Boosting grain yield by including leguminous bioenergy crops in the rotation – a life cycle approach

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ABSTRACT

Introduction of rotational grass/clover for anaerobic digestion in a grain production system was evaluated using life cycle assessment. Energy requirement, global warming potential and land use were compared in two scenarios; one cropping system including only cereals and another also including two-year grass/clover. Use of fossil fuels and greenhouse gas emissions were reduced substantially, mainly due to replacement of diesel with biogas, but also when digested grass/clover biomass replaced N mineral fertilizer. High N use efficiency throughout the production chain was required for a high replacement rate of mineral fertilizer. The residual effect from rotational grass/clover increases the yield potential and provides N for subsequent crops. Both these aspects should be included in LCA of break crops through evaluation of crop sequences rather than specific crops. We recommend that introduction of different rotational crops relying on N-fixation be evaluated as a future strategy for improving productivity and environmental performance.
Keywords: Crop rotation, multifunctional bioenergy crops, N-fixation, land competition

1. Introduction

Bioenergy production in the EU is currently based largely on annual oilseed, starch, and sugar crops (Pedroli et al. 2013). Using common crops for bioenergy production may perpetuate monoculture cropping and there is thus a need for more innovative production systems with multifunctional benefits. At present, only a small proportion of bioenergy feedstock comes from perennial ligno-cellulosic species such as miscanthus, willow, reed canary grass, and switchgrass (AEBIOM 2013). Introducing perennial crops which stay in place for a longer period of time decreases the flexibility and increases the investment costs, and might therefore be less attractive from the farmer's perspective (Gabrielle et al. 2014).

There has been a substantial increase in global crop production in recent decades, but there are now indications that the yield increase has started to slow down (Foley et al. 2011). Sustainable intensification of existing farmland is required to meet the predicted future increase in demand for food. Sustainable intensification is often discussed in terms of higher efficiency, as more product delivered per unit input of different resources (Smith 2013). Soil fertility is critically important for obtaining high yields, and strategies for maintaining and increasing soil fertility are thus essential components of sustainable intensification. Replacing monoculture with more varied cropping systems can improve soil structure, decrease the vulnerability to pests and diseases, and improve long-term productivity (Zegada-Lizarazu and Monti 2011). Introducing bioenergy crops with benefits for subsequent food crops in a crop sequence can thus improve current cropping systems, thereby mitigating negative land use impacts to a varying extent. Perennial or annual crops relying on symbiotic fixation of nitrogen (N) are of special interest as feedstock for bioenergy production from an environmental point of view. One reason is their potential to reduce the N mineral fertilizer requirement of the actual crop and of subsequent crops in the rotation. Another reason is their potential to increase yield in subsequent crops in both the short and long term (*e.g.*, Gan et al. 2003). According to a literature review examining cropping systems in different countries, mean yield benefits of up to 20% or more can be obtained when break crops are included in crop sequences (Kirkegaard et al. 2008). These multifunctional aspects are important to consider in assessments of crops relying on symbiotic N-fixation and in future policy development.

In this paper, we briefly describe how the introduction of perennial grass/clover in rotation with cereal crops affects subsequent food crops, using results from an LCA study conducted with Swedish data. The aims were to evaluate energy use, greenhouse gas emissions, and land use for grain production when rotational grass/clover is included for anaerobic digestion in a cereal cropping system, and to discuss how rotational aspects affecting yield potential can be included in life cycle assessments.

2. Methods

In the scenario study, life cycle assessment was used to evaluate two crop rotations: (i) a reference scenario including winter wheat-winter wheat-spring barley in a three-year crop rotation and (ii) a grass/clover scenario including two-year grass/clover followed by winter wheat-winter wheat-spring barley. The functional unit was 1 tonne of harvested grain, since the main focus was on how grain production was affected when introducing grass/clover for biogas production into the rotation.

The scenario study included only the operating phase. The assumed location was the county of Uppland in eastern Sweden. It was assumed that the grass/clover was digested and further upgraded to vehicle fuel quality, replacing diesel. The generation of biogas in the grass/clover scenario was accounted for through subtraction of the avoided burdens from the other activities in this scenario. The digested mixture of grass and clover replaced mineral N fertilizer otherwise used in cereal production. Band-spreading with trailing hoses was assumed for the digested grass/clover. In total, 73% of the N requirement of the cereals in the grass/clover scenario was met by digestate, while 27% was met by N mineral fertilizer. More details and references are provided in Tidåker et al. (2014), while yields and fertilizer rates are summarized in Table 1.

Special consideration was given to the effects of the grass/clover on subsequent cereal crops in the rotation. The cereal yield assumed in the grass/clover scenario was modified based on a compilation of numerous Swedish field experiments examining the residual effects of two-year grass/clover (Lindén 2008). Accounting for higher expected yield after grass/clover ley is also recommended in practical farming by the Swedish Board of Agriculture. Therefore, additional yield in the first and second year of winter wheat following grass/clover of 1000 and 400 kg ha^{-1}, respectively, was assumed. According to recommendations by the Swedish Board of Agriculture, the N delivered from the N-fixing clover to the subsequent crop could be expected to be 40 kg ha^{-1}. Changes in soil organic carbon in the two different crop rotations were modelled using ICBM (Andrén and Kätterer 1997).

Table 1. Assumptions in the two scenarios based on regional standard yield data, long-term field experiments, and guidelines for fertilization from the Swedish Board of Agriculture

	Yield (kg ha^{-1})	**Fertilizer (kg N ha^{-1})[b]**	**Type of fertilizer**
REFERENCE			
Spring barley	4300	80	Mineral fertilizer
Winter wheat	5600	135	Mineral fertilizer
GRASS/CLOVER SCENARIO			
Spring barley	4300	80	Digestate
Grass/clover[a]	7000		
Winter wheat I	6600	110	Mainly mineral fertilizer
Winter wheat II	6000	140	Digestate

[a] Grass/clover yield expressed in kg DM.
[b] Only N considered to be available for the crop was accounted for.

3. Results

The primary energy use was 1480 MJ in the reference scenario and -2900 MJ in the grass/clover scenario, *i.e.*, more energy was produced in the latter scenario than was required for grain production (Table 2). Replacing diesel with biogas was the most important factor explaining the difference, followed by the avoided use of mineral fertilizer in the grass/clover scenario.

The contribution to global warming potential (GWP) was 351 kg CO_2-equivalents for the reference scenario and -102 kg CO_2-equivalents for the grass/clover scenario. These figures included carbon sequestration in the cropping systems under study, but not indirect land use change. The replacement of mineral fertilizer in the grass/clover scenario decreased the emissions of greenhouse gases, but this gain was offset by the increased emissions due to more field operations being required and higher N_2O emissions in the grass/clover scenario.

The production of 1 tonne of grain occupied 0.20 ha in the reference scenario and 0.31 ha in the grass/clover scenario. The higher land requirement in the grass/clover scenario was due to the fact that the cereals occupied only 60% of the total area. However, due to the yield-increasing effect of the grass/clover, grain production in this scenario was 66% of that in the reference scenario, *i.e.*, higher than the proportion of occupied land.

Table 2. Primary energy use and global warming potential (GWP) for the two scenarios

	Reference scenario		**Grass/clover scenario**	
	Energy use	**GWP**	**Energy use**	**GWP**
Farm operation + transport	327	24	781	66
Mineral fertilizer production	1156	156	425	46
Direct field emissions		177		273
Indirect emissions		12		24
Gas production			1972	156
Carbon sequestration		-18		-216
Substitution of diesel			-6080	-451
TOTAL	1482	351	-2902	-102

4. Discussion

Bioenergy production based on dedicated crops grown on arable land has been increasingly questioned due to its negative land use impact. Competition between food, feed, and fuel crops is an important aspect to consider, especially since the demand for food is projected to increase substantially. This competition can be reduced or even eliminated for bioenergy crops by using residues or perennials from marginal land, or by growing additional crops between the main seasons or between rows (Tilman et al. 2009). However, bioenergy substrates are unlikely to be produced commercially on marginal land due to low economic incentives (Bryngelsson and Lindgren 2013) and residues for bioenergy production are limited. Rotational grass/clover could be another alternative, because it provides several benefits in a cropping system perspective, *e.g.*, N-fixation, carbon sequestration, *etc*. In this study, the improved short-term soil productivity due to crop sequencing effects was addressed by assuming higher yield potential for winter wheat in the first and second year after the grass/clover crop. It is likely that a long-term increase in productivity will also occur if the break crop recurs in the crop rotation, so assuming only a two-year effect might be somewhat conservative.

Different indicators for land use impact have been suggested, with soil organic matter proposed as a general indicator of soil fertility (Milà i Canals et al. 2007). Changes in soil productivity through increased yield potential can not only be measured as a separate indicator for land use impact, but can also be directly reflected in the area required for producing a certain amount of crops.

Higher yield potential for subsequent cereal crops following the grass/clover could not offset more than a small proportion of the displaced grain yield. However, the increasing yield potential together with carbon sequestration and N delivered from crop residues can counterbalance some of the negative impact from *e.g.*, indirect land use change, and is thus important to consider as a future strategy for mitigating climate change and decreasing the competition between food, feed, and fuel crops. It is therefore a need for environmental assessments of rotational crops relying on N-fixation in different cropping systems, taking into account their multiple benefits. One such crop besides clover is alfalfa (Gabrielle et al. 2014).

The N delivered to the wheat, as a residual effect from the grass/clover, replaces N mineral fertilizer in the subsequent crops. Applying a cropping system perspective and including the crop sequence rather than one specific crop is thus crucial to capture the multiple benefits. Digested mixtures of grass and legumes have the potential to replace a considerable proportion of the N fertilizer otherwise used in cereal production. Careful handling of the N-rich residue is crucial for many environmental aspects, and a sound management strategy is thus important. Experimental field data indicate large variations in ammonia volatilization (Webb et al. 2013). Anaerobic digestion increases the pH in the residue, which increases the risk of N losses. More experimental studies evaluating different biogas management systems are required in order to maximize the environmental benefits and minimize the emissions.

5. Conclusions

Introducing rotational grass/clover for anaerobic digestion into crop sequences can sequester carbon and replace a considerable proportion of the N mineral fertilizer otherwise required in cereal production. Furthermore, subsequent crops benefit from the residual effect of the grass/clover, thus increasing the grain yield potential. All these multiple benefits can help counteract some of the negative effects of indirect land use change and need to be included in assessment of leguminous crops for bioenergy production.

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