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Carbon footprints of crops from organic and conventional arable crop rotations – using a life cycle assessment approach

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ABSTRACT

Many current organic arable agriculture systems are challenged by a dependency on imported livestock manure from conventional agriculture. At the same time organic agriculture aims at being climate friendly. A life cycle assessment is used in this paper to compare the carbon footprints of different organic arable crop rotations with different sources of N supply. Data from long-term field experiments at three different locations in Denmark were used to analyse three different organic cropping systems ('Slurry', 'Biogas' and 'Mulching'), one conventional cropping system ('Conventional') and a "No input" system as reference systems. The 'Slurry' and 'Conventional' rotations received slurry and mineral fertilizer, respectively, whereas the 'No input' was unfertilized. The 'Mulching' and 'Biogas' rotations had one year of grass-clover instead of a faba bean crop. The grass-clover biomass was incorporated in the soil in the 'Mulching' rotation and removed and used for biogas production in the 'Biogas' rotation (and residues from biogas production were simulated to be returned to the field).

A method was suggested for allocating effects of fertility building crops in life cycle assessments. The results showed significantly lower carbon footprint of the crops from the 'Biogas' rotation (assuming that biogas replaces fossil gas) whereas the remaining crop rotations had comparable carbon footprints per kg cash crop. The study showed considerable contributions caused by the green manure crop (grass-clover) and highlights the importance of analysing the whole crop rotation and including soil carbon changes when estimating carbon footprints of organic crops especially where green manure crops are included.

1. Introduction

Globally, organic crop production is often dependent on imported livestock manure that is acquired also from conventional farms (Knudsen et al., 2011a; Oelofse et al., 2011; Duval, 2009). The dependency on conventional livestock manure is considered problematic by parts of the organic sector and in Denmark the organic farming movement recently decided to phase out the use of conventional livestock manure in organic agriculture by 2021 (Jørgensen and Kristensen, 2010; Oelofse et al., 2013). Prohibiting conventional livestock manure in organic agriculture requires adaptations in the organic farming systems with regard to nutrient management; in particular in terms of enhancing biological nitrogen (N) fixation and improved N use efficiency. With the rapid expansion of the global organic area during the last decade (Willer and Kilcher, 2012), alternative solutions to secure N supply in organic crop plant production systems need to be explored, such as the use of appropriate crop rotations and green manure (such as e.g. grass-clover) (maybe combined with biogas production). Green manure crops are primarily nitrogen fixing crops grown for a specific period, to add nutrient and soil organic matter to the crop rotation. They are typically harvested when green and then ploughed under and incorporated into the soil.

This is especially of great importance in stockless organic farming systems, where nutrients cannot be distributed in time and space with the livestock manure. Typically, stockless organic farm systems integrate legumes in their rotations, which are ploughed under to increase the nitrogen pool in the soil. However, this management has disadvantages because the supply of nitrogen due to the decomposition of the organic material in the soil does not match with the patterns of demand of the following crops. As a result, nutrient losses may increase and the efficiency of nitrogen use decrease.

In response to this limited matching of supply and demand the fermentation of green manure and subsequent distribution of the

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digestate according to the demand of the plants has been suggested (Stinner et al., 2008). Instead on including one green manure legume crop in the rotation, the integration of legume catch crops in the rotation is another option to improve nitrogen use efficiency in organic crop rotations. Catch crops are crops mainly grown from harvest of one crop until sowing of the following crop, having the purpose of 'catching' nitrogen primarily from the soil and/or the atmosphere. They are normally ploughed in the soil before the sowing of the next main crop. While compared to the biogas option, the nitrogen fixation of the catch crops over the whole rotation may be lower but the efficiency may be higher since no main crops are planted only for nitrogen fixation.

Various scenarios for N supply in organic crop rotations were explored in a long-term crop rotation experiment in Denmark as described in Askegaard et al. (2011), Chirinda et al. (2010a, 2010b) in terms of crop yields, N leaching, N_2O emissions etc. The experiment showed large differences between sites in crop yield and N losses as affected by variations in soil and climatic conditions, but in all cases crop yields were highly dependent on N inputs in fertiliser and livestock manure (Olesen et al., 2009). However, taking into account, that some rotations rely more on external input, such as mineral nitrogen fertilizer or livestock manure than others, and also influence soil carbon differently, it is not clear which rotations and production systems are most efficient in relation to global warming impact; a key challenge for organic food production (IFOAM, 2005). Therefore, the combined climate impact of alternative solutions to crop nutrient supply needs to be assessed.

Life cycle assessment (LCA) is recognised as an appropriate tool to estimate the climate impact or carbon footprint of crop production (Hillier et al., 2009). However, contrary to conventional systems, organic plant production systems rely to a high degree on recycling of nutrients and using crop residues or green manure crops as a mean to fertilise the crops and maintain soil fertility. This constitutes a challenge when using LCA for analysing carbon footprint of organic crops, since the crops and their respective yields in an organic crop rotation are often interlinked through fertility building (and exploiting) crops (Olesen et al., 2007, 2009). Furthermore, the need to include soil carbon changes in the carbon footprint of the crops is also more relevant since organic crop rotations often increase soil carbon sequestration (Gattinger et al., 2011; Chirinda et al., 2012). Nemecek et al. (2011) and Cooper et al. (2011) have also used LCA to analyse organic farming systems based on long-term field experiments, but only at one location. Cooper et al. (2011) analysed the full crop rotations, but did not assess LCA of the single crops or include soil carbon changes in the study. Michel et al. (2010) have used LCA to analyse organic farming systems which include biogas production, but these were mainly dairy systems of which the long-term effects on soil carbon were excluded.

The objective of this study was to compare different organic arable rotations with different sources of N supply regarding their effect on the carbon footprint of the whole rotations and the crops in the rotation. Therefore, data from long-term field experiments at three different locations in Denmark were used to analyse three different organic cropping systems, one conventional cropping system and a "no input" system as reference systems.

2. Materials and methods

2.1. The organic crop rotation experiment

2.1.1. Field experiment

This study used data from long-term crop rotation experiments that were initiated at three different sites in Denmark in 1997; Jyndevad, Foulum, and Flakkebjerg (Table 1). The layout of the experiment was described by Askegaard et al. (2011). Results from 2006 to 2008 was used in the present paper.

Table 1
Characteristics of the field site with long-term crop rotations 2006–2008.

	Jyndevad	Foulum	Flakkebjerg
Location	54°54′N, 9°8′E	56°30′N 9°34′E	55°30′N 11°27′E
Rainfall (mm year^{-1})	964	704	626
Mean annual temperature (°C)	7.9	7.3	7.8
Soil type	Coarse sandy soil (Orthic Haplohumod)	Sandy loam (Typic Hapludult)	Sandy loam (Typic Agrudalf)
Clay content, 0–25 cm (%)	4.5	8.8	15.5

Here we selected four organic crop rotations with different N supply and one conventional rotation as a reference. All crop rotations had a four year rotation cycle and included three main cash crops; potatoes (*Solanum tuberosum* L.), winter wheat (*Triticum aestivum* L.) and spring barley (*Hordeum vulgare* L.) and then either faba beans (*Vicia faba* L.) as cash crop or grass-clover for green manure (Fig. 1). Catch crops were mainly undersown in the cereals (spring barley and winter wheat) or faba beans in the spring. The catch crops of the organic cropping systems were either pure stands of perennial ryegrass (*Lolium perenne* L.) or a mixture of perennial ryegrass, chicory (*Cichorium intybus* L.), white clover (*Trifolium repens* L.) and red clover (*Trifolium pratense* L.) and the grass-clover ley was a mixture of perennial ryegrass and white and red clover (Olesen et al., 2007, 2009).

The first organic scenario (Slurry) represents the typical situation where livestock manure in the form of slurry (often conventional pig slurry) is imported and used at the arable farms and all four crops can be sold as cash crops. The second organic rotation (No input) represents a scenario where all four crops can be sold as cash crops, but no organic fertilizer is used. Soil fertility is maintained only through the use of catch (cover) crops. The third organic scenario (Mulching) represents a solution where the faba beans are replaced by a green manure crop (grass-clover) that is incorporated in the soil for fertility building and thus only three cash crops can be produced in the rotation. The fourth organic rotation (Biogas) represents an alternative similar to the 'Mulching' rotation, where the green manure crop is not incorporated in the soil but harvested and used for biogas production. Residues from the biogas plant are simulated to be returned to the field. For this we use pig slurry containing an equivalent amount of nitrogen as expected from the residues from the biogas plant. Furthermore, a 'Conventional' rotation was also included that is similar to the 'Slurry' rotation, where all four crops can be sold as cash crops, but mineral fertilizer is used instead of slurry and in addition pesticides are used. Where possible, catch crops were included in the rotations (Fig. 1). At each site, the experiment comprised two replicate blocks for the five scenarios, and all crops in the rotations were present every year in the experiment.

The organic rotations were managed according to organic farming regulations. Harrowing was used to control weeds in the organic rotations, while agrochemicals were used to control weeds, pests and diseases in the conventional rotation.

2.2. Life cycle assessment approach

A life cycle assessment (LCA) approach until farm gate was used in the present study focussing on greenhouse gas emissions. The main assumptions made are presented in the following section.