Designing sustainable crop rotations using Life Cycle Assessment of crop combinations

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Abstract: *The introduction of grain legumes in crop rotations offers the potential to reduce the environmental impact of European agriculture. The main advantage is the independence of nitrogen fertilisers due to symbiotic N_2 fixation and hence the reduced use of fossil energy and lower global warming potential at the crop rotation level. As the assessment of a large number of crop rotations with Life Cycle Assessment (LCA) is very time consuming we applied a new crop combination approach i.e. for each crop a LCA is calculated for each possible preceding crop and in a second step the rotations are composed using these crop combinations. The procedure enables a fast assessment of several rotations as the production inventories of a main crop have to be only slightly adjusted for several preceding crops. In this paper the authors show preliminary results for several rotations and the associated crop combinations. These results indicate that the introduction of a spring pea in a standard rotation (oilseed rape, winter wheat, winter barley) might reduce the global warming potential (GWP) by around 6%. If the fertilisation of cereals and oilseed rape is also reduced the overall GWP decreases by 11%. For nutrient enrichment the reduction potential is around 6% and respectively 13% for the combined approach.*

Keywords: *optimisation, crop rotations, legumes, cover crops, life cycle assessment, sustainability*

Introduction

In the European Union the available amount of plant materials rich in protein is largely exceeded by its demand. Animal production in particular requires large imports of soya bean meal which are used in concentrates in meat, egg, and milk production. These imports entail adverse environmental aspects, for example linked with the long distance transport, and the conversion of natural and semi-natural habitats in the producing countries with potentially negative consequence on biodiversity and soil quality. Moreover the introduction of grain legumes in crop rotations might reduce the environmental impacts of the European agriculture (Baumgartner *et al.,* 2008). The main advantage is the reduced mineral fertilisation due to the symbiotic N_2 fixation and hence a reduced use of fossil energy at the crop rotation level (Nemecek *et al*. 2008). Despite these possibilities of reducing the environmental impacts of agricultural production, legume cultivation has been neglected within the EU for many years. The reason for this is mainly the lower profitability of grain legumes compared to other crops. The goal of the CAS DAR project "Amelioration of the economic and environmental performance of crop rotations with oilseed rape, wheat and peas" is to assess and optimise the environmental and economic performance of crop rotations including oilseed rape and wheat, with and without grain legumes. In addition the project team is studying the effect of reduced mineral nitrogen fertilisation in oilseed rape, wheat and barley and the effect of cover crops.

As a first step we assessed the environmental impact of the crops using production data assembled by the partners from the Chambers of Agriculture for typical cultivation in the Burgundy, Beauce, and Moselle regions. The authors analysed the crops with ART's SALCA (Swiss Agricultural Life Cycle Assessment) life cycle assessment (LCA) method (Gaillard & Nemecek, 2009). This analysis encompasses actual production from cultivation up to harvest and transport to the farm, as well as environmental impacts linked with input factors (e.g. mineral and organic fertilisers, machinery, pesticides) and direct field emissions (e.g. nitrate, nitrous oxide, pesticides). We decided to analyse the impact categories of non renewable energy demand, global warming potential, eutrophication, acidification and the eco- and human toxicity to give an overview of the resource, nutrient, and toxicity management. Furthermore we chose to use the functional units of ha*year and kg dry matter yield in order to take into account land cultivation and production aspects. To give a broader overview of the sustainability of the different crop rotations, the project partners performed an economic analysis based on the mean prices from 2006-2008. As a second step we optimised the environmental and economic sustainability of the standard crop rotation by creating new rotations. In order to find a sustainable solution, the team had to evaluate many crop rotations, which was not feasible in a small project. Therefore we used a new approach. We established the inventories for each crop for all possible combinations of preceding – succeeding crop, since the former strongly influences the management of the latter. This allowed us to take into account the rotational effects and to create and analyse new crop rotations quickly. In this paper we present only selected results for the Burgundy region.

Goal and scope definition

Goal of the Study

The goal of the life cycle assessment (LCA) study in this project is to assess the environmental impacts of introducing peas into standard rotations in selected French regions using a new approach of crop combinations. Compared to a LCA of a single crops this approach includes the rotational effects on fertilisation, yield, and cultivation. Compared to a LCA of several rotations the crop combinations facilitated a faster assessment, as they could be used in a modular manner to create new rotations.

In addition the authors decided to include combinations with cover crops and reduced fertilisation in the study in order also to assess these management options.

Study Regions and Crop Rotations

The project partners chose Beauce, Burgundy and Moselle as case study regions according to the following criteria:

- Arable regions with a potential to increase the grain legume area
- Data availability
- Regional partners that participate in the CASDAR project.

The Chamber of Agriculture and the UNIP selected 12 crop rotations for Burgundy (Table I). Rotation 1 is the standard rotation in Burgundy; rotations 2 to 10 diversify rotation 1 by introducing new crops (spring barley, peas, sunflower) and in most cases also one cover crop. The last two rotations are the same as no. 1 and 3, but with reduced N-fertilisation in cereals and oilseed rape.

System Definition and Boundary

The boundary of the system was analogous to other LCA studies (Nemecek et al., 2005 and Nemecek et al., 2008) set at the farm gate (Fig. 1). The considered system includes all inputs (Infrastructure, fertiliser, pesticide production) and processes (operation of machines, field operations) required to deliver a storable product at the farm gate and also the direct field emissions (nitrate, heavy metals, etc.). The temporal system of each crop combination starts at the harvest of the preceding crop and ends with the harvest of the main crop. Any period between the harvesting of a crop and soil tillage or sowing of the next crop is attributed to the latter. At the rotational level the system begins and ends with the harvest of the last crop in the rotation.

Table 1. Overview of the crop rotations analysed in Burgundy. OSR = oilseed rape, wW = winter wheat, wB = winter barley, sB = spring barley, sP = spring peas, wP = winter peas, SF = sunflower, (cc) = cover crop (Phacelia).

	Year							
No.	1	2	3	4	5	6	7	kg N*ha^{-1}*a^{-1}
R_1	OSR	wW	WB	OSR	wW	wB		163
R_2	OSR	wW	WB	OSR	wW *CC*	sB		158
R_3	OSR	wW	WB *CC*	SP	wW	wB		135
R_4	OSR	wW	WB *CC*	SP	OSR	wW	wB	133
R_5	OSR	wW	WB	WP	wW	wB		135
R_6	OSR	wW	WB *CC*	SF	wW	wB		145
R_7	OSR	wW *CC*	SP	OSR	wW	wB		130
R_8	OSR	wW *CC*	SP	WW	wB			132
R_9	OSR	wW *CC*	SP	WW *CC*	SF	wW	wB	127
R_10	sP	OSR	WW	WB *CC*	SF	wW	sB *CC*	114
R_11	OSR-40N	wW-30N	wB-20N	OSR-40N	wW-30N	wB-20N		132
R_12	OSR-40N	wW-30N	wB-20N *CC*	SP	wW-30N	wB-20N		111

Functions and Functional Units

The multifunctionality of agriculture cannot be adequately described using one functional unit (FU). Nemecek et al. (2005) propose utilizing three FU's to consider the following aspects of agricultural production.

1. Land management function: describes the cultivation of land with the FU Impact per hectare and year. Regarding this function the goal is to minimise the environmental impacts in terms of area and time.
2. Productive function: agricultural activities aim at producing food, feed or biomass for other uses (bioenergy, renewable materials). The goal is to minimise the environmental impacts in terms of product units (e.g. impact per kg of dry matter (DM)).
3. Financial function: from the perspective of the farmer, income is the main motivation for agricultural production. The FU is impact per €.

In this study we followed their proposal and use the functional units ha^{-1} y^{-1} and kg DM^{-1} to describe the impacts of single crop combinations and the functional units ha^{-1} y^{-1} and € gross margin II^{-1} for the evaluation of rotations.

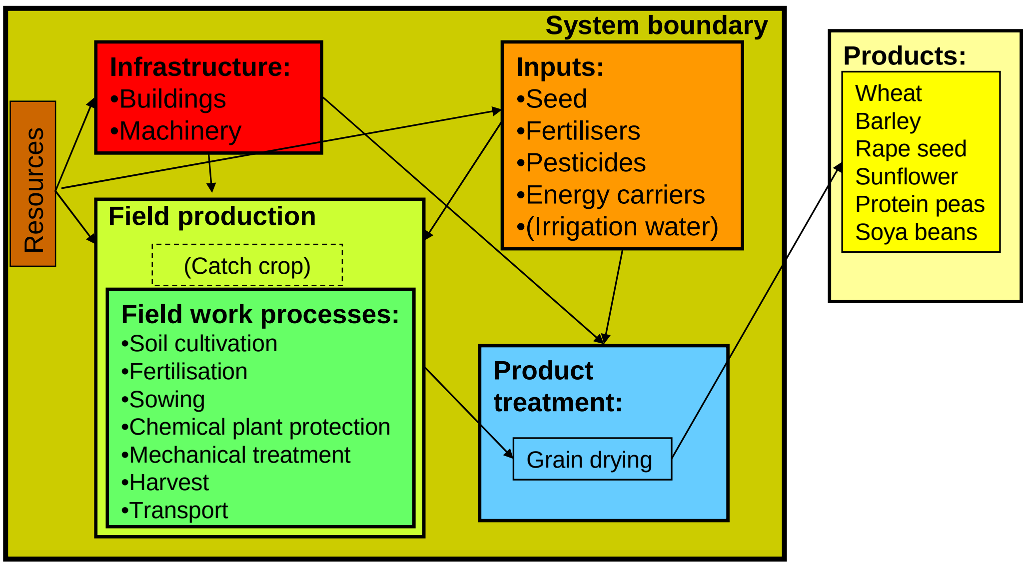

Figure 1. Description and delimitation of the system investigated.

Allocation Procedures

No co-products, for example straw, result from the systems investigated, because only arable cropping farms without livestock are considered. Hence no allocation is required. The shared infrastructure (buildings, machinery) is allocated following the procedures described in Nemecek et al. (2005) and Nemecek and Kägi (2007).

Life Cycle Inventory Analysis

Chambers of Agriculture partners compiled the production inventories, i.e. agronomical-technical description of the cropping systems. The authors use life cycle inventories from the ecoinvent database version 2.01 (Frischknecht et al., 2007, Nemecek and Kägi, 2007) for the infrastructure, inputs and processes and the models described in the SALCA method (see Gaillard & Nemecek, 2009 and Nemecek et al., 2005 and 2008) to estimate the various direct field emissions (NH_3, N_2O, Phosphorus, NO_3^-, heavy metals and pesticides). For the calculations we apply ART's SALCA-crop v3.1 tool consisting of modules programmed in Microsoft EXCEL® and a system implemented in the TEAM™ software (Version 4.0) from PriceWaterHouse Coopers/Ecobilan, Paris, France.

Life Cycle Impact Assessment

The SALCA method developed within ART's Life Cycle Group (Gaillard & Nemecek, 2009), includes relevant impact categories and mid-point impact assessment methods, mainly from the EDIP97 (Hauschild & Wenzel, 1998) and CML01 methods (Guinée et al., 2001), but also models developed by ART. The following environmental impacts are considered:

- Demand for non-renewable energy resources (Hischier et al., 2009).
- Global warming potential over 100 years (IPCC 2007).
- Ozone formation potential (EDIP97)
- Eutrophication potential (EDIP97)
- Acidification potential (EDIP97)
- Terrestrial and aquatic ecotoxicity potential (CML01)
- Human toxicity potential (CML01)
- SALCA Biodiversity (Jeanneret et al., 2006)
- SALCA Soil quality (Oberholzer et al., 2006).

Life Cycle Assessment Results

In this paragraph we present some selected LCA results for the global warming and eutrophication potential impact categories. To demonstrate the procedure of creating sustainable rotations first, the crop combination results are presented followed by the results for the rotations.

Crop Combinations

The global warming potential (GWP) of the crop combinations is between 2058 kg CO_2-eq per ha in spring peas after cereals including a cover crop (CER_CC_sP) and 2739 kg CO_2-eq ha^{-1} in winter wheat after oilseed rape without cover crop (OSR_XX_wW, Fig. 2). Comparing the impact per kg dry matter (DM) cereals have the lowest GWP ranging from 0.47 to 0.53 kg CO_2-eqivalent (CO_2-eq) followed by spring pea (0.76 kg CO_2-eq) and oilseed rape (0.83-1.08 kg CO_2-eq) because of their low DM yield. In most crops the main cause of the GWP is the production of nitrogen fertiliser. Around 48 to 61% of the total impact is linked to this process. Other important sources are direct field emissions of nitrous oxide (N_2O) and nitrate (NO_3^-) causing 13 to 21% of the GWP and soil tillage (7-10%). In spring pea without mineral nitrogen fertilisation the direct field emissions are mainly responsible for the GWP (46%). Other important origins are tillage (15%) and the production of pea seed (15%). The eutrophication potential shows a comparable picture with the exception that the impact is highest for barley (Fig. 3). The potential lies between 56 and 123 kg nitrogen equivalent (N-eq.) ha^{-1} in the crop combination CER_CC_sP and winter barley after cereals (CER_XX_wB). Looking at the results per kg DM again wheat but also the spring peas have the lowest impacts (0.015-0.016 kg N-eq) followed by barley (0.020-0.021 kg N-eq) and oilseed rape (0.023-0.028 kg N-eq). The main sources are direct field emissions (N_2O, NO_3^-, phosphorus) causing 67-84% of the eutrophication and indirect emissions; mainly N_2O emitted in the production process of N-fertilisers (11-23%). There are two reasons for the high direct field emission in barley. The mineralisation exceeds the uptake after sowing in late summer and autumn and the fertilisation exceeds the uptake in spring.

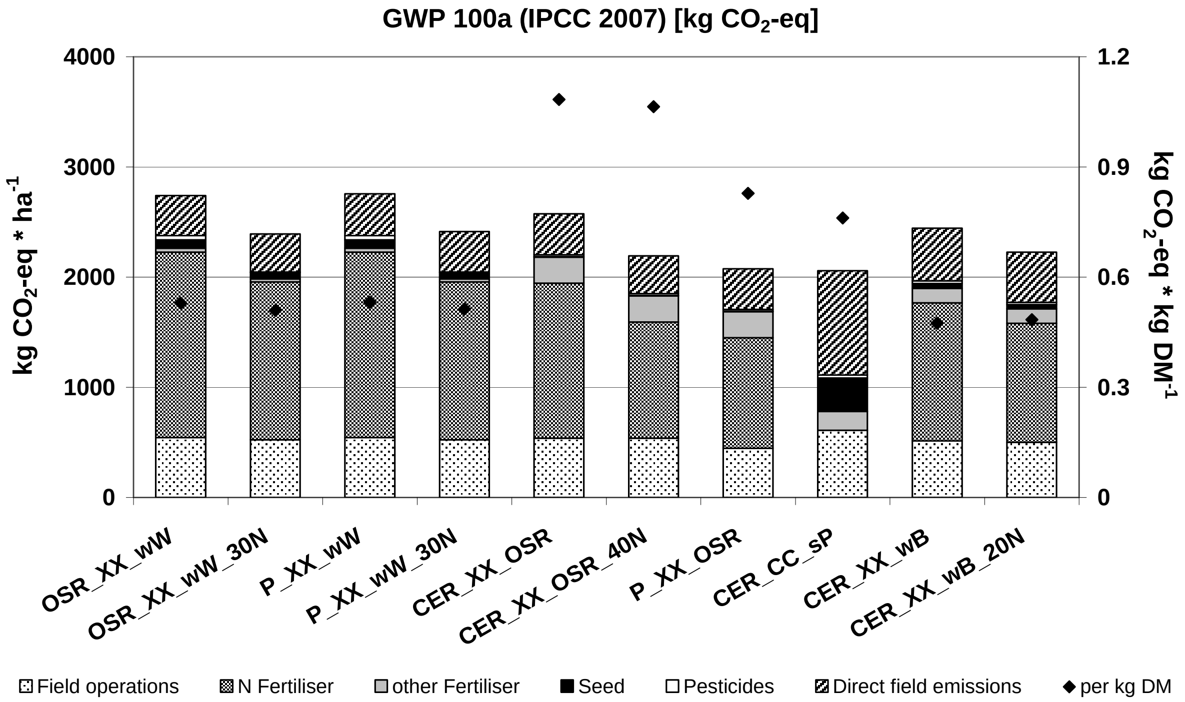

Figure 2. Global warming potential over 100 years for the single crop combinations per hectare indicated by the bars and per kg DM indicated by the points. The first group of characters indicates the previous crop, the second group an optional cover crop, the third group the main crop, and the fourth group, if shown, a reduced fertilisation. OSR = oilseed rape, P = peas, CER = cereals, wW= winter wheat, sP = spring peas, wB = winter barley, _xx_ = without cover crop, CC = with cover crop, _nnN = nitrogen fertilisation reduced by nn kg

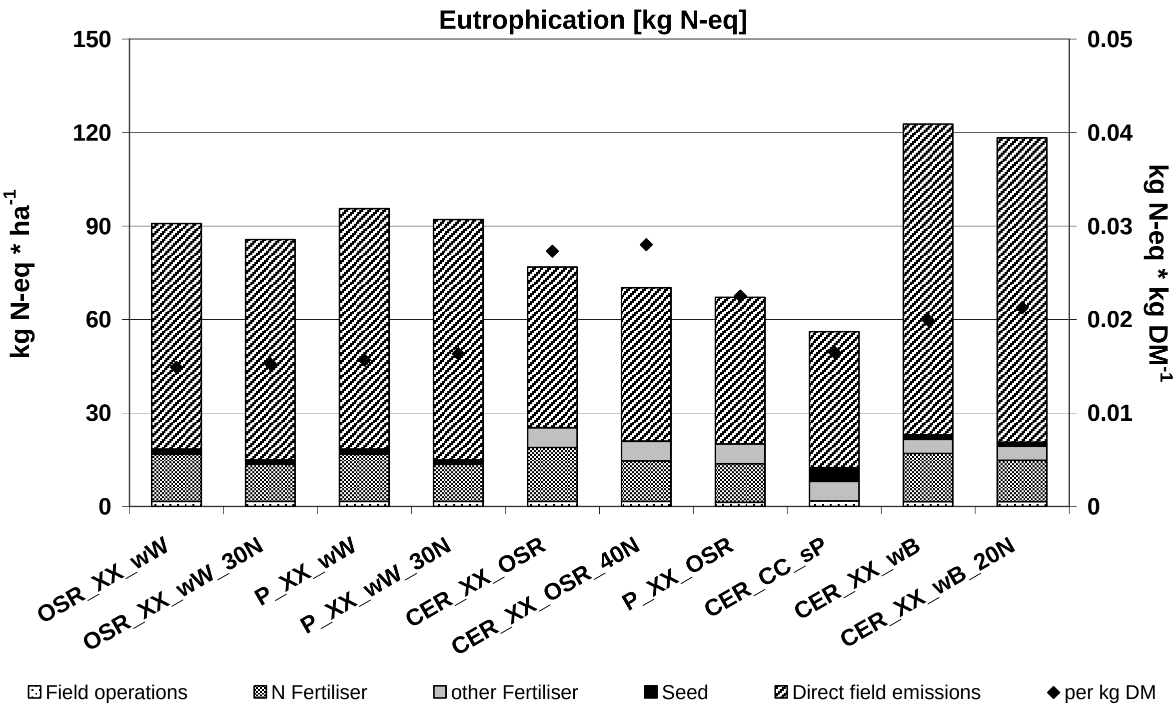

Figure 3. Eutrophication potential for the single crop combinations per hectare indicated by the bars and per kg DM indicated by the points. The first group of characters indicates the previous crop, the second group an optional cover crop, the third group the main crop, and the fourth group, if shown, a reduced fertilisation. OSR = oilseed rape, P = peas, CER = cereals, wW= winter wheat, sP = spring peas, wB = winter barley, _xx_ = without cover crop, CC = with cover crop, _nnN = nitrogen fertilisation reduced by nn kg

Crop Rotations

Similarly to the previous section, we present the GWP and eutrophication potential impact categories per hectare and year and in addition per € gross margin II. The rotations are compiled in Table I. Rotation 1 (R_1) is the standard rotation in Burgundy with oilseed rape, winter wheat and winter barley. In R_3 a spring pea with cover crop replaces the second oilseed rape, in R_4 the spring pea is inserted between the first winter barley and the second oilseed rape and in R_7 the spring pea with cover crop replaces the first winter barley. Rotation 11 and 12 are Rotation 1 and 3 with a reduced fertilisation in the cereals and the oilseed rape.

The GWP of the rotations ranges between 2312 kg CO_2-eq per hectare and year in R_12 and 2586 kg CO_2-eq in R_1 (Fig. 4). Fertiliser production contributes most to the GWP followed by field emissions and soil tillage. The standard rotation has the highest impact. In all other rotations the GWP is 6 to 8% lower due to the reduced nitrogen fertilisation in the crop following the spring pea or in all crops (R_11). Reducing the fertilisation in all crops and integrating a spring pea in addition yields the highest GWP reduction (11%). Moreover in all rotations with a spring pea the GWP is lower compared with the corresponding rotation without pea (R_3, R_4 and R_7 compared with R_1 and R_12 compared with R_11). Although the R3-R12 rotations have a slightly lower gross margin II (1 to 13€) in comparison to R_1 their impact per € is still lower.

The calculated eutrophication potential is between 84 kg N-eq. $ha^{-1} * a^{-1}$ (R_7) and 97 kg N-eq. $ha^{-1} * a^{-1}$ (R_1). The fertilisation is mainly responsible due to the direct field emissions and the indirect emissions generated during the fertiliser production (Fig. 5). Similar to the GWP the standard rotation has the highest impact. In all other rotations the GWP is reduced by 2 to 13% compared to R_1. The difference can be explained by the introduction of a spring pea (R_3, R_4 and R_7), the reduction of nitrogen fertilisation (R_11) or a combination of both (R_12). The introduction of spring peas in combination with a cover crop has several positive effects at the rotational level. First, the crop combination CER_XX_sP is the one with the lowest NO_3^- losses (Fig. 3). Second, in the spring pea no nitrogen fertiliser is applied and so the N-fertilisation for the whole crop rotation and also the induced emissions of N_2O are lower. The second point is also valid for the reduction of N-fertilisation in R_11 and R_12. As mentioned before, using the functional unit € gross margin II does not change the ranking.

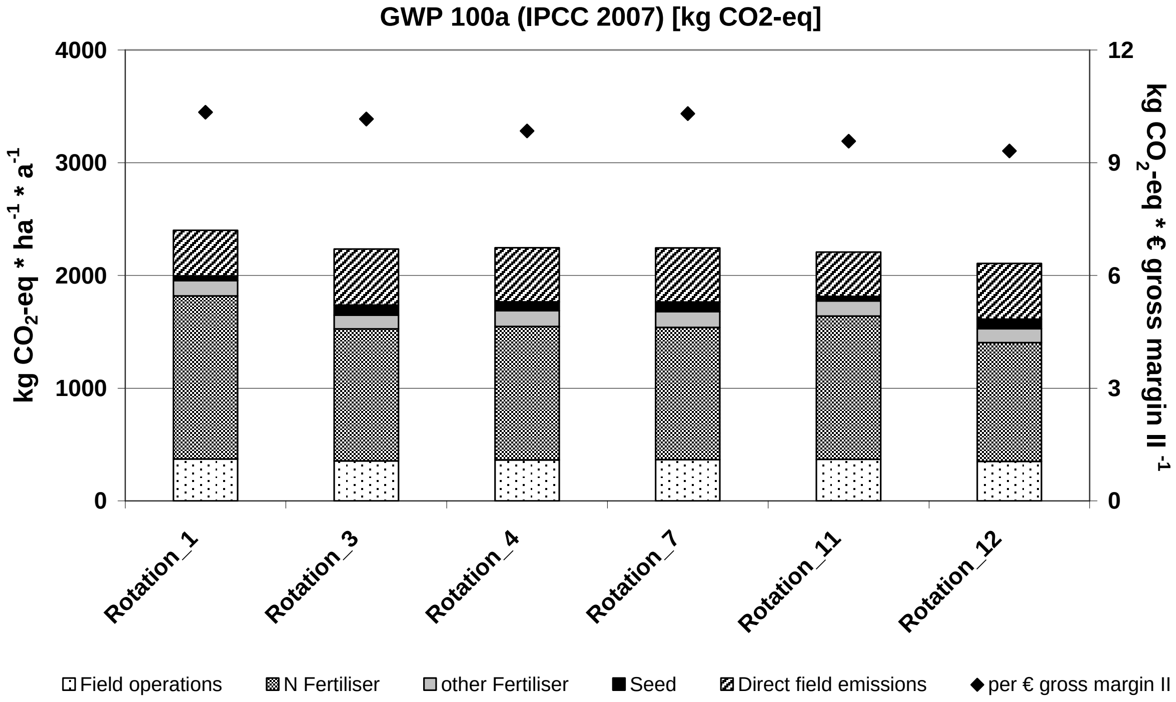

Figure 4. Global warming potential over 100 years for the selected crop rotations per hectare indicated by the bars and per kg DM indicated by the points. The crops of the crop rotations are given in Table 1.

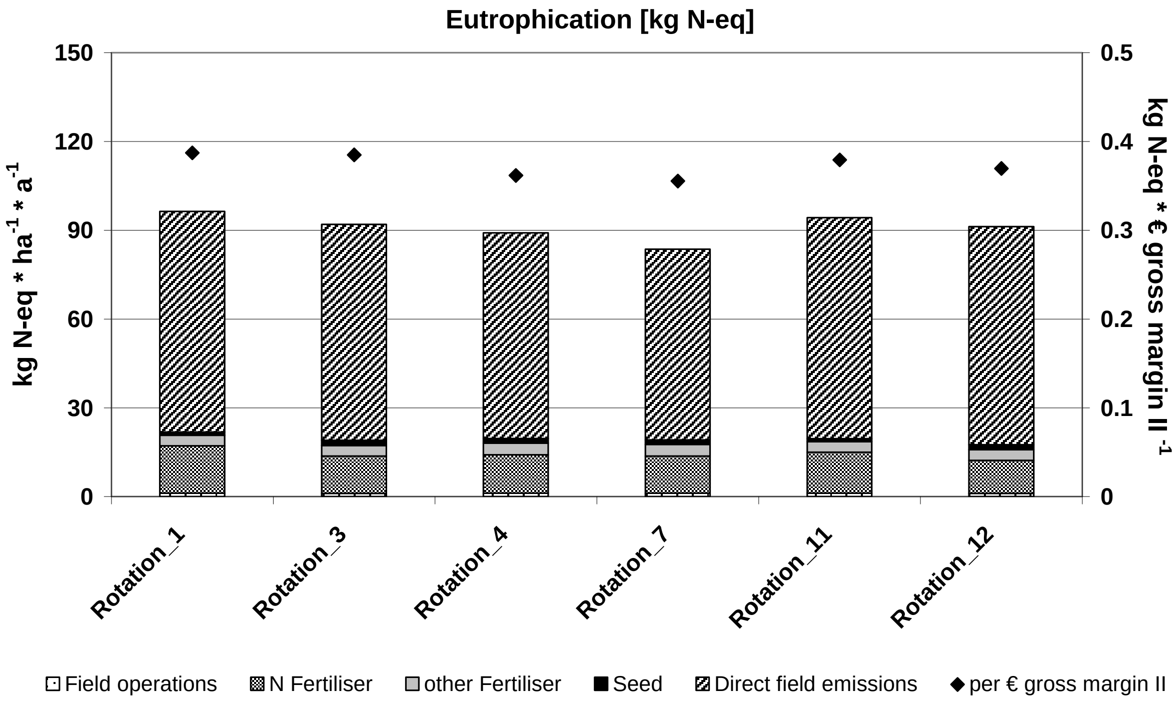

Figure 5. Eutrophication potential for the selected crop rotations per hectare indicated by the bars and per kg DM indicated by the points. The crops of the crop rotations are given in Table 1.

Conclusions

The results of the assessment for Burgundy show that the introduction of a grain legume in a standard rotation (e. g. oilseed rape, winter wheat, winter barley) has positive environmental effects regarding the GWP and eutrophication potential impact categories. This is also valid for the impact categories not shown here. The main benefit with regard to the GWP and the eutrophication potential is reduced nitrogen fertilisation at the rotational level which has two main consequences.

- less emissions from the energy intensive fertiliser production (CO_2, N_2O)
- less direct field emissions (N_2O, NH_3, NO_3)

Although the emissions from the cultivation of peas partly counterbalance the second point the effect is strong enough to cause an overall reduction in GWP. Replacing a crop (CER_XX_wB, or CER_XX_OSR) in the rotation by a spring pea with cover crop or introducing a spring pea with a cover crop as an additional crop also reduces the eutrophication potential. This is mainly an effect of the cover crop which lowers the leaching in the pre-winter period compared to other considered crops without cover crop.

In general it is also possible to diminish the GWP by reduced nitrogen fertilisation of cereals and oilseed rape. But this alternative decreases the eutrophication potential only slightly (Fig. 5, Rotation 11), because for most of the crops, high nitrate leaching occurs in late summer and autumn. In this period the mineralisation exceeds the demand of the plants. To reduce the eutrophication potential the cultivation of a cover crop is much more effective than a reduced nitrogen input.

The results show that crop combinations are a good tool to evaluate a large number of crop rotations with LCA. Effects of the previous crop can be well represented, while long-term effects are not considered by this approach. The creation of several combinations for the same main crop with a subsequent analysis of rotations is much faster than creating whole crop rotations as only a few values have to be changed. Furthermore the inventories can be adapted easily to create new rotations or to use this approach for new regions.

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