Potatoes-Wheat) does not contain ley and has considerably larger yield. The other rotation with ley (Rotation 1, Rye-Ley-Ley-Rye-Beans-Rye) is merely average from a soil perspective, and gives relatively low yield.

These results do not match the general view that ley in the crop rotation is very beneficial for the soil, and that the positive effects on following yields may even be enough to make up for the years without food crops. Since no new experimental data was created for this study, it is possible that the existing data for ley, especially for the carbon input from roots that are left in the soil from one season to the next, were misinterpreted, leading to partially incorrect results.

However, if ley was used for biogas production and the resulting digestate returned to the field, a very positive effect was seen on the soil. If a main objective is to improve soil quality, this option might be a very good one – especially if biofuels are desired as well.

The rotations with beans (legumes) do not perform particularly well, whether energy yield, protein yield or carbon effects are studied. The beans yield relatively low harvests, with relatively small amounts of residues, resulting in low carbon input to the soil. The increased harvests of the following years do not fully compensate for the low bean yield. Despite the relatively high protein content of beans (about 20 % of total solids, compared to about 12 % for rye and about 16 % for winter wheat), the lower yield results in a lower total amount of protein.

The data for beans may not tell the whole truth, however. Beans and other legumes are valuable in especially a vegetarian diet, since they contain essential amino acids which are not found in sufficient amounts in grains. Beans are also valuable because of their higher protein content, making it easier to eat enough protein in relation to carbohydrates (energy) in a vegetarian diet, even though it is, of course, easy to concentrate the protein from for example wheat. Using crop rotations with legumes can still be recommended, even if they are not the most efficient ones.

Conclusions

Using biogas slurry has a positive effect on the soil, compared to only using synthetic fertilizers. This is intuitive, and was also known from previous studies. The positive effect is mainly due to an increased carbon input. Carbon from biogas slurry is also relatively stable, since most of the easily degraded organic compounds have been used in the biogas process.

Harvesting straw has a negative effect on the soil, compared to leaving it on the field. However, since most of the straw is quickly degraded in the soil anyway, the negative effect is not big enough to significantly impact potential harvests. Furthermore, burning straw instead of oil as a fuel prevents CO_2 emissions five times as large as the difference in carbon balance in the soil. Based on this, leaving straw on the field for the sake of carbon balance cannot be recommended over harvesting it as a fuel.

Of all the tested crop rotations,

1. Rye-Ley-Ley-Rye-Beans-Rye
2. Rye-Rye-Rapeseed-Rapeseed
3. Rye-Ley-Ley-Rye-Potatoes-Rye
4. Rye-Rye-Potatoes-Wheat
5. Rye-Rye-Potatoes-Beans-Wheat-Rye-Potatoes-Rapeseed,

Rye-Rye-Potatoes-Wheat (Rotation 4) turned out to be the most productive in terms of total solids, energy yield and protein yield. In other words, it produces more food than the other options. This rotation is not the best from a soil carbon perspective, but it does keep the soil around 2 % carbon in most scenarios, which is enough to keep it fertile. When weighing yield against carbon effects, it must be seen as a positive trade off to keep the soil fertile while getting high yields of food, rather than slightly improving the soil but needing larger areas to grow food. Occupying new land, for example forest or grassland, for food production will most likely lead to larger losses in carbon (from soil and biosphere to atmosphere) elsewhere.

If, however, priority is on the quality of the local soil and on production of biofuels rather than maximising food production, Rye-Ley-Ley-Rye-Potatoes-Rye (Rotation 3) with ley used for biogas production is the best option. This may be the case if the soil carbon content is below 2 %, and a rapid increase is needed to improve future harvests.

The often assumed positive carbon effects of merely growing ley in crop rotations cannot be supported by this study. The tested rotations with ley are only marginally better in terms of soil carbon, and their yield is considerably lower than that of the rotations without ley. However, when biogas is produced from ley and the resulting digestate spread on the field, large positive effects can be seen.

However, the carbon effects of ley in crop rotations are not the only reason why it might be beneficial. Another reason is the nitrogen left in the soil, improving the conditions for the crops of following years. In this study, the nitrogen effect is illustrated by an increased harvest in the year directly following the years with ley. However, in reality, a small effect remains for several years, and for the sake of simplicity, this prolonged effect is not included here. In a future study, it might be interesting to look more closely at the long term effects of ley in crop rotations on the yield, the need for mineral fertilizer and the difference in fossil fuel use (if any) that come with a smaller need for synthesised nitrogen.

Based on the results from this study, it seems reasonable to promote – as part of a strategy for sustainable rye cultivation – the cultivation of rye in crop rotations together with high yielding crops and harvesting the straw for bioenergy purposes. Regarding the fertilizer strategy, biogas digestate (biogas slurry) should preferably be used, at least from a soil carbon perspective, and if ley is part of the crop rotation, it should be used for biogas production and the slurry spread on the field.

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