ENVIRONMENTAL LIFE CYCLE ASSESSMENT OF DANISH CEREAL CROPPING SYSTEMS

JESPER HEDAL KLØVERPRIS, SANDER BRUUN AND INGRID K. THOMSEN

DCA REPORT NO. 081 • AUGUST 2016

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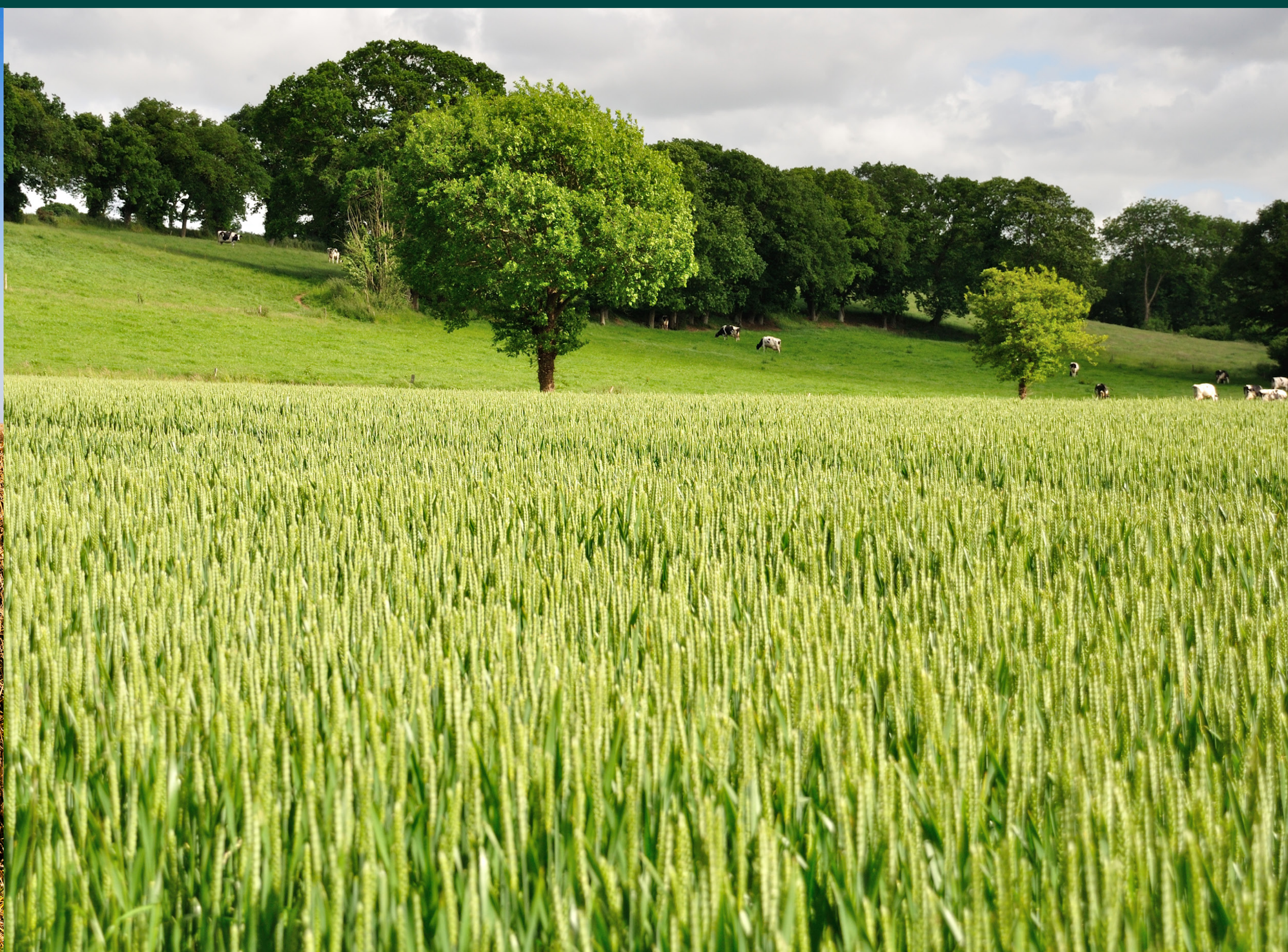

Environmental Life Cycle Assessment of Danish cereal cropping systems

Supplementary information and clarifications (October 2019)

(presentation of authors corrected November 2019)

In an effort to ensure that this report complies with Aarhus University's guidelines for transparency and open declaration of external cooperation, the following supplementary information and clarifications have been prepared in collaboration between the AU researcher (s) and the faculty management at Science and Technology:

As declared in the preface, the report publish results from a study established in cooperation between Novozymes, University of Copenhagen and Aarhus University.

Jesper Hedal Kløverpris, Novozymes, provided a first draft of the LCA-analysis, following ISO LCA-standards.

Based on discussions held in the project group (Bent T. Christensen, Ingrid K. Thomsen, and Elly Møller Hansen at the Department of Agroecology (AU), Sander Bruun (KU) and Leif Knudsen (SEGES – Planter & Miljø)), authors Jesper Hedal Kløverpris (Novozymes), Sander Bruun (KU) and Ingrid K. Thomsen (AU) finalized the report. The entire project group reviewed the report concerning language and understanding.

The project partner, SEGES – Planter & Miljø (Leif Knudsen) took part in the discussion and reviewing of the report. As head of the entire PlantePro project (Bent T. Christensen) and as coauthor of the report (Ingrid K. Thomsen), Aarhus University vouch for the scientific content in the report.

The project partner Sejet Plant Breeding I/S was not involved in the creation of this report but has provided seeding materials for field experiments involved the PlantePro project.

ENVIRONMENTAL LIFE CYCLE ASSESSMENT OF DANISH CEREAL CROPPING SYSTEMS:

Impacts of seeding date, intercropping, and straw removal for bioethanol

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Preface

This report presents a comparative environmental assessment of six Danish cereal cropping systems with different straw removal rates using a life cycle assessment (LCA) approach. The activity is a subcomponent of the PlantePro project funded by the Ministry of Environment and Food under the Green Development and Demonstration Program (GUDP: Miljøsikret planteproduktion til foder og energi). The PlantePro project was led by Aarhus University (AU) and included partners from University of Copenhagen (KU), Novozymes A/S, SEGES P/S, and Sejet Plant Breeding I/S.

The LCA has been conducted by Jesper Hedal Kløverpris from Novozymes A/S with important inputs on field emissions provided by Sander Bruun, Martin Preuss Nielsen, and Clément Peltre at the Dept. of Plant and Environmental Sciences, KU. Bent T. Christensen, Ingrid K. Thomsen, and Elly Møller Hansen at the Department of Agroecology (AU), Sander Bruun (KU) and Leif Knudsen (SEGES – Planter & Miljø) have all participated in defining and structuring the study, provided essential data inputs, and taken part in the discussion and reviewing of the present report. Nassera Ahmed from Novozymes A/S has assisted in the LCA modeling.

The study and the presentation generally follow the ISO standards for LCA (14040 and 14044) but the report has not been subject to external critical review. The modeling of environmental impacts has been performed with the LCA software tool SimaPro 8 (version 8.0.3) using the impact assessment method called CML-IA baseline. The agroecosystem model 'Daisy' was applied to simulate processes in the cropping systems. This simulation work has been published separately (Peltre et al., 2016).

Besides being a stand-alone assessment of six different cereal cropping systems, the present report also serves as documentation for a spreadsheet-based 'greenhouse gas calculator' that allows users to modify assumptions and derive new results for other cropping systems. The most recent version of the calculator can be accessed together with the online version of the present report on Novozymes' homepage under 'Published LCA studies'.

August 2016

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Contents

Summary

The present life cycle assessment (LCA) estimates potential environmental impacts from changes in Danish cereal cropping systems. As part of that, the study briefly considers the isolated environmental impacts from utilization of cereal straw in a biorefinery, which produces bioethanol, biogas, bioelectricity, and biofertilizers.

Goal and Scope

The study compares the following six cropping systems:

1. Spring barley with oilseed radish as catch crop and 100% straw incorporation
2. Spring barley with oilseed radish as catch crop and 50% straw removed for biorefining
3. Winter wheat with normal seeding date and 100% straw incorporation
4. Winter wheat with normal seeding date and 50% straw removed for biorefining
5. Winter wheat with early seeding date and 50% straw removed for biorefining
6. Winter wheat with normal seeding date, intercropping of oilseed radish, and 50% straw removed for biorefining

The geographical scope of the study is a cereal producing area in west Denmark.

System 1 is considered as the reference system. Accordingly, the functional unit of the LCA is defined as the feed equivalent to 1 Mg (metric ton) of spring barley grain (85% dry matter) in terms of metabolizable energy (for growing pigs) and crude protein (12.2 GJ and 73 kg, respectively).

The wheat systems provide higher yields than the reference barley system and therefore provide the functional unit with less use of land. Meanwhile, it is a premise of the study that the Danish cropland area remains unchanged. We therefore consider replacement of feed production elsewhere (wheat from Germany and, to some extent, soybean meal from South America) to balance the output of feed from the systems. This aligns with the system expansion methodology applied in consequential LCA.

In addition, we consider (in a separate analysis) the effect of increased Danish grain production on the global agricultural area, i.e. we include greenhouse gas (GHG) emissions from (avoided) land use change at the frontier between agriculture and native land. This is in line with the so-called 'indirect land use' (ILUC) methodology that has evolved in recent years in LCA, especially within bioenergy LCA. ILUC emissions are embedded in several regulatory frameworks in the US (e.g. the federal Renewable Fuel Standard and California's Low Carbon Fuel Standard) and have also been the topic of lengthy discussions in the EU over the last five years (leading to a cap on so-called first generation or starch/sugar-based biofuels).

For the systems with straw removal for biorefining, we also use the system expansion methodology. This means that we consider the environmental implications of replacing gasoline with bioethanol, natural gas with biogas, and marginal grid electricity with bioelectricity.

While this report can be read as a stand-alone study, it also works as documentation for a spreadsheet-based GHG calculator that can be used to change assumptions and assess other cropping systems.

Impact Categories and Methods

The study focuses on two categories of environmental impacts:

- Global warming (GHG emissions)
- Nutrient enrichment (eutrophication)

The study seeks to apply consequential LCA and is therefore using marginal data and the use of so-called 'system expansion' in case of co-products/multi-output processes.

Characterization factors from the 'CML-IA baseline version 3.01' method are applied and the system modeling is performed in SimaPro 8 (LCA software tool).

The temporal and technological scope is 'near-term'.

Inventory Analysis

The inventory analysis includes inputs to and outputs from the cropping systems and the biorefinery. As previously mentioned, the analysis also includes replaced feed and energy production resulting from cropping system outputs beyond the functional unit. Besides, the eutrophication impacts from raising the level of bioethanol in gasoline have been estimated[1].

GHG results for feed production

The results of the study depend on time perspectives for land use change (LUC) emissions (ΔSOC and ILUC) and assumptions about gasoline displaced by bioethanol (average vs. marginal) and the type of electricity (renewable, average, or coal-based) displaced by bioelectricity from the biorefinery.

The GHG impact of the reference system is 590 and 580 kg CO_2e/Mg spring barley equivalent with changes in soil organic carbon (ΔSOC) seen over 20 and 100 years, respectively. In the reference system, assumptions about displaced gasoline and electricity are irrelevant because there is no energy production from straw. A 20 year time

[1] Combustion processes result in nitrogen-containing emissions to air (e.g. NO_x and ammonia), which can later be deposited on land or water bodies and thereby contribute to eutrophication of ecosystems. Changing the fuel mix (e.g. by adding ethanol to gasoline) can change the emissions from combustion and thereby have an impact on eutrophication.

perspective for land use-related emissions is typically recommended in European LCA and also a requirement for GHG analysis in EU's Renewable Energy Directive (EU RED).

GHG results for the six studied cropping systems are given below with ΔSOC seen in a 20 year time perspective and marginal Danish electricity assumed to come from renewables (mainly wind). Additional yield is assumed to replace international feed produced elsewhere (one-to-one). An average gasoline emission factor from the EU RED (83.8 g CO_2e/MJ) has been applied[2]. We stress that these assumptions are used in the following summary unless otherwise stated. The assumptions about electricity and gasoline are relevant for systems with straw removal because these aspects determine the climate benefits of bioethanol and bioelectricity production.

1. System 1 (spring barley, catch crop, 100% straw incorporation) 590 kg CO_2e/Mg spr. barley eq.
2. System 2 (spring barley, catch crop, 50% straw for biorefining) 440 kg CO_2e/Mg spr. barley eq.
3. System 3 (winter wheat, 100% straw incorporation) 470 kg CO_2e/Mg spr. barley eq.
4. System 4 (winter wheat, 50% straw for biorefining) 270 kg CO_2e/Mg spr. barley eq.
5. System 5 (winter wheat, early seeded, 50% straw for biorefining) 35 kg CO_2e/Mg spr. barley eq.
6. System 6 (winter wheat, intercrop, 50% straw for biorefining) 270 kg CO_2e/Mg spr. barley eq.

As shown above, GHG emissions from feed production are reduced by 26% when removing 50% of the barley straw for biorefinery purposes (system 2 vs. 1). This is almost entirely explained by the net benefits of straw utilization. N_2O field emissions are reduced due to straw removal and, in addition, gasoline, natural gas, and grid electricity are displaced. On the other hand, the net level of soil organic carbon (SOC) is reduced and the auxiliaries for the biorefinery (e.g. enzymes) also entail GHG emissions. However, the net effect is a reduction in GHG emissions. This is accompanied by a relative loss in SOC (the change in system 2 minus the change in the reference system) of 1% over 20 years and 3.8% over 100 years. There are no indications that these small changes should be critical in terms of soil fertility.

Shifting from spring barley to winter wheat (system 3 vs. 1) reduces GHG emissions associated with feed production with roughly 20% (but only about 10% if ΔSOC is averaged over 100 years). This is mainly explained by differences in SOC and higher grain yields leading to (assumed one-to-one) displacement of feed production elsewhere.

Shifting to winter wheat with 50% utilization of straw in a biorefinery (system 4 vs. 1) reduces GHG feed emissions by 54% because it both gives the benefits of higher yield and energy production. When winter wheat is grown with intercropping of oilseed radish (system 6), SOC sequestration increases but, at the same time, the N_2O emission increases because more biomass enters the soil and because of an increased retention of N in the

[2] Number expected to be updaded to a higher value in the near future

soil/plant system. Coincidentally, these two effects cancel each other (in a 20 year LUC perspective) and therefore feed production in system 6 also reduces the climate impact of feed production by roughly 55%.

Shifting to early seeded winter wheat (system 5 vs. 1) gives even higher GHG benefits than systems 4 and 6 (with normal seeding date of winter wheat). Early seeded winter wheat with utilization of 50% straw for biorefining gives a GHG emission reduction (compared to the reference system) of 94%. This is due to even higher yields, more straw for bioenergy, and even further reduced N_2O emission from the field. From a climate perspective, system 5 is clearly the best option. However, it is important to note that issues related to increased probability of so-called crop winterkill, plant diseases, higher weed pressure, and increased pesticide use associated with early seeding have not been factored into the LCA, meaning that the positive effects modelled for this scenario can only be achieved if these issues can be effectively dealt with.

Based on two different time perspectives for ΔSOC (20 and 100 years) and three different assumptions regarding marginal electricity at the Danish grid (renewable, coal-based, and average grid mix), the ranking of the six cropping systems in terms of best climate performance is as follows:

1. System 5 (early sown winter wheat, 50% straw for biorefining)
2. System 6[3] (winter wheat, intercrop, 50% straw for biorefining)
3. System 4[4] (winter wheat, 50% straw for biorefining)
4. System 2 (spring barley with 50% straw for biorefining)
5. System 3 (winter wheat with 100% straw incorporation)
6. System 1 (spring barley with 100% straw incorporation)

Eutrophication results for feed production

In terms of contributions to nutrient enrichment of the environment (eutrophication), assumptions about displaced electricity on the grid are also important because combustion-based power plants emit nutrient containing pollutants, which will later be deposited in the environment.

In general, we rank the six systems in the following order in terms of their contributions to nutrient enrichment (lowest emissions indicated by lowest score).

1. System 5 (early sown winter wheat, 50% straw for biorefining)
2. System 6 (winter wheat, intercrop, 50% straw for biorefining)
3. System 3 (winter wheat with 100% straw incorporation)
4. System 4 (winter wheat, 50% straw for biorefining)

[3] Slightly worse than system 4 in a 20 year perspective but slightly better over 100 years
[4] Slightly better than system 6 in a 20 year perspective but slightly worse over 100 years

5. System 1 (spring barley with 100% straw incorporation)
6. System 2 (spring barley with 50% straw for biorefining)

As shown, the barley systems are the least attractive in terms of eutrophication, i.e. any shift to one of the wheat systems will lead to an overall reduction in nutrient emissions to the environment. It is however important to note that for the wheat systems with the higher yields, a large part of the reduction takes place outside of Denmark (through displacement of international feed production).

GHG results for straw-based ethanol

Based on the cropping system analysis summarized above, we also isolated the effects of producing cellulosic ethanol and biorefinery co-products from straw. We derived results for straw-based ethanol in three different systems by comparison to the corresponding system without straw removal. The comparisons are listed below.

- System 2 vs. system 1: Ethanol from spring barley straw
- System 4 vs. system 3: Ethanol from winter wheat straw
- System 6 vs. system 3: Ethanol from winter wheat straw with intercropping of oilseed radish to mitigate loss of SOC associated with straw removal

The production of cellulosic ethanol comes out with very low life cycle GHG emissions even under the most conservative assumptions (renewable marginal electricity and 20 year LUC perspective). For wheat straw ethanol from system 4 and 6, the GHG impact was respectively 9 and 7 g CO_2e/MJ, corresponding to roughly 90% GHG savings as compared to gasoline.

Note that if marginal electricity on the Danish grid is assumed to come from renewable technologies, it is much better (from a climate perspective) to use straw for bioethanol than for power production.

A more elaborate and expanded version of the bioethanol analysis with the full range of results is intended for subsequent publication in a peer-reviewed journal.

Conclusions and perspectives

Early seeding of winter wheat is environmentally beneficial as it reduces life cycle GHG emissions and nitrogen losses to the aquatic environment.

Yield improvements on existing agricultural land are beneficial because they reduce the pressure on land resources elsewhere. Additional cereal production will (fully or in part) replace crop production elsewhere. Meanwhile, quantification of the exact implications in terms of GHG and nutrient emissions is challenging.

Utilizing straw from Danish cereal cropping systems to produce cellulosic ethanol and other biorefinery co-products reduces the life cycle GHG emissions from Danish grain production by at least one quarter and potentially much more. The exact result is highly affected by assumptions regarding grid electricity replaced by bioelectricity from the biorefinery (renewable, fossil-based, or average).

Straw removal leads to a decrease in SOC and thereby higher emissions of CO_2 to the atmosphere. Meanwhile, there is an inverse relationship between soil CO_2 emissions and N_2O emissions from the field. In the long run, however, the N_2O effect becomes dominating (in terms of GHG emissions).

Intercropping of oilseed radish in wheat production reduces nutrient enrichment and mitigates some of the SOC loss from straw removal. However, the use of this intercrop increases N_2O emissions from the field, which more or less cancels the soil C storing effect (in terms of GHG emission) in a 20 year time perspective. In a 100 year perspective, the N_2O effect again becomes dominating.

Recommendations

It is recommended that the environmental performance of Danish cereal crop production is considered in a full life cycle perspective taking into account the implications of yield changes as well as the implications of utilizing straw for energy purposes. Regulation of cereal cropping for environmental benefits should also adopt this perspective in order to avoid a narrow view on Danish cropland as opposed to the entire life cycle and other affected processes. Only with this approach can burden-shifting of environmental impacts be avoided.

List of abbreviations

1G	First generation (1G) ethanol produced from starch or sugar
2G	Second generation (2G) ethanol produced from cellulosic materials, such as straw
C	Carbon
CHP	Combined heat and power
DE	Germany
DLUC	Direct land use change
dm	dry matter
GHG	Greenhouse gas
ILUC	Indirect land use change
K	Potassium
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MJ	Mega joule
Mg	Mega gram (equal to one metric ton or 1,000 kg)
N	Nitrogen
P	Phosphorus
RE	Renewable energy
SOC	Soil organic carbon (C)

1 Introduction

Danish crop production primarily provides feed for Danish livestock such as pigs, poultry, and dairy cattle. These animals are fed with rations containing a balanced mix of energy, protein, and other important feed constituents to ensure optimal growth and production. Some of the protein used in Danish livestock production is imported as soybean meal from mainly South America while Danish dairy products, pork, and other agricultural products are sold on international markets. Hence, it is clear that Danish crop and livestock production is intimately linked to (and embedded in) international trade.

At the same time, Danish crop production has an impact on the Danish environment, e.g. through loss of nitrogen (N) to the aquatic environment. On the basis of EU's Water Framework Directive, Denmark has implemented several measures to mitigate nitrogen (N) and phosphorus (P) losses from agricultural fields. This includes mandatory use of cover crops (e.g. oilseed radish) on a certain share of land (e.g. as part of a spring barley crop rotation). Meanwhile, new regulation opens up for the possibility of using early seeding of winter wheat and other autumn-sown cereals to replace a certain share of cover crops.

Besides nutrient leaching to the aquatic environment, crop production also emits greenhouse gases (GHGs, e.g. nitrous oxide, N_2O; carbon dioxide, CO_2) to the atmosphere and thereby contributes to global warming.

The present study uses life cycle assessment (LCA) to elucidate potential changes in Danish cereal crop production and their effects on nutrient enrichment of ecosystems (also referred to as eutrophication) and global warming. The changes studied include shifting from spring barley to winter wheat (normal or early seeding), removal of straw for production of bioethanol, and intercropping of oilseed radish between two successive crops of winter wheat. It is assumed that the Danish area under cereal cropping remains constant wherefore changes in yields will affect grain production elsewhere.

2 Goal and Scope

This chapter describes the objectives and the frames of the study.

2.1 Goal definition

The purpose of this study is to assess specific environmental implications of specific changes in Danish cereal crop production.

Intended application

The study is an input to the PlantePro project[5], which investigates several strategies to increase plant production and reduce environmental impacts of the production. The study also functions as documentation for a greenhouse gas (GHG) assessment tool also developed for the PlantePro project.

Reasons for carrying out the study

The study is conducted to better understand the environmental implications of specific changes in Danish cereal crop production, e.g. change in choice of cereal type and change in straw utilization.

Intended audience

The study is meant to inform stakeholders and contribute to the general debate about Danish crop production and the local/global environment. The intended audience is informed participants in this debate, including advisory services, consultant companies, researchers, and opinion leaders and decision makers in this field.

Comparative assertion

The study compares different systems and makes claims about those that are more environment friendly from an overall perspective.

Data Requirements

The study relies on upstream production data for typical inputs to agriculture (fertilizers, seeds, etc.), mainly derived from LCA databases such as ecoinvent. Besides, the study relies on modeling of nutrient and emission flows in the agricultural field systems studied. This modeling has been conducted with the agroecosystem simulation model Daisy. A detailed description of the modeling work is available in Peltre et al. (2016). Finally, the study relies on some data from the literature, e.g. data on so-called indirect land use change (ILUC). The data flows are illustrated in Figure 1.

[5] Full Danish project title: 'Miljøsikret planteproduktion til foder og energi'

Limitations

The Daisy simulation model (used for modeling of crop yields and field emissions) does not embrace effects of potential crop disease issues, e.g. related to early seeding of winter wheat. Furthermore, the C sequestration in soil from intercropping of oilseed radish in winter wheat (also modeled with Daisy) may be underestimated due to potential underestimation of inputs of roots and belowground storage organs. Sequestration of C in soil from applying biorefinery by-products (biofertilizer) on agricultural land was also excluded in the analysis. The study has first and foremost focused on GHG emissions but it also contains substantial information regarding contributions to eutrophication with N and other nutrients. However, loss of P (and K) from the studied Danish cropping systems has not been included and N-containing gaseous emissions from combustion of lignin at the biorefinery have been modeled with proxy data.

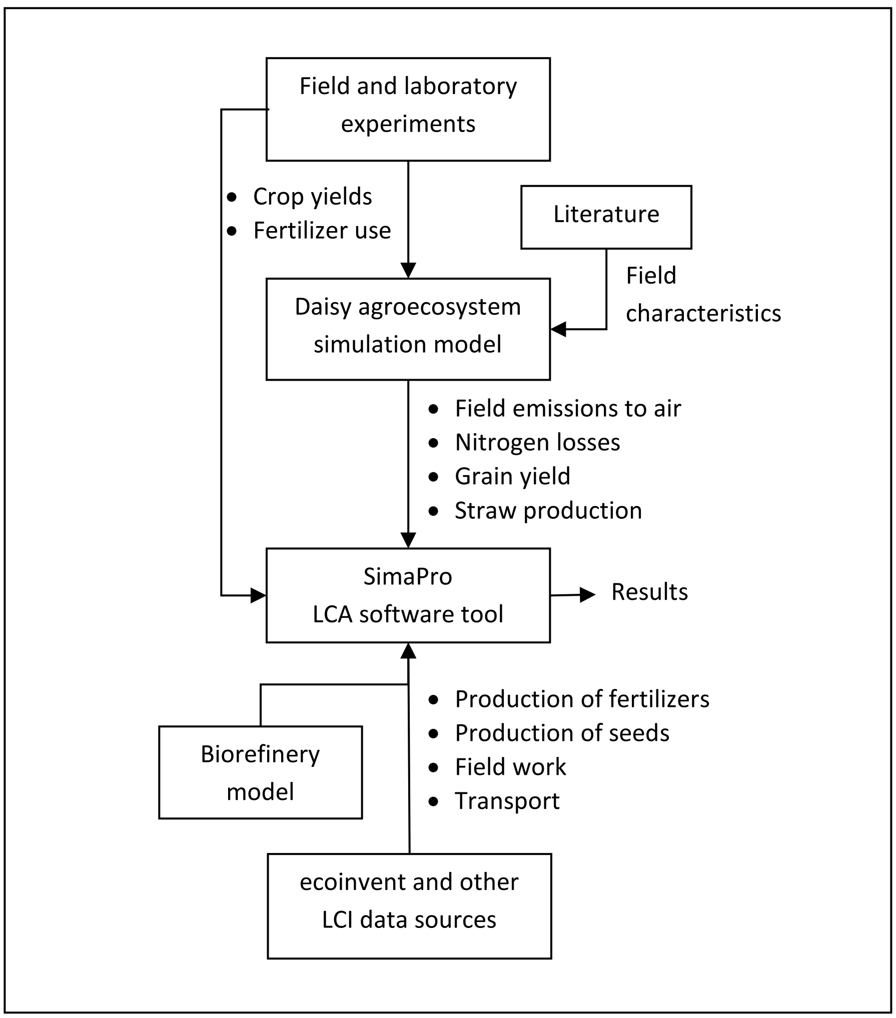

Figure 1. Data flows in the LCA

Critical Review

The study has not been subject to external critical review.

Type and Format of Report

The present report is a technical document and a deliverable to the PlantePro project. The present document is generally structured on the basis of the guidelines given in the ISO standards for LCA (ISO 2006a, ISO 2006b).

2.2 Scope definition

This section elaborates on system characteristics, the functional unit, methodology, impact categories, etc.

2.2.1 Product systems studied

The present LCA takes its starting point in one hectare of Danish cropland and considers the changes caused by a shift from a reference system to another cropping system.

All of the selected systems have the following common features.

- Soil type: JB6 (sandy loam)
- Initial soil C: 1.5%
- Climate: Typical for Western Denmark (average annual temperature 7.8 °C; average annual precipitation 700 mm; average reference evaporation 679; average global radiation 115 W m^{-2})

The selected cereal cropping systems are detailed in Table 1. Note that spring barley with a catch crop of oilseed radish (system 1) is considered the reference system. This means that the LCA will explore the implications (in terms of GHG emissions and nutrient enrichment) of shifting from the reference system to the other five selected systems. System 1 was selected as the reference system because it has been a widely used cereal on the agricultural land in question. Biorefinery use of straw (cf. Table 1) involves production of cellulosic ethanol with biogas, electricity, and biofertilizers as co-products. In the Daisy simulations, straw removal is based on 50% straw removed and 50% straw incorporation into the soil. In practice, this may be implemented by removing 100% of the straw every second year. This distinction is not expected to have any significance within the time perspective applied in this study.

Table 1. Cereal cropping systems studied in the present LCA

#	Main crop	Sowing time*	Catch crop or intercrop#	Straw incorporation	Comments
1	Spring barley	Normal	Oilseed radish	100%	Reference system
2	Spring barley	Normal	Oilseed radish	50%	50 % straw removed for use in biorefinery
3	Winter wheat	Normal	None	100%	Continuous winter wheat production
4	Winter wheat	Normal	None	50%	50 % straw removed for use in biorefinery
5	Winter wheat	Early	None	50%	50 % straw removed for use in biorefinery
6	Winter wheat	Normal	Oilseed radish	50%	50 % straw removed for use in biorefinery

* For winter wheat, early and normal seeding means wheat planted on 7 and 23 September, respectively.
# Oilseed radish used as catch crop during fall and winter or as an intercrop between two successive wheat crops

The cropping systems in Table 1 were chosen to shed light on the following questions:

What happens if…

- 50% straw is removed from a spring barley/oilseed radish cropping system for biorefining (1 vs. 2)?
- spring barley (and oilseed radish) is replaced by winter wheat (1 vs. 3)?
- spring barley (and oilseed radish) is replaced by winter wheat and…
  - 50% straw is used for biorefining (1 vs. 4)?
  - 50% straw is used for biorefining and winter wheat is seeded early (1 vs. 5)?
  - 50% straw is used for biorefining and oilseed radish is intercropped in winter wheat (1 vs. 6)?

Thus, we consider a shift from a reference system to another system on a given area of Danish agricultural land. We consider this area to be constant. When crop yield increases, the cropped area will not be reduced to maintain the same output of livestock feed. Instead we consider increased Danish crop yields to replace feed production elsewhere. This will be further discussed in Section 2.2.5 and Section 3.2.

2.2.2 Geographical scope

The geographical scope for the present LCA is Western Denmark.

2.2.3 Temporal scope

The present LCA considers a near-term temporal scope roughly representative for 2015-2020. This means the results are based on parameters relevant to this time period, e.g. crop yields, bioethanol yields, etc. It is important to be aware that these numbers most likely will change in the future and that this must be considered when interpreting results.

2.2.4 Technological scope

The study considers agricultural crop production consistent with the near-term temporal scope described above. Hence, all cropping systems are subject to conventional management using current technology in Danish agriculture. Some of the cropping systems involve straw removal for production of cellulosic ethanol (a new technology with room for improvement) and displacement of gasoline production (a technology optimized during many decades but also facing challenges in relation to continued extraction of crude oil).

2.2.5 The functional unit

The present study seeks to answer the following question: What are the environmental consequences of shifting from the reference cropping system (spring barley with oilseed radish and 100% straw incorporation) to other cropping systems with spring barley or winter wheat and different combinations of catch/cover crops, seeding times, and straw use (see Table 1).

To answer this question, results will be considered at three levels:

- Level 1: Changes in reference flows and emissions when looking only at one hectare of cropland.
- Level 2: Changes in environmental impacts when looking holistically at environmental impacts caused by a shift in cropping system on one hectare of cropland (intermediate step)
- Level 3: Changes in environmental impacts when looking holistically at environmental impacts caused by a shift in the production of one Mg of spring barley grain equivalent (based on metabolizable energy and crude protein for growing pigs).

In order to compare cropping systems at level 2 and 3, we need to ensure that each system delivers the same amount of metabolizable energy and crude protein (despite of different grain yields). We do this by expanding the systems. To balance metabolizable energy and crude protein, we either add or subtract production of wheat produced in Germany or soybean meal produced in South America. In this way, each system delivers the same amount of metabolizable energy and crude protein. The rationale is that a change in Danish grain production will impact grain trade with neighboring grain producers and remaining balances in protein will be leveled out by adjusting Danish imports of soybean meal. This is further discussed in Section 3.2. In the same way, we expand the systems to ensure they deliver the same amount of energy. Hence, the co-products from straw utilization are assumed to replace equivalent products on the market. For instance, bioethanol is assumed to replace a corresponding amount of gasoline.

2.2.6 The system boundaries and cut-off criteria

The study covers all relevant agricultural and biorefinery operations as well as upstream production of inputs to these processes. The study considers effects of changes in feed production per hectare of agricultural land as well as the implications of biorefinery co-products (such as co-produced bioelectricity).

The cut-off criteria are defined as follows: Omitted aspects must be considered of low importance for the end results and this should be explained and justified. Whenever omissions or simplifications are used in the report, it is explicitly stated.

2.2.7 Methodology and impact categories

The study adheres to the ISO standards for LCA[6] (although a critical review has not been conducted) and applies the so-called consequential approach where the aim is to study the consequences of shifting from one system to another (in this case different cereal cropping systems of which some include ethanol production from straw). System expansion[7] is used when dealing with multi-output processes and marginal data (as opposed to average data) is, to the extent possible, used for all important foreground and background processes (see subsequent section on 'market processes' in the ecoinvent database). Economic modeling has not been applied directly but the present LCA draws on other studies that have used economic modeling to derive results for indirect land use change (ILUC). So-called rebound effects[8] have not been considered as part of this study[9]. Hence, substitution among products providing similar functions have been assumed to occur on a one-to-one basis[10], mainly based on the principles described by Ekvall and Weidema (2004). The general principles applied in the study are described by Wenzel et al. (1997). Environmental impacts are expressed at midpoint level and environmental modeling is facilitated in the SimaPro 8 LCA software.

[6] ISO (2006a) and ISO (2006b)

[7] See e.g. Ekvall and Weidema (2004)

[8] An example of the rebound effect could be the following: A consumer has the choice between two alternatives of which one is more environmentally friendly. The consumer chooses this alternative. This also happens to be the cheaper alternative. Hence, the consumer saves money. The money saved is used to buy a plane ticket for a short vacation and, due to this rebound effect, the more environmentally sound alternative ends up causing more pollution than the more expensive (and more polluting) alternative. For more, see e.g. Thiesen et al. (2006).

[9] The applied ILUC results are the exception to this general approach since the ILUC modeling implicitly includes rebound effects. Note that ILUC is included in a separate analysis to assess the potential impact of this method as compared to the general system expansion approach (assuming one-to-one substitution).

[10] For example, organic fertilizers have been assumed to replace inorganic fertilizers based on their nutrient content without considering potential rebound effects in the fertilizer market.

The following two environmental impact categories have been considered:

- Global warming: This impact category covers emissions to the atmosphere, which have an impact on the global climate. These emissions are GHGs measured in CO_2 equivalents (CO_2e; GWP100). GWP100 values from the 'CML-IA baseline' method (version 3.01) are used as characterization factors (25 and 298 for methane and nitrous oxide, respectively[11]).
- Nutrient enrichment (eutrophication): Emissions of nutrients such as N and P may change the species composition and productivity of terrestrial and aquatic ecosystems and cause oxygen depletion in aquatic ecosystems due to algal bloom. This impact is measured in phosphate equivalents (PO_4^{3-}e) and characterization factors from the 'CML-IA baseline' method (version 3.01) are applied in the present study.

2.2.8 'Market processes' in the ecoinvent database

In order to obtain marginal data for the consequential analysis, we rely to some extent on so-called global market processes in the ecoinvent 3 database (ecoinvent 2014). These processes will be referred to later in the report and are therefore briefly introduced and explained here.A market process in the ecoinvent database seeks to represent the composite of marginal suppliers/technologies that are affected when the demand for a given product or service changes. For example, if a region or country has an increasing electricity market and expansion of production capacity takes place by building natural gas-fired power plants, alternative supply to the grid (e.g. from a cellulosic bioethanol plant) would reduce the need for additional natural gas-fired plants and these would therefore constitute the marginal technology, i.e. the technology affected by a change. Also, some suppliers of a given commodity (say fertilizers) may be constrained in their production for different reasons and hence would not be part of the marginal composite of suppliers reacting on a change in demand. Importantly, it is the *longer-term changes in production capacity* that represent marginal technologies. These changes are sometimes referred to as 'the build margin'. In other words, marginal technologies are constituted by the production capacity that would or would not be installed because of the change studied. For an in-depth discussion of this topic, we refer to Section 14.6.1 in Weidema et al. (2013).

[11] Based on IPCC's fourth assessment report (AR4)

3 Inventory Analysis

This chapter describes the systems and the data that forms the basis for the present LCA.

3.1 System description confined to one hectare of cropland (level 1)

The reference cropping system consists of spring barley production with oilseed radish as catch crop and 100% straw incorporation (further details available in Section 2.2.1). This system receives a number of inputs (fertilizers, seeds, etc.) and has an output of feed grain, which is assumed to be used for pig feed. In addition, nutrients leaches from the system to the surrounding environment and GHGs are emitted to the atmosphere. A simplified sketch of the system is shown in Figure 2.

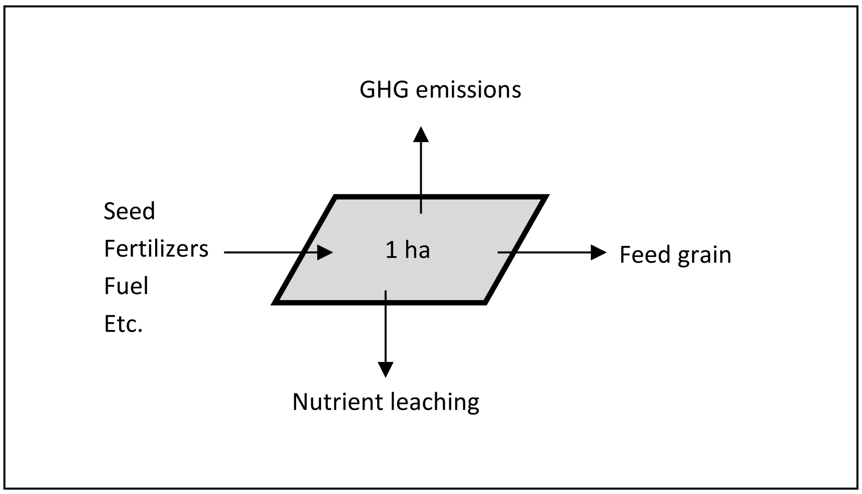

Figure 2. Simplified sketch of the reference system at 'level 1'

As previously mentioned, some of the cropping systems also have an output of straw (see Table 1). This will be used in a biorefinery to produce ethanol, electricity, and biogas. We assume that barley straw has the same characteristics as wheat straw (same ethanol yield, etc.). A further description of the biorefinery is given in Section 3.4.8.

In Table 2, the assumed inputs and outputs (incl. nutrient leaching and GHG emissions) are shown per hectare for all six cropping systems studied (see Table 1) including the energy carriers produced from utilization of the straw. As shown, the Danish cereal cropping systems are not assumed to be irrigated. Besides, pesticides have not been considered in the present assessment because they only have a marginal influence on the two impact categories studied. For instance, pesticides account for less than 0.7% of the total life cycle GHG emissions from wheat grain produced in Germany and less than 2% of the contributions to nutrient enrichment (based on ecoinvent3 and CML-IA baseline). Use of lime for regulating soil pH has also been disregarded as this reference flow also would have a very minor influence on the considered impact categories. For instance, lime accounts for less than 0.1‰ of the total life cycle GHG emissions from French wheat grain and less than 0.03‰ of the contributions to nutrient enrichment (based on ecoinvent3 and CML baseline). For many other crop processes, lime is not even mentioned in the life cycle inventory data.

As shown in Table 2, the input of N fertilizer is constant in the spring barley systems (109 kg N/ha) and the winter wheat systems (200 kg N/ha), regardless of whether straw is removed or not. This is because the input of N fertilizers is regulated by Danish law. Hence, the farmer will not compensate for N removed from the field via straw by additional N fertilizer inputs. However, the farmer is expected to compensate for the P and K removed with the straw as the application of these nutrients are governed by their availability in the soil as monitored by regular soil sampling. This is reflected in the fertilizer inputs shown in Table 2.

Table 2. Inputs and outputs (incl. N_2O emissions and changes in SOC) per hectare of cropping system

	Reference flow	Unit	Systems and main crops 1: SB	2: SB	3: WW	4: WW	5: WW	6: WW	Comments
Input	Land occupation	Ha	1	1	1	1	1	1	
	N fertilizer	kg N	109	109	200	200	200	200	
	P fertilizer	kg P	21	23	21	24	24	24	LCA Food (2003)[a]
	K fertilizer	kg K	62	94	62	105	115	105	LCA Food (2003)[a]
	Traction (diesel)	GJ	4	4	5	5	5	5	LCA Food (2003)
	Lubricant oil	l	0.3	0.3	0.4	0.4	0.4	0.4	LCA Food (2003)
	Seeds, grain	kg	140	140	180	180	140	180	
	Seeds, catch crop	kg	12	12	0	0	0	12	DLBR (undated)
Output	Feed grain	kg dm	5,852	5,841	7,814	7,813	8,349	7,807	
	Straw	kg dm	0	1,879	0	2,876	3,506	2,887	
	- Ethanol	l	0	564	0	863	1,052	866	
	- Electricity, net	kWh	0	509	0	779	950	782	
	- RE gas for grid	m^3	0	110	0	168	204	168	Upgraded biogas
	- Biofertilizer, N	kg N	0	3	0	5	6	5	
	- Biofertilizer, P	kg P	0	1	0	1	1	1	
	- Biofertilizer, K	kg K	0	17	0	26	32	26	
	N leaching[b]	kg N	16	16	24	24	17	21	Daisy results
	N loss[c]	kg N	6	6	11	11	6	9	Daisy results
	N_2O emissions[d]	kg N	5	4	6	5	4	5	Daisy results
	N_2O emissions[d]	kg CO_2e	2,235	1,915	2,869	2,381	1,832	2,462	
	ΔSOC/y, 20 y avg	kg C	-49	-139	210	3	82	73	Daisy results
	CO_2/y, 20 y avg[e]	kg CO_2e	179	508	-771	-12	-301	-266	
	ΔSOC/y, 100 y avg	kg C	-34	-103	85	-25	52	8	Daisy results
	CO_2/y, 100 y avg[e]	kg CO_2e	123	378	-313	92	-192	-29	
	GHG soil[f], 20 y	kg CO_2e	2,414	2,424	2,098	2,369	1,531	2,196	Annual average
	GHG soil[f], 100 y	kg CO_2e	2,358	2,293	2,556	2,473	1,640	2,433	Annual average

[a] Inputs of P and K fertilizers for systems with straw removal have been modified (see text)
[b] N leaching to ground water
[c] N loss to surface waters through drain
[d] Direct emissions from Daisy + indirect emissions (derived from Daisy results based on IPCC methodology, see text)
[e] Average annual CO_2 emissions from the field caused by changes in soil organic carbon (ΔSOC)
[f] The sum of CO_2 emissions from changes in soil organic carbon (SOC) and N_2O emissions

Note that Table 2 includes total GHG soil emissions ('GHG soil') at the bottom. These numbers have been derived by converting N_2O emissions and CO_2 emissions from changes in SOC to CO_2 equivalents (using the IPCC GWP100 for N_2O of 298). The field emissions allow for an assessment of the GHG implications of removing straw. When comparing scenario 1 to scenario 2 and scenario 3 to 4, one can isolate the effects of straw removal (not considering subsequent use for energy purposes). Interestingly, scenario 1 and 3 (100% straw incorporation) have lower GHG soil emissions than respectively scenario 2 and 4 (50% straw incorporation) in a 20 year time perspective while emissions are higher in a 100 year time perspective. The reason is that much of the CO_2 emission caused by straw removal (reduction in SOC) is counter-balanced by reduced N_2O emissions and, in the 100 year time perspective, the removal of straw actually leads to a climate benefit (in itself) because the reduced N_2O emissions (in CO_2 equivalents) exceed the increased CO_2 emissions from reductions in SOC. The reduced emissions of CO_2 from soil reflects that, as time passes, the SOC pool will move towards a new, although lower, steady-state (equilibrium) with a balance between input and output of C.

It is noted that the modeled N_2O emissions are relatively high compared to standard IPCC methodology, which stipulates a default (direct) N_2O emission of 1% of the nitrogen added to the system. In the present study, the N emitted directly as N_2O from the field ranges from 1.9% (system 5) to 4.2% (system 1) of the N applied as fertilizer. In comparison with the IPCC methodology, the Daisy model is much more advanced. In the Daisy model, N_2O emissions are a consequence of nitrification and denitrification. The denitrification process depends on soil type and the amount of easily degradable organic matter. The high emissions of N_2O thus reflect that the JB6 soil type and cropping systems are relatively conductive to denitrification.

Removal of straw is also associated with losses of SOC. This is potentially a problem because SOC is generally believed to be important for maintaining soil quality (Diacono and Montemurro 2010). Ultimately this could lead to lower yields and a need for larger areas to provide the same amount of grain and straw. However, the changes in SOC content simulated in the scenarios are rather small. All systems start out with a SOC content of 1.5% and System 2 which is losing most carbon ends up having 1.42% C after 100 years while the reference system ends up with 1.47%. The relative loss in SOC[12] in system 2 is 1% after 20 years and 3.8% after 100 years. Oelofse et al. (2015) did not observe any effect of SOC on yields in Danish soils and concluded that when there is no nutrient limitation, SOC levels above 1% is sufficient to sustain yields. Therefore, there are no indications that these small changes should be critical in terms of soil fertility.

The upstream impacts from production of P fertilizers are included in the present LCA, but Daisy does not model the downstream emissions of P to the aquatic environment. Therefore, no P emissions have been assigned to the crops produced in the six systems studied. This is only of minor relevance, since it is N emissions that contribute the most to nutrient enrichment. For example, P emissions for wheat produced in Germany accounts for less than 1% of the total life cycle contribution to nutrient emissions (based on ecoinvent3 and CML-IA baseline).

Based on Table 2, it is possible to compare total emissions to the environment and the output of feed and energy between the different systems. However, due to potential trade-offs (e.g. reduction in SOC as a result of straw utilization for energy), it is challenging to decide which system is more environmentally beneficial (although

[12] The change in SOC in the system studied (in percent) minus the change in the reference system (in percent)

scenario 5 looks like a clear winner) and impossible to establish a full account of these benefits. We therefore 'go beyond the hectare' as described in the next sections.

3.2 Systems description including life cycle and long-term market effects (level 2)

To rate the six cereal cropping systems in terms of environmental impacts, it is necessary to look beyond the effects occurring directly in the agricultural field (and in the biorefinery). For instance, the upstream effects of producing fertilizers and other inputs need to be considered. Also, if the output of feed grain changes, it is necessary to consider how that will impact production of feed elsewhere. Furthermore, the energy produced from straw will impact the environmental performance of a cropping system due to replacement of other energy sources. All these elements are considered at 'level 2' of our inventory analysis. At level 2, we expand each cropping system to include induced or avoided production of feed and energy caused by changes in feed and energy production as compared to the reference system. Figure 3 illustrates these effects.

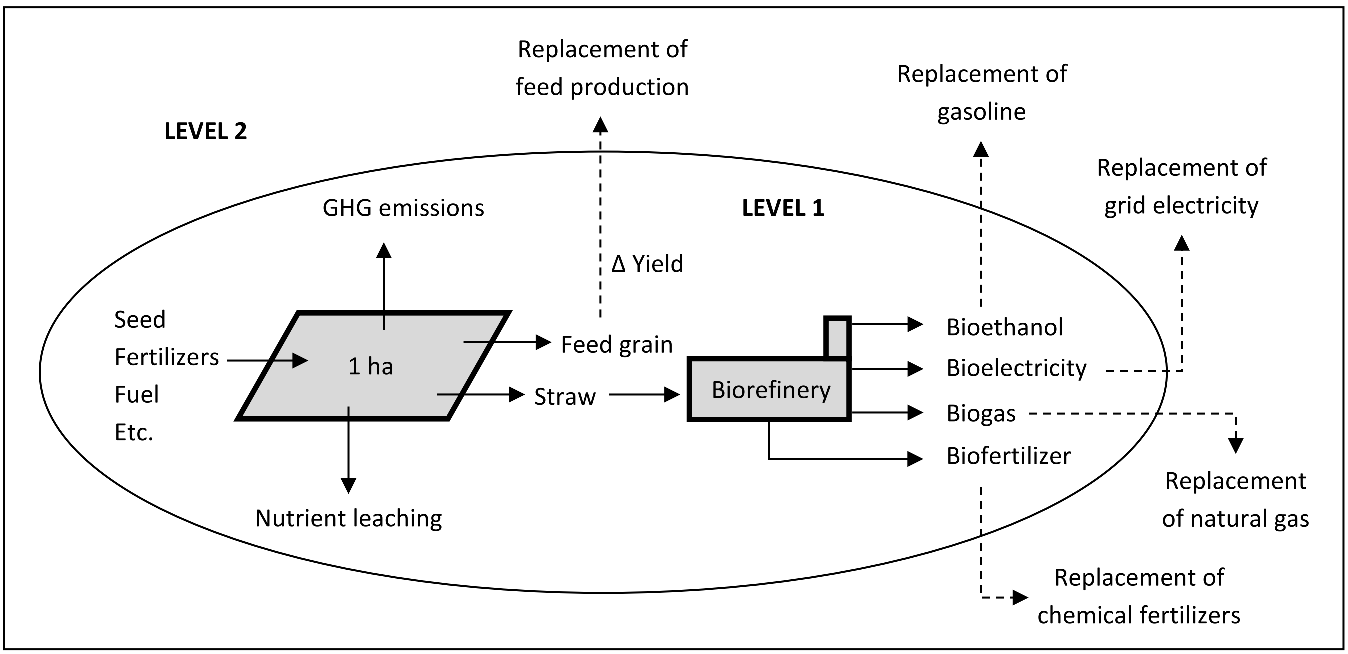

Figure 3. Diagram illustrating the expanded system (level 2) where changes in the output of feed grain (Δ Yield) impact feed production elsewhere, and where bioenergy from straw replace gasoline, electricity on the grid, and natural gas. This expansion of the cropping systems ensures system equivalency (in terms of feed and energy output) and thereby allows for comparison between the systems.

Table 3 shows how system equivalence (in terms of feed and energy outputs) is obtained for each of the six cropping systems. The first part of the table (Main system) shows outputs from the main system in terms of feed grain and energy carriers obtained when straw is used at the biorefinery (ethanol, renewable energy gas, and net output of electricity). Note that the output of feed grain in Table 3 has been sub-divided into 'Feed energy' (metabolizable energy for growing pigs) and 'Feed protein'. The applied conversion factors have been shown in

Table 4. For protein, the output of N in grain (as estimated with the Daisy model) has been multiplied with a factor of 6.25 kg protein/kg N.

Table 3. Main outputs (from field and biorefinery) and system expansions (level 2)

	Reference flows	Unit	Systems and main crops						Comments
			1: SB	2: SB	3: WW	4: WW	5: WW	6: WW	
Main system[a]	Feed grain	Kg	6,884	6,871	9,193	9,192	9,822	9,185	85% dm
	- Feed energy	GJ	84	84	122	122	130	122	Metabolizable
	- Feed protein	Kg	507	503	839	836	895	840	
	Ethanol	GJ	0	12	0	18	22	18	
	RE gas for grid	m3	0	110	0	168	204	168	
	Electricity, net	kWh	0	509	0	779	950	782	
System expansion	Wheat (DE)	Kg	0	4	-2,822	-2,833	-3,520	-2,809	
	- Feed energy	GJ	0	0	-38	-38	-47	-38	
	- Feed protein	Kg	0	0	-339	-340	-422	-337	
	Soybean meal	Kg	0	8	15	27	87	10	
	- Feed energy	GJ	0	0	0	0	1	0	
	- Feed protein	Kg	0	3	6	11	35	4	
	Gasoline	GJ	0	-12	0	-18	-22	-18	
	Natural gas	m3	0	-110	0	-168	-204	-168	
	Grid electricity	kWh	0	-509	0	-779	-950	-782	
	N fertilizer	kg N	0	-2	0	-4	-5	-4	
	P fertilizer	kg P	0	-1	0	-1	-1	-1	
	K fertilizer	kg K	0	-17	0	-26	-32	-26	
Sums	Feed energy	GJ	84	84	84	84	84	84	
	Feed protein	Kg	507	507	507	507	507	507	
	Liquid fuel	GJ	0	0	0	0	0	0	Eth./ gasoline
	Methane gas[b]	m^3	0	0	0	0	0	0	RE gas/NG
	Electricity	kWh	0	0	0	0	0	0	

[a] Biofertilizer not shown
[b] 'Methane gas' is here used as a common term for RE gas and natural gas (both containing the same amount of CH_4)

Table 4. Applied data for feed energy (metabolizable energy) and feed protein (crude protein)

Reference flow	Dry matter content[a] %	Metabolizable energy (ME)[a] MJ/kg	Crude protein %	
Danish spring barley	85	12.2	7.3	Based on Daisy and 6.25 kg protein/kg N
Danish winter wheat	85	13.3	9.1	Based on Daisy and 6.25 kg protein/kg N
Wheat (DE)	86	13.4	12.0	Based on inputs from SEGES
Soybean meal	88	14.4	39.9	Based on inputs from SEGES

The second part of Table 3 (System expansion) shows how each system has been expanded to ensure system equivalence. Changes in the yield of feed grain (barley or wheat) grown in Denmark are assumed to be balanced by changes in international feed production to ensure that the output of feed energy and feed protein is constant in all cropping systems studied. We assume that increased Danish grain production displaces wheat production elsewhere in the EU and that any remaining changes in feed protein on the EU market will be balanced by a change in imports of soybean meal from South America.

The rationale for choosing soybean meal from South America to balance changes in Danish feed protein production is that the majority of the feed protein for Danish pigs, which is not sourced internally in Denmark or in the EU, comes from South America.

The impacts on international feed production resulting from a change in Danish crop yield may potentially lead to changes at the 'agricultural frontier' where agriculture meets native land. This so-called indirect land use change (ILUC) has been discussed in Section 3.4.11.

The second part of Table 3 (System expansion) also shows the different energy carriers replaced through use of straw for bioenergy. Bioethanol is assumed to replace gasoline on an energy basis (MJ to MJ), renewable energy (RE) gas is assumed to replace natural gas on a volume basis (m^3 to m^3), and bioelectricity is assumed to replace marginal electricity on the grid, also on an energy basis (kWh to kWh).

The last part of Table 3 (Sums) shows the summed outputs from each of the six systems studied. This is to illustrate that each system has the same net output as the reference system (system 1).

3.3 System description relating to one Mg of spring barley equivalent (level 3)

At level 3, we normalize the results of level 2 to one Mg (metric ton) of 'spring barley equivalent' by dividing all inputs and outputs by a factor of 6.88 (the yield of spring barley in the reference scenario given in Mg/ha, 85% dry matter).

3.4 Modeling of reference flows

The three previous subsections have laid out the modeling of the foreground system in the present LCA study. In order to make the impact assessment, we rely on a number of different processes from different sources. These will be described in more detail in the following subsections.

For some processes, we have used consequential LCI data from the ecoinvent database. The ecoinvent database is a licensed data source and it is not permitted to publish significant shares of the database. We have therefore, in some cases, used different data for the GHG assessment tool (in order not to violate the license agreement with ecoinvent). The alternative data is not always consistent with the consequential modeling approach generally applied in the study and the applied GHG emission factors for N fertilizer and wheat produced in Germany differ enough to cause a significant deviation from the results in the present report. However, the overall conclusions remain more or less the same, except that system 3 performs better than system 2 in the calculator due to a higher credit for yield increases as compared to the report.

3.4.1 N fertilizer

Nitrogen fertilizer has been modeled with the 'global market process' in the ecoinvent 3 database ('Nitrogen fertiliser, as N {GLO}| market for | Conseq, U'). For a brief description of 'global market processes' in the ecoinvent database, see end of Section 2.2.8.

For the GHG tool, a value of 5.88 kg CO_2e/kg N has been used (Biograce 2015). This is substantially lower (roughly 50%) than the ecoinvent data used in the present report.

3.4.2 Field emissions from N fertilizers

Emissions of nitrous oxide (N_2O) to the atmosphere and N losses to the aquatic environment have been modeled with the Daisy model (results available in Table 2).

For the GHG tool, it is necessary for the user to insert a value for N_2O emissions. Table 2 can be used for inspiration. Alternatively, it can be assumed that 1% of the input of N fertilizer (as N) is emitted as direct N_2O emissions, i.e. 0.01 kg N · (44 kg N_2O / 28 kg N) / kg N = 0.0157 kg N_2O/kg N in accordance with IPCC methodology.

3.4.3 P fertilizer

P fertilizer production has been modeled with a 'global market process' for P fertilizer (Phosphate fertilizer, as P_2O_5 {GLO}| market for | Conseq, U) available in the ecoinvent 3 database (ecoinvent 2014).

This process covers the upstream processes for production of P fertilizer, incl. transport. It does not cover loss of P when the fertilizer is applied to cropland. Neither is this simulated by the Daisy model. Hence, leaching of P from Danish cropland is not included in the study. See also discussion in Section 3.4.10.

For the GHG tool, a value of 2.32 kg CO_2e/kg P has been used (derived from Biograce 2015). This is lower than the ecoinvent data used in the present report.

3.4.4 K fertilizer

K fertilizer has been modeled with a 'global market process' for K fertilizer ('Potassium chloride, as K_2O {GLO}| market for | Conseq, U') available in the ecoinvent 3 database (ecoinvent 2014).

Just as for P, the loss of K at the field is not included in the study. This is of minor relevance since K does not cause any significant environmental problems.

For the GHG tool, a value of 0.694 kg CO_2e/kg K has been used (derived from Biograce 2015).

3.4.5 Field work (traction and lubricant oil)

For the general field work operations (tillage, sowing, harvesting, etc.), we rely on the following information from LCA Food (2003):

- Danish spring barley: 4029 MJ traction and 0.31 liters of lubricant oil per hectare
- Danish winter wheat: 4921 MJ traction and 0.39 liters of lubricant oil per hectare

To distinguish between scenarios with and without straw removal, cover crops, and intercropping, we also rely on information extracted from Table 1 in Dalgaard et al. (2002):

- Pressing and loading: 2.0 l diesel per Mg (59 MJ traction/Mg)
- Sowing: 3.0 l diesel per ha. (89 MJ traction/ha)

Based on LCA Food (2003), we convert liters of diesel to traction by use of the conversion factor 0.028 kg diesel/MJ traction (results shown above in parentheses). On the basis of the data shown above, we have obtained the numbers for traction shown in Table 2.

3.4.6 Crop seeds

For impacts associated with the production of crop seeds, we have used the following ecoinvent processes:

- Spring barley: 'Barley seed, for sowing {GLO}| market for | Conseq, U'
- Winter wheat: 'Wheat grain {DE}| wheat production | Conseq, U'
- Oilseed radish: 'Pea seed, for sowing {GLO}| market for | Conseq, U'

As we had no specific data for oilseed radish seeds, we chose a proxy in the form of pea seeds. We believe this choice has only minor implications because doubling or halving of the impacts for oilseed radish would not have any impact on the conclusions of the present report.

For the GHG tool, we have used an 'average grain seed GHG emissions factor' based on the barley and wheat seed processes mentioned on the list above (0.79 kg CO_2e/kg seed). The 'radish seed emission factor' in the GHG tool (1.3 kg CO_2e/kg seed) is approximated by an average of emissions from rapeseed, pea, and corn seeds (all ecoinvent 3 processes).

3.4.7 Transport of straw

For transport of straw, we have used the process called 'Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6 | Conseq, U'.

For the GHG tool, we have used a GHG factor of 0.22 kg CO_2e/Mg·km for a '28t truck' (LCA Food 2003).

3.4.8 Straw utilization in biorefinery

We assume that straw removed from the field is used in a biorefinery concept that produces (cellulosic) bioethanol, bioelectricity, biogas, and biofertilizers (see Figure 4). The straw goes through pretreatment (steam explosion) followed by enzymatic hydrolysis, fermentation, and distillation. The bioethanol production step (see upper box in Figure 4) generates four main outputs:

1. Bioethanol
2. Vinasse (slurry with high organic content)
3. Biogas (from straw gasification)
4. Lignin (complex organic polymer)

The vinasse is used for biogas production (see lower box in Figure 4), which is then upgraded to 'renewable energy gas' (RE gas) that can replace natural gas. Some biogas is also generated during ethanol production. This is also assumed to be upgraded to natural gas. Lignin is the most energy dense part of the straw. It is a polymer of aromatic alcohols known as monolignols. All of the lignin is assumed to be used in the biorefinery's internal combined heat and power (CHP) plant (see middle box in Figure 4) – providing energy for the plant itself (steam and electricity) and electricity to the grid. Besides the steam for internal use, it is assumed that 1.51 MWh electricity can be produced per Mg of lignin (90% dm). This allows for annual exports of 69 GWh of electricity to the grid (when taking into account the internal electricity used at the CHP plant and the electricity used for ethanol production, biogas production, and biogas upgrade). The data used is based on a concrete modeling of a CHP plant.

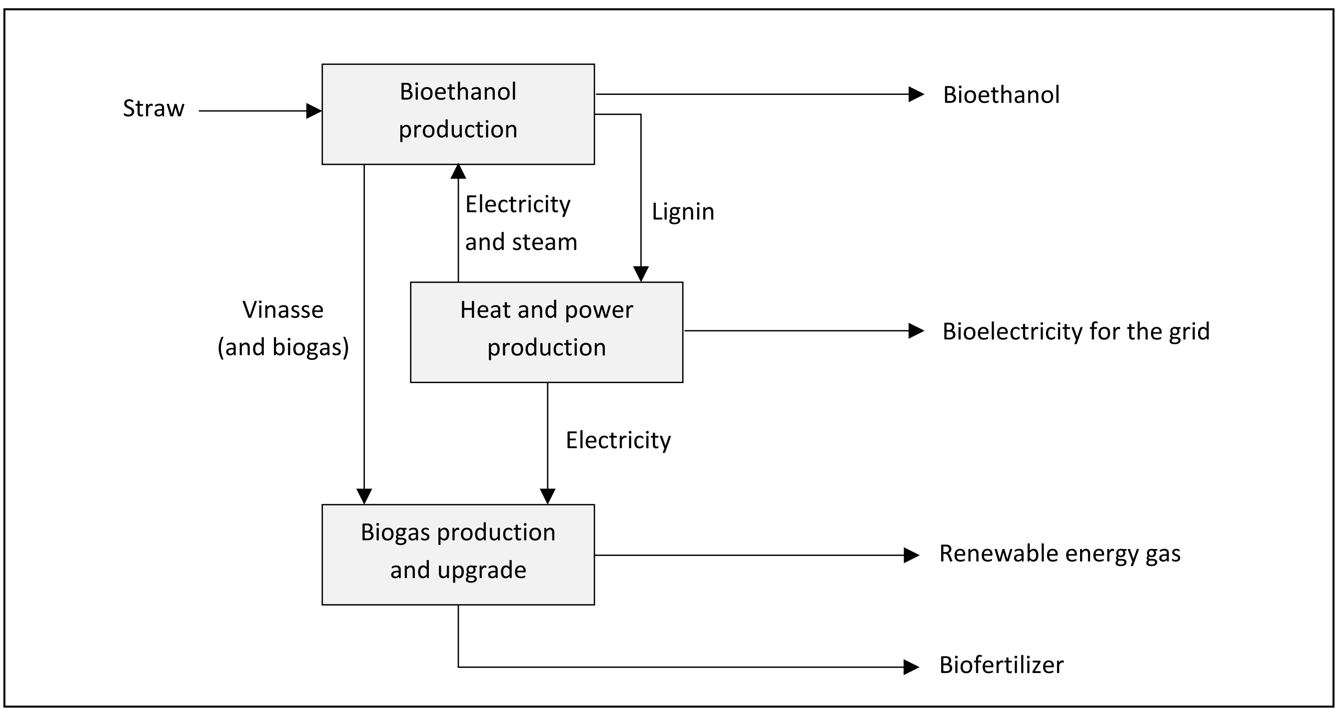

Figure 4. Simplified overview of the main biorefinery processes

Since the lignin is an organic material derived from an annual crop, its combustion is considered carbon neutral. Meanwhile, the combustion of lignin for combined heat and power does result in emissions to air that contribute to eutrophication. To include this aspect, we assume lignin combustion has roughly the same emissions as combustion of wood pellets (since no lignin combustion process is readily available for use in LCA). We rely on information from the process called 'Electricity, high voltage {DK}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Alloc Def, U' from the ecoinvent 3 database (ecoinvent 2014). On this basis, we derive an emission factor of 0.21 g PO_4^{3-}e/kWh electricity produced from lignin[13]. In the impact assessment, we multiply this number with the gross electricity production at the biorefinery in each of the scenarios with straw removal.

In addition to the four main outputs listed above, the ethanol production step also has an output of heat in the form of warm condensate and warm cooling water. This excess heat is not considered in the present LCA, which means the benefits of the ethanol production is to some extent underestimated. On the other hand, no fugitive emissions of methane from biogas production are assumed.

As for the auxiliaries used in the biorefinery, they can be summarized as follows:

1. Enzymes: It is assumed that the biorefinery will use 'full broth' enzyme product, which will be produced by Novozymes in Kalundborg and transported roughly 290 km by truck to the biorefinery.
2. Yeast: The biorefinery will use yeast for the fermentation processes where C5 and C6 sugars will be converted to ethanol.
3. Acids and bases: The biorefinery will use sodium hydroxide, sulfuric acids, and phosphoric acid for pH control at various steps in the process.
4. Process control agents: De-foaming agent and precipitation chemicals
5. Other auxiliaries: P fertilizer, polymer, magnesium sulphate, urea, hydrated lime, beet molasses, activated carbon, ammonia, calcium oxide, and water.

All biorefinery auxiliaries have been covered in the LCA, except for the process control agents (due to lack of data). Collectively, these make up less than 0.5 percent of the total inputs. In addition to the auxiliaries, the biorefinery has an input of natural gas used for process energy (production and combustion fully covered by the LCA).

The biorefinery described above resembles quite closely a specific large scale biorefinery project in the planning stage in Denmark known as the Maabjerg Energy Concept (MEC). There are however some differences between the set-up assumed in the present LCA and the actual project design (see list below).

[13] This number was obtained by analyzing the wood chip electricity process in SimaPro to get the total eutrophication emissions per kWh. Hereafter, emissions not relevant for the present LCA (e.g. emissions related to drying of wood chips) were subtracted.

1. Part of the excess heat in condensate/cooling water will be utilized in the planned real-world project as opposed to the assumptions applied in the present LCA
2. Not all of the lignin will be used for on-site CHP production in the planned real-world project. Some of the lignin will be sold to replace coal or waste in other power plants. In any case, the lignin will be used for electricity production.
3. Not all of the biogas will be upgraded in the planned real-world project. Some will be sold directly as biogas whereas it is all assumed to be upgraded in the present LCA.

None of the simplifying assumptions explained above favor bioethanol production in the present LCA. Hence, the simplifying assumptions made in the present LCA can be considered conservative.

As shown in Figure 4, the biorefinery also has an output of biofertilizer. More specifically, this is a nutrient-rich sludge approved for spreading on agricultural fields. It is assumed that P and K in the biofertilizer replace chemical fertilizers on a one-to-one basis (e.g. one kg P in the biofertilizer replaces one kg nutrient P in chemical fertilizers). For N, it is assumed that the biofertilizer has the same leaching characteristics as cattle manure, i.e. that 70% of the N will replace N in chemical fertilizers (see Example 9 in NaturErhvervstyrelsen 2015). This replacement assumption is based on 'timely delivery' of the biofertilizer, i.e. application on agricultural fields in the spring. The chemical fertilizer replacement is shown in Table 3. In cropping systems with straw removal, the use of biofertilizer reduces chemical fertilizer use by 2% for N, 3-6% for P, and 18-28% for K.

The N in the biofertilizer that does not replace chemical N fertilizers (30%) is considered to be lost to the aquatic environment, assuming the same split between surface waters and groundwater as modeled for chemical fertilizers in the different cropping systems with the Daisy model (roughly 30-70). This extra N in the cropping systems with straw removal also results in extra N_2O emissions. This aspect has not been modeled by the Daisy model. Instead, it is assumed that 1% of the 'extra' N applied in the systems with straw removal is emitted directly as N_2O and 0.75% of the leached/lost (extra) N is emitted as (indirect) N_2O. This is the standard procedure recommended by IPCC (2006).

The present LCA study does not consider any increased soil C sequestration from application of biofertilizer on agricultural land, although this is likely to occur. Again, this can be considered a conservative approach as it does not favor cropping systems with straw removed for biorefining.

3.4.9 Changes in soil organic carbon (SOC)

All changes in SOC have been simulated by the Daisy model including effect of early seeding of wheat, catch crops, and straw removal. The only exception is additional C sequestration from applications of biofertilizer on agricultural land, which was not simulated. Had this aspect been included in the present study, the estimated climate benefits of using straw for biorefining would have been larger.

3.4.10 Wheat production in Germany

We assume that changes in Danish grain production impact the production of wheat in the EU with remaining imbalances in protein supply being leveled out by changes in import of soybean meal. More specifically, we assume that the 'first order trade effect' will impact wheat production in the only country that has a direct land border with Denmark, namely Germany. German wheat production has been modeled with the process called 'Wheat grain {DE}| wheat production | Conseq, U' available in the ecoinvent 3 database (ecoinvent 2014).

As opposed to the modeling of the Danish cropping systems, the ecoinvent process for German wheat includes P emissions to the aquatic environment. This creates an inconsistency when Danish yield increases are assumed to replace German wheat production. Meanwhile (as mentioned in Section 3.1), the contribution of P in nutrient enrichment from German wheat is very small (<1% of the total impact) and does not influence the overall conclusions of the present study.

In the GHG tool, a GHG emission factor for wheat of 0.68 kg CO_2e/kg has been used based on a Danish wheat process from LCA Food (2003). This number is slightly higher than the ecoinvent result.

3.4.11 Indirect land use change (ILUC) from changes in Danish grain supply

As discussed above, a change in Danish crop supply is likely to impact crop production in neighboring countries. This may in turn influence crop production elsewhere and eventually lead to conversion (or abandonment) of land at the 'agricultural frontier' where agriculture meets native land (see e.g. Kløverpris et al. 2008). This effect is known as indirect land use change (ILUC) and has particularly been discussed for bioenergy, although it remains relevant for all mechanisms which influence supply and demand of agricultural products and agricultural land area.

The ILUC approach is a different way of accounting for the effect of yield changes in the present study as compared to the assumption of one-to-one replacement of German wheat and soybean meal from South America ('classical' system expansion). Since application of the two methods together would result in double counting of the 'international feed effect', we exclude ILUC from the main results of the study and discuss ILUC results separately in Section 4.2.

The ILUC theory is basically about the market response to a change in crop demand or crop supply. According to the theory, such a change leads to a change in the price of crops, which will in turn give three combined and mutually dependent responses:

1. A change in consumption of crops (lower at higher price, higher at lower price)
2. A change in crop production intensity[14] (higher at higher price, lower at lower price)

[14] Crop production intensity represents the yield (output per unit of land) as a function of the inputs to the field in terms of pesticides, fertilizers, irrigation, labor, capital, different management initiatives, etc. Since crop yields are not proportional to

3. A change (indirectly) in cropland area (higher at higher price, lower at lower price)

The first of these effects (the consumption response) has to our knowledge not been quantified in terms of environmental impacts. Schmidt et al. (2015) suggest the effect on consumption is irrelevant in the longer term because a change in crop demand or supply will eventually be met by a corresponding (one-to-one) change in crop production based on a combination of intensification and area cultivated (effects number 2 and 3 on the list above). Thereby, there would be no consumption response. In the present report, we do not consider the 'consumption aspect' explicitly.

As for the second effect (the intensity response), a higher output of Danish grain would reduce inputs to crop production elsewhere and thereby result in a lower yield (elsewhere). This effect has not been studied to the same extent as the third effect (the area effect) and, for the same reason; we do not consider it in the present study, either.

We do however consider the third effect, which is about the area indirectly brought into or taken out of production as a result of a studied change. When such land use conversions take place (e.g. conversion of forest or grassland to cropland), C is emitted to the atmosphere as a results of oxidation of below- and above-ground biomass. Since the global cropland area is still expanding, higher crop yields in Denmark can help to avoid some of this expansion. Hence, the impact of *avoided* ILUC is assumed to be 'numerically' the same as the impact of *induced* ILUC.

We estimate GHG emissions from ILUC based on a study conducted by IFPRI (the International Food Policy Research Institute) for the European Commission (Laborde 2011). The approach is further described below.

Laborde (2011) assessed ILUC emissions for different types of liquid biofuels. While Laborde (2011) looked at ILUC derived from an increase in crop *demand* (for grain-based or first generation bioethanol), the present study is generally considering an increase in crop *supply* (caused by a shift from the reference spring barley system to a higher-yielding alternative[15]). Hence, the ILUC considered in the present study is entirely related to changes in crop yields. Nevertheless, the IFPRI study by Laborde (2011) is useful because a change in crop demand translates into a price signal just as a change in crop supply does. Hence, it is a matter of the sign of the ILUC (positive or negative). By a slight modification of the IFPRI ILUC results (described in the following text), we get an indication of the ILUC emissions related to a change in either supply or demand of 1 kg of wheat.

Laborde (2011) estimated an ILUC factor of 14.4 g CO_2e/MJ for first generation bioethanol produced from wheat grain (in a 'business as usual' scenario with a 20 year time perspective). The author of the IFPRI report estimates

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the level of inputs to the field (see e.g. Kløverpris et al. 2008), the economically optimal use of inputs is determined by the crop price.

[15] System 2 (spring barley with straw removal) being the exception with a slight decrease in yield compared to the reference system

that the 90% confidence interval (CI) spans from 8.3 to 18.4 g CO_2e/MJ, i.e. -42%/+28%. This indicates the large uncertainty associated with ILUC modeling.

To implement the result in the present study, we convert to GHG emissions per kg wheat grain partly via the following factors:

- Assumed bioethanol yield: 0.33 kg ethanol per kg wheat
- Ethanol energy content: 26.9 MJ/kg ethanol

To establish a meaningful picture of wheat ILUC emissions, it is important to account for the feed co-product from 'first generation' bioethanol (so-called dried distiller's grains with solubles or DDGS). This mainly consists of the protein in the wheat. Laborde (2011) does not single out the influence of the DDGS on results so we rely on another ILUC study by Hertel et al. (2010). In this study, the authors estimate that the ILUC emissions of maize grain ethanol would have been 112% higher without the DDGS co-product. On this basis, we estimate ILUC emissions related to European wheat as follows:

Wheat ILUC factor: $14.4\ g\ CO_2e/MJ \cdot 26.9\ MJ/kg \cdot 0.33\ kg/kg \cdot (1+112\%) = 271\ g\ CO_2e/kg$

We have used this number for modeling wheat ILUC emissions in the present LCA. We assume that the previously mentioned 90% CI (-42%/+28%) is also relevant for the wheat ILUC factor, which illustrates the relatively high uncertainty associated with this number.

While the ILUC approach does involve a high degree of uncertainty, we note that all systems in our analysis are treated equally in our assessment of implications of changes in yield production per hectare of Danish agricultural land.

3.4.12 Production of soybean meal in South America

It is assumed that a change in Danish crop production will impact wheat production and protein production elsewhere. As for the protein part, we assume that Danish imports of soybean meal from South America will be affected. We recognize that the nutritional value of cereal protein and soy protein may differ but in the present LCA study we assume a one-to-one replacement. Soybean meal has been modeled based on data documented by Schmidt (2015).

Soybean meal is co-produced with soy bean *oil*. The meal portion is assumed to be the 'driving process', i.e. it is the demand for soybean *meal*, which determines the production of soybean *oil*. If Danish import of soybean meal is then reduced, it will also result in a reduction in soybean *oil* production. This will in turn result in a drop in the global supply of vegetable oil, which is likely to be 'filled up' by the marginal supply of vegetable oil, primarily assumed to come from Southeast-Asian palm oil. On this basis, avoided use of soybean meal leads to reduced production of soybean oil, which in turn leads to increased production of palm oil. Since palm oil production and expansion is assumed to be associated with substantial land use change (GHG) emissions, ecoinvent 3 actually suggests that a reduction in the use of soybean meal leads to an increase in GHG emissions (due to the link to Southeast-Asian palm oil production). While the linkages between soy and palm oil are generally acknowledged, there is some skepticism towards the data in ecoinvent 3. For instance, the Danish '2.-0 LCA Consultants' recommend another dataset published by Schmidt (2015). However, we apply the ecoinvent process, mainly because the issue has no vital impact on our conclusions. Thus changes in soybean meal production are very small compared to changes in German wheat production (cf. Table 3). The modeled changes in international feed production (wheat grain and soybean meal) generally show a decrease in GHG emissions as a result of a higher Danish crop supply as would intuitively be expected.

3.4.13 Replacement of gasoline

The replacement of gasoline with straw-based ethanol involves three elements of importance for the present LCA:

1. Avoided upstream gasoline emissions
2. Induced upstream ethanol emissions
3. Impact on engine exhaust emissions when ethanol is added to gasoline

As for avoided upstream GHG emissions from gasoline (part of item 1 on the list above), we rely on the 'fossil fuel comparator' from EU's Renewable Energy Directive (RED), which covers both upstream emissions and combustion emissions. The directive states that the GHG reference for biofuel comparisons '*shall be the latest available actual average emissions from the fossil part of petrol and diesel consumed in the Community*' and '*If no such data are available, the value used shall be 83.8 g CO_2e/MJ*'. This value is substantially smaller than many other 'fossil fuel comparators' and it is not specified how this value was derived. Besides, it is an average value and thereby not consistent with the consequential LCA approach. Nevertheless, we use this value in order to make a conservative assessment of the cropping systems with straw removal, i.e. an assessment that understates rather than overstates the climate benefits of using straw for cellulosic ethanol production.

For comparison, Ecofys (2014) recommended using a GHG value for marginal gasoline of 115 g CO_2e/MJ, i.e. 37% higher than the RED value (83.8 g CO_2e/MJ). This was based on a scrutiny of oil market mechanisms, including the role of OPEC. Ecofys (2014) found that the longer-term marginal supply of crude oil will come from unconventional sources.

As for avoided upstream eutrophication from gasoline (also part of item 1 on the list above), we rely on a gasoline process in the ecoinvent 3 database (ecoinvent 2014). In the present LCA, we model the contribution to eutrophication from this process (per liter of gasoline). We ignore transport of gasoline, which can be considered conservative (not favoring bioethanol production).

As for avoided upstream ethanol emissions (item 2 on the list above), this is all covered by other processes in the LCA (Daisy modeling of field emissions, transport of straw, etc.).

As for the impact on engine exhaust emissions when ethanol is added to gasoline (item 3 on the list above), we also rely on EU's RED fossil fuel comparator for the GHG part (also covering combustion emissions). For the eutrophication impact category, we apply the following approach to assess the impacts on exhaust emissions when adding ethanol to gasoline in the lower blending range (roughly 0-10%).

Based on inventory data from the ecoinvent (2) database, we focused on exhaust emissions related to the nutrient enrichment (eutrophication) impact category[16]. This boils down to NO_x and ammonia. To estimate the impacts on these emissions, we compared exhaust emissions from driving 1 km in a passenger car with pure gasoline ('E0') and gasoline with 5% ethanol blended in ('E5'). We used the following processes from the ecoinvent2 database:

- E0: 1 km Operation, passenger car, petrol, EURO3/CH U
- E5: 1 km Operation, passenger car, ethanol 5%/CH U

Both processes use the same engine technology (EURO3). The differences in operation (exhaust) emissions (when shifting from E0 to E5) are as follows:

- Ammonia: -7.14 mg/km (-2.50 mg PO_4^{3-} equivalents)
- NO_x: 7.10 mg/km (0.92m g PO_4^{3-} equivalents)

Thus, NO_x emissions will increase while emissions of ammonia will decrease when blending in ethanol in the 0-5% range. We convert this to change in emissions per gram of ethanol (3.35 gram ethanol per km in the E5 blend):

- Ammonia: -2.13 mg/g eth. (-0.75 mg PO_4^{3-} equivalents)
- NO_x: 2.12 mg/g eth. (0.28 mg PO_4^{3-} equivalents)

3.35 g ethanol corresponds to 2.21 g gasoline (based on energy content). Thereby, above results can also be expressed per g of gasoline replaced (with ethanol):

- Ammonia: -3.23 mg/g gasoline equivalent
- NO_x: 3.21 mg/g gasoline equivalent

[16] Note that gases affecting global warming (the other impact category considered in the present LCA) are covered by the RED/Ecofys data discussed previously in this section

We use the data above to model the impact from blending ethanol into gasoline. Note that when converting to PO_4^{3-} equivalents (the metric for eutrophication in the applied CML impact assessment method), the impact from blending in ethanol is a reduction in the contribution to nutrient enrichment of 0.47 g PO_4^{3-} equivalents per gram ethanol. We stress that this is only an indication and that further analysis would be required to develop a more robust estimate. Table 5 summarizes our modeling of gasoline replacement.

Table 5. Modeling of 1 liter gasoline replaced with ethanol (excl. upstream ethanol emissions)

Emissions	Quantity	Unit	Comments
Avoided upstream eutrophication emissions	-0.37	g PO_4^{3-}e	Based on ei3
Avoided GHG emissions (upstream and combustion)	-2.69	kg CO_2e	Based on EU RED
Change in ammonia combustion emissions	-2.40	g	Derived from ei2
Change in NO_x combustion emissions	2.39	g	Derived from ei2

3.4.14 Natural gas production and combustion

To model (avoided) production and combustion of natural gas, we combine two data sources. For production and upstream processes, we rely on the ecoinvent process 'Natural gas, high pressure {DK}| market for | Conseq, U). This process does not include combustion of the gas. We therefore convert m^3 natural gas to GHG emissions by an assumed energy density of 38.5 MJ/m^3 and an assumed emission factor of 51 g CO_2/MJ. We add these GHG emissions to the ecoinvent process for natural gas production. We assume that combustion of RE gas instead of natural gas will not have any impact on eutrophication emissions. Note that this assumption only applies to the combustion (not production and other upstream processes).

3.4.15 Electricity replaced on the Danish grid

All scenarios with straw removal for biorefining include net production of electricity at the biorefinery. This bioelectricity replaces electricity on the grid. Determining the origin of the replaced electricity can be challenging and depends on perspective. Denmark has a political target to be free of fossil fuels by 2050. Denmark is therefore phasing out fossil fuels in the electricity sector and phasing in renewables, mainly wind but also solar energy. According to a study by '2.-0 LCA Consultants' (Muñoz et al. 2015), future marginal electricity in Denmark will therefore entirely be made up of renewables (mainly wind). In this perspective, electricity exports from a biorefinery will simply reduce the need for future installation of wind power capacity. Meanwhile, the only reason why Denmark can (presumably) phase out fossil energy is the renewable technologies (and energy savings). In this perspective, bioelectricity and wind electricity (as well as solar and other renewables) should be ascribed a credit for reduced fossil electricity production. The two perspectives above (marginal electricity is fully renewable or marginal electricity is fully fossil) are also summarized by Energistyrelsen (2014, Section 5.5, subsection 3). The two perspectives result in different conclusions. We explore both options and also a third one where electricity from the biorefinery is assumed to replace average electricity on the Danish grid. For our main analysis, we will assume that future marginal electricity on the Danish grid is fully renewable. Note that this is a conservative approach (in the sense that it does not favor use of straw in a biorefinery). The three electricity scenarios are listed in Table 6.

Table 6. Danish electricity scenarios

Scenario	Electricity mix	Data source
Renewable	81% wind, 13% solar, 5% biomass	Muñoz et al. (2015)
Fossil	100% coal	Muñoz et al. (2015)
Average	36% coal, 28% imports, 15% wind, 14% nat. gas, 4% biomass, 3% other	Ecoinvent (2014)

Note that in the 'fossil electricity scenario', we assume that bioelectricity replaces electricity fully based on coal. This is to consider an extreme scenario (the opposite of the 'renewable' extreme). Meanwhile, part of the lignin from the biorefinery could actually be used as a direct substitute for coal in some power plants (cf. Section 3.4.7). Hence, coal substitution is not completely unrealistic.

4 Impact assessment

This chapter presents results for the two selected impact categories (global warming and nutrient enrichment/eutrophication). Unless otherwise stated, results are based on the renewable marginal electricity scenario.

4.1 Global warming

Figure 5 presents GHG emissions (level 2) for the reference scenario with SOC changes and ILUC emissions annualized[17] over 20 years.

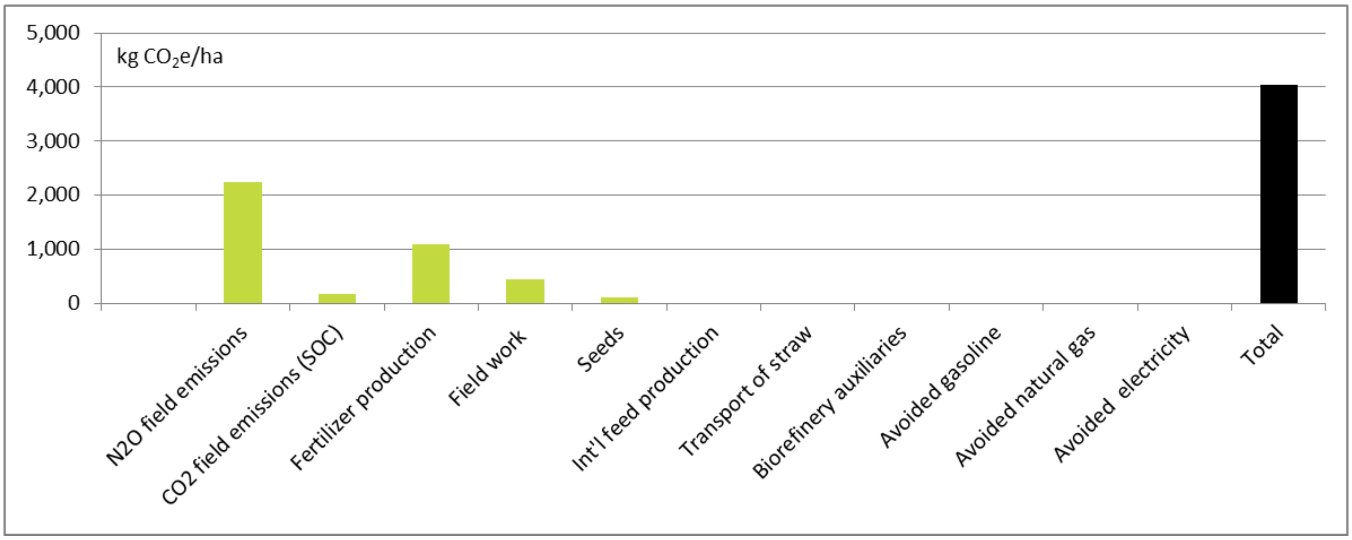

Figure 5. System 1 (reference system; spring barley with catch crop and 100 % straw incorporation): GHG emissions (GWP100) presented per hectare (level 2) with changes in soil organic carbon (SOC) annualized over 20 years

The reference system shows a total emission of 4,000 kg CO_2e/ha. With an output of 6.9 Mg/ha of spring barley grain (Table 3), the GHG emission corresponds to 590 kg CO_2e/Mg spring barley [4,000 kg CO_2e/6.9 Mg spring barley].

System 2 is similar to system 1 except that 50% straw is removed and used for production of bioenergy (ethanol, power, and renewable energy gas) and biofertilizers. The bioenergy and biofertilizers are considered co-products of the grain production. Hence, a GHG credit is assigned to the grain based on the GHG savings obtained when the co-products replace other products in the market (e.g. when ethanol is replacing gasoline). Results are shown in Figure 6.

[17] Average annual emission calculated based on total emissions over the relevant time period

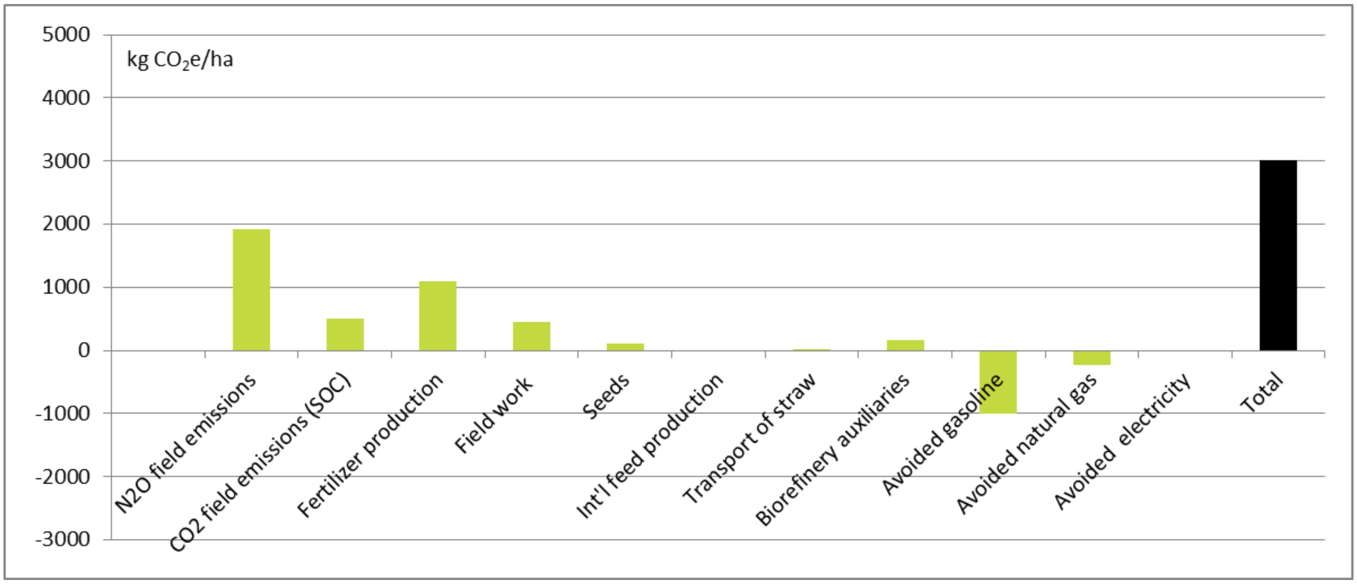

Figure 6. System 2 (spring barley with catch crop and 50% straw removed): GHG emissions (GWP100) presented per hectare (level 2) with changes in SOC annualized over 20 years

Due to the straw removal in system 2, there is a slight reduction in yield of roughly 0.2% (see Table 2 and Table 3). With the methodology applied in the present LCA, this means that there is a slight increase in feed production elsewhere with related GHG emissions. In Figure 6, this is shown as 'Int'l feed production'. Because of the small change in grain yield compared to the reference system this change remains insignificant whereas the use of straw for energy purposes is important. Straw removal reduces SOC (Table 2) which (seen in isolation) leads to higher GHG emissions from the field. However, straw removal also reduces N_2O emissions due to the removal of N and easily degradable straw C from the system. The net effect in a 20 year perspective is slightly higher field GHG emissions in system 2 as compared to system 1.

In a 100 year perspective, however, the reduction in N_2O emissions (as measured in CO_2 equivalents) exceeds the increase in CO_2 emissions from changes in SOC and system 2 benefits from the replacement of gasoline, natural gas, and marginal electricity on the grid. Assuming marginal electricity to be fully renewable in the future, the benefit from bioelectricity production is small. Despite of this, system 2 emerges as more climate-friendly than system 1. The GHG emissions per Mg of spring barley grain (functional unit at level 3) become 440 kg CO_2e/Mg spring barley, i.e. 26% lower than the reference system. We arrive at this number by dividing the total emissions (3,000 kg CO_2e; see Figure 6) with 6.9 Mg spring barley equivalents because all systems provide the same amount of feed as the reference system (Table 3).

Figure 7 shows GHG results for winter wheat with 100% straw incorporation (system 3). Because of a higher application of N fertilizer and incorporation of all straw, the N_2O field emissions are now higher. The most remarkable changes compared to the reference system are the negative CO_2 field emissions (sequestration of C in the soil as opposed to oxidation of SOC in the reference system) and a substantial credit for displacement of international feed production. The latter is explained by the significant yield increase obtained when shifting from spring barley (the reference system) to winter wheat (cf. Table 2 and Table 3).

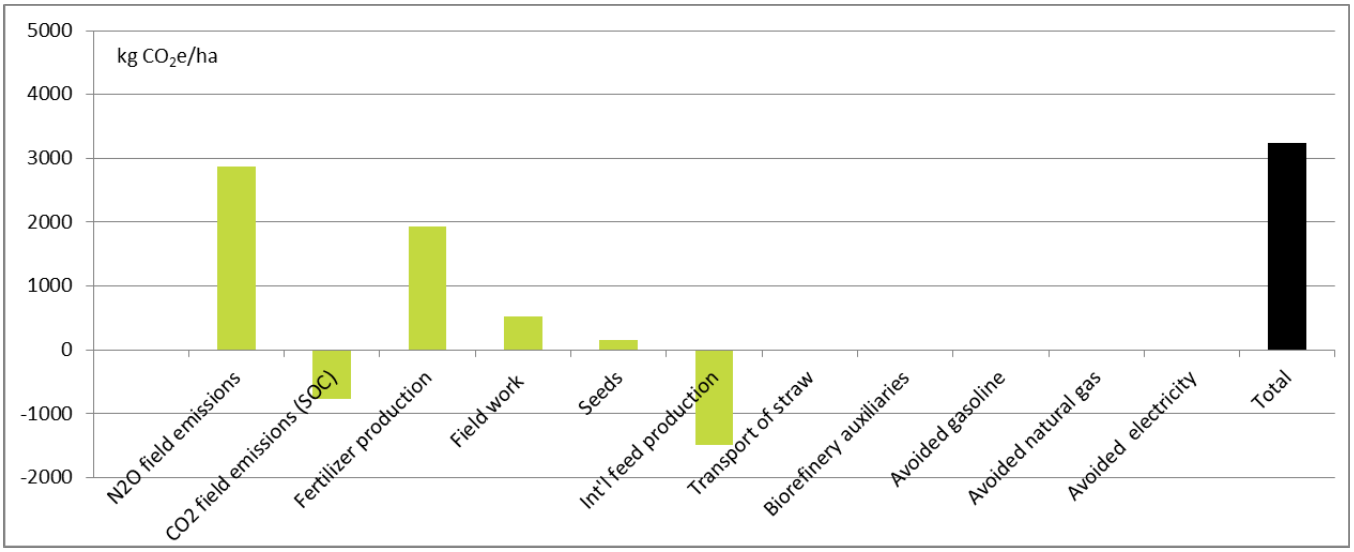

Figure 7. System 3 (winter wheat with 100% straw incorporation): GHG emissions (GWP100) presented per hectare (level 2) with SOC changes annualized over 20 years.

The GHG emissions in system 3 amount to 470 kg CO_2e/Mg spring barley equivalent [3,200 kg CO_2e/6.9 Mg spring barley]. This is 20% less than in the reference system.

Figure 8 shows results for winter wheat with 50% straw removal (system 4). Compared to system 3, SOC is reduced due to straw removal but, on the other hand, N_2O emissions to the atmosphere are also reduced. In addition there is a benefit from international feed replacement (as in system 3) and from avoided fossil fuels (as in system 2).

All in all, the GHG emissions from system 4 amount to roughly 270 kg CO_2e/kg spring barley equivalent [1,900 kg CO_2e/6.9 Mg spring barley]. This is 54% less than in the reference system.

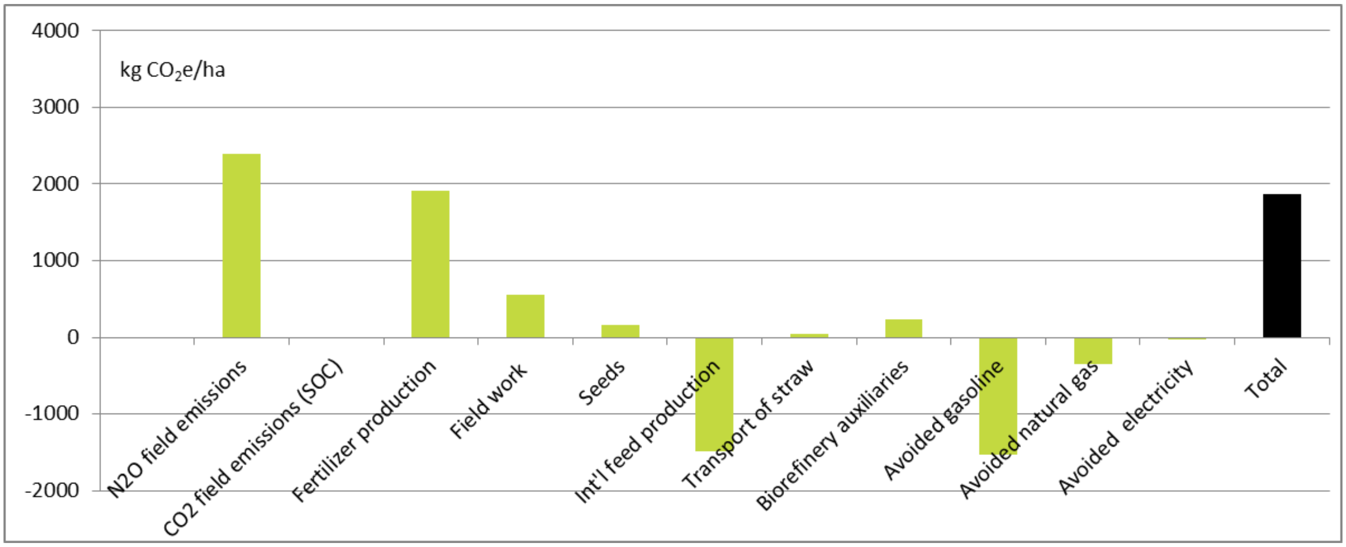

Figure 8. System 4 (winter wheat with 50% straw removal): GHG emissions (GWP100) presented per hectare (level 2) with SOC changes annualized over 20 years.

Figure 9 shows GHG results for early seeded winter wheat with 50% straw utilization. Due to a higher yield than in the other winter wheat systems, N_2O emissions are further reduced (less N available for denitrification in the soil), international feed production is further reduced, and more fossil fuels are avoided (due to higher yield of straw).

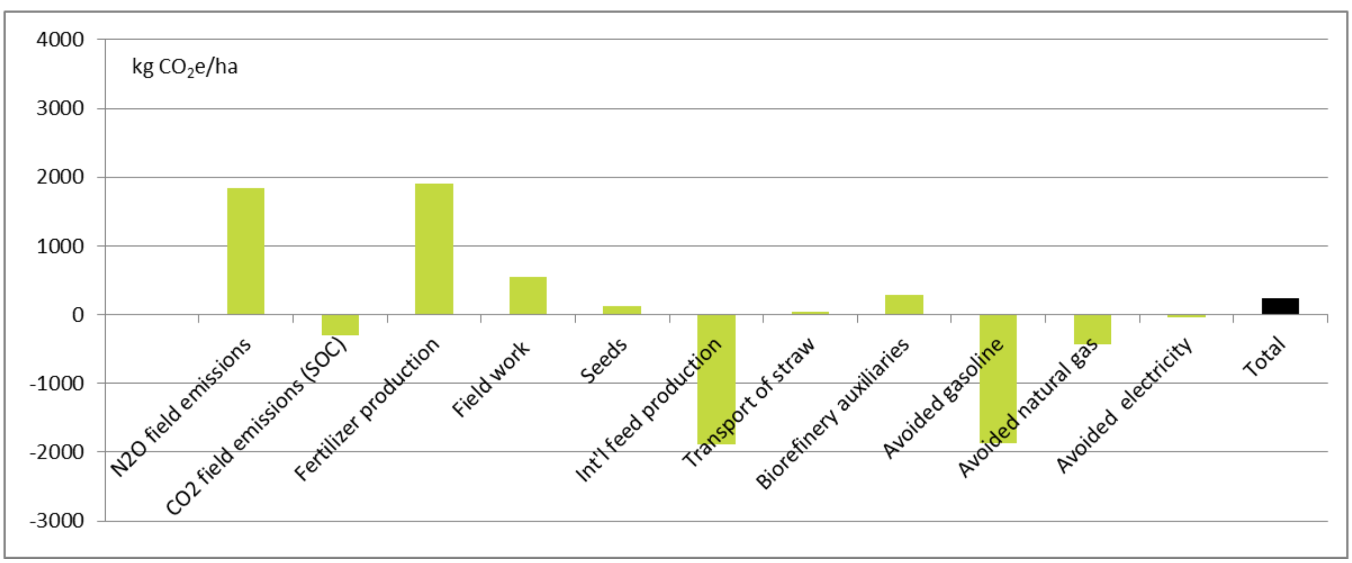

Figure 9. System 5 (early seeded winter wheat with 50% straw incorporation): GHG emissions (GWP100) presented per hectare (level 2) with SOC changes annualized over 20 years.

The total GHG emissions from system 5 amount to only 35 kg CO_2e/Mg spring barley equivalent [240 kg CO_2e/6.9 Mg spring barley]. This is 94% less than in the reference system.

Figure 10 shows GHG results for winter wheat with 50% straw utilization and intercropping with oilseed radish (same as system 4, except for the oilseed radish). When comparing to system 4 (Figure 8), the intercropping of oilseed radish is to some extent mitigating the reduction in SOC resulting from straw removal. However, the intercropping cannot fully compensate for the loss of SOC, which is apparent when comparing to system 3 (Figure 7). The root mass of oilseed radish may have been underestimated in the Daisy modeling leading to an underestimated SOC accumulation and the GHG results should be interpreted with this in mind. Because of a short growing season, the oilseed radish may not be able to fully compensate for loss of SOC caused by the removal of 50% straw.

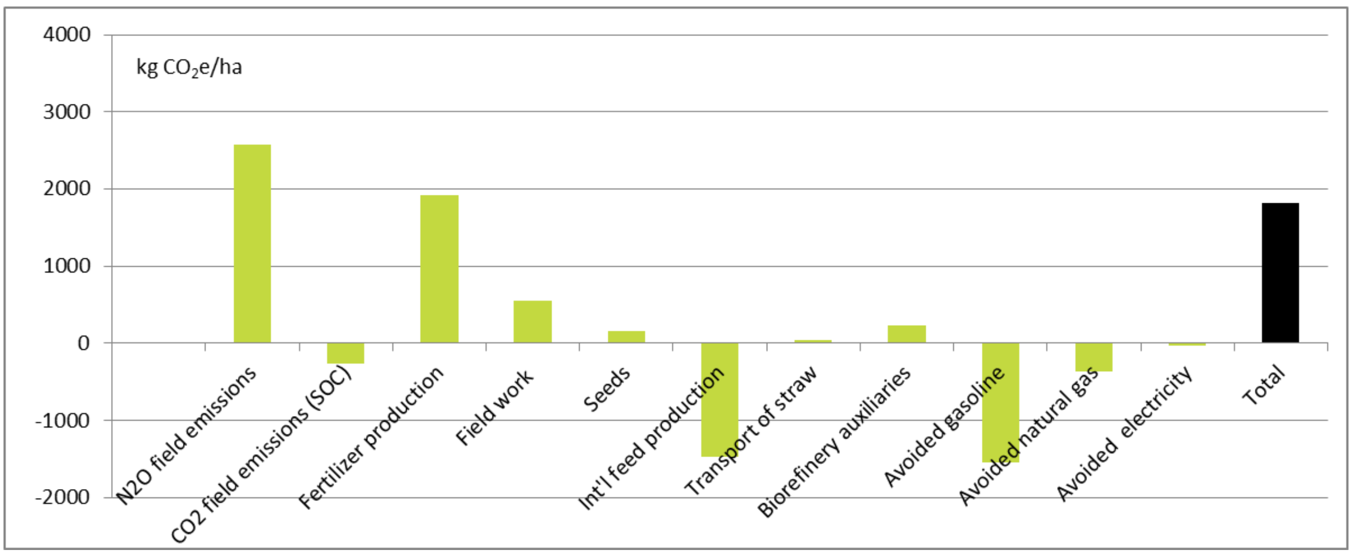

Figure 10. System 6 (winter wheat with 50% straw removal and intercropping of oilseed radish): GHG emissions (GWP100) presented per hectare (level 2) with SOC changes annualized over 20 years.

The GHG emissions from system 6 are 270 kg CO_2e/Mg spring barley equivalent [~1800 kg CO_2e/6.9 Mg spring barley]. This is 55% less than in the reference system.Table 7 summarizes the GHG results shown in the previous figures.

Table 7. GHG results assuming renewable marginal electricity and annualizing LUC emissions over 20 years (errors due to rounding)

	Systems and main crops (kg CO_2e/ha)					
	1: SB[a]	2: SB[b]	3: WW[c]	4: WW[d]	5: WW[e]	6: WW[f]
N_2O field emissions	2,200	1,900	2,900	2,400	1,800	2,600
CO_2 field emissions (SOC)	180	510	-770	-12	-300	-270
Fertilizer production	1,100	1,100	1,900	1,900	1,900	1,900
Field work	440	460	530	550	550	560
Seeds	100	100	160	160	130	170
Int'l feed production (incl. ILUC)	0	-3	-1,500	-1,500	-1,900	-1,500
Transport of straw and enzymes	0	26	0	40	48	40
Biorefinery auxiliaries	0	150	0	240	290	240
Avoided gasoline	0	-1,000	0	-1,500	-1,900	-1,500
Avoided natural gas	0	-230	0	-360	-430	-360
Avoided electricity	0	-23	0	-35	-43	-35
Total	4,000	3,000	3,200	1,900	240	1,800

[a] Spring barley with oilseed radish as catch crop and 100% straw incorporation (reference system)
[b] Spring barley with oilseed radish as catch crop and 50% straw utilized in biorefinery
[c] Winter wheat with 100% straw incorporation (normal seeding)
[d] Winter wheat with 50% straw utilized in biorefinery (normal seeding)
[e] Winter wheat sown early and with 50% straw utilized in biorefinery
[f] Winter wheat with intercropping of oilseed radish and 50% straw utilized in biorefinery (normal sowing time)

Table 8 summarizes the GHG results (level 2) for land use emissions in a 20 and 100 year perspective, and implications of different assumptions regarding marginal Danish electricity. Assumptions regarding Danish marginal electricity have little influence on most reference flows, i.e. the category 'Other' (reflecting all GHG emissions, except from changes in SOC and avoided Danish electricity) is more or less constant for each system. The reason is that most reference flows (e.g. fertilizers) are modeled based on 'global market processes', which are unaffected by assumptions regarding marginal Danish electricity (cf. Section 3.4).
The results shown in

Table 8 have also been depicted in Figure 11. When emissions from changes in soil organic carbon (ΔSOC) are averaged over 100 years (thereby having less weight), the total emissions from system 1 (spring barley) and 3 (winter wheat) with 100% straw incorporation are not so different. System 3 obtains a credit for avoided international feed production (see

Table 8) but the higher yields come at the expense of higher N fertilizers and seed rates (
Table 2). Therefore, these two systems end up with almost similar GHG performance in a 100 year perspective. Interestingly, if the international feed aspect is excluded (no GHG credit assigned for higher crop yields), system 3 performs much worse than the reference system (system 1) in terms of GHG emissions.

Table 8. GHG results for different assumptions regarding marginal electricity and different LUC time perspectives (errors due to rounding)

Avoided DK power	LUC[g] time horizon	Breakdown	Systems and main crops (kg CO_2e/ha)					
			1: SB[a]	2: SB[b]	3: WW[c]	4: WW[d]	5: WW[e]	6: WW[f]
Renewable	20 y avg.	CO_2 from field	180	510	-770	-12	-300	-270
		Avoided DK power	0	-23	0	-35	-43	-35
		Other	3,900	2,500	4,000	1,900	580	2,100
		Total	4,000	3,000	3,200	1,900	240	1,800
	100 y avg.	CO_2 from field	120	380	-310	92	-190	-29
		Avoided DK power	0	-23	0	-35	-43	-35
		Other	3,900	2,500	4,000	1,900	580	2,100
		Total	4,000	2,900	3,700	2,000	350	2,100
Coal-based	20 y avg.	CO_2 from field	180	510	-770	-12	-300	-270
		Avoided DK power	0	-520	0	-790	-970	-800
		Other	3,900	2,600	3,900	1,800	460	2,000
		Total	4,100	2,600	3,100	1,000	-800	970
	100 y avg.	CO_2 from field	120	380	-310	92	-190	-29
		Avoided DK power	0	-520	0	-790	-970	-800
		Other	3,900	2,600	3,900	1,800	460	2,000
		Total	4,000	2,400	3,600	1,100	-700	1,200
Average grid mix	20 y avg.	CO_2 from field	180	510	-770	-12	-300	-270
		Avoided DK power	0	-260	0	-390	-480	-390
		Other	3,900	2,500	3,900	1,800	490	2,100
		Total	4,100	2,800	3,100	1,400	-290	1,400
	100 y avg.	CO_2 from field	120	380	-310	92	-190	-29
		Avoided DK power	0	-260	0	-390	-480	-390
		Other	3,900	2,500	3,900	1,800	490	2,100
		Total	4,000	2,700	3,600	1,500	-180	1,600

[a] Spring barley with oilseed radish as catch crop and 100% straw incorporation (reference system)
[b] Spring barley with oilseed radish as catch crop and 50% straw utilized in biorefinery
[c] Winter wheat with 100% straw incorporation (normal seeding)
[d] Winter wheat with 50% straw utilized in biorefinery (normal seeding)
[e] Winter wheat with early seeding and 50% straw utilized in biorefinery
[f] Winter wheat with intercropping of oilseed radish and 50% straw utilized in biorefinery (normal seeding)
[g] LUC (land use change) covers changes in soil organic carbon

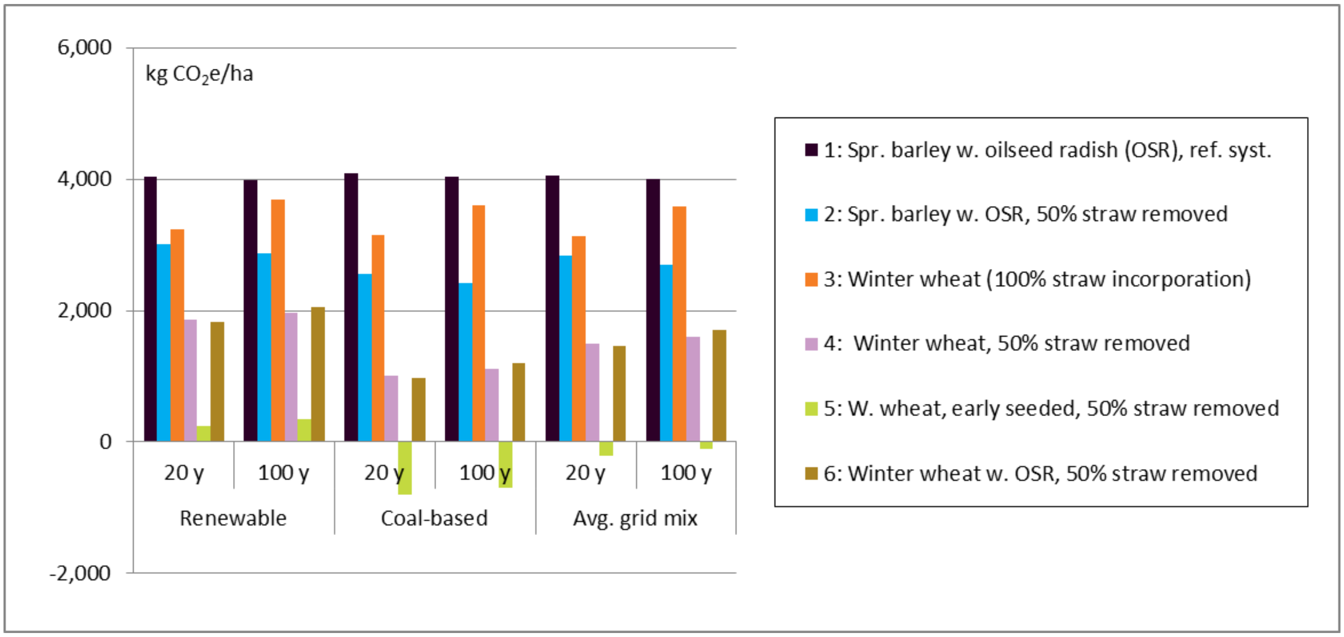

Figure 11. GHG results for different assumptions regarding marginal electricity and different LUC time perspectives (20 and 100 years).

Figure 11 also shows that system 4 and 6 has almost similar GHG performance, regardless of time perspective and assumptions about marginal electricity. Both systems grow winter wheat as the main crop with 50% straw removed for biorefining but system 6 includes intercropping with oilseed radish. The oilseed radish provides a GHG advantage in terms of soil C sequestration (Table 7). However, oilseed radish retains more N in the soil (reduced N leaching) and provides crop residues with easily degradable C, leading to higher simulated N_2O field emissions. In terms of GHG emissions, the higher N_2O emission is almost counterbalanced by increased SOC storage.

The systems with straw utilization for bioenergy generally perform better than the systems without straw removal. Moreover, the wheat systems perform better than the barley due to higher yields and higher soil C retention (more pronounced in the 20 year perspective than the 100 year perspective, cf. Table 8).

The best performing system in terms of global warming regardless of time perspective and assumptions about marginal electricity is system 5 (early sown winter wheat with 50% straw removal for biorefinery utilization). If marginal Danish electricity is derived from coal, system 5 shows negative emissions (see Table 8 and Figure 11). This is also the case if bioelectricity is assumed to replace average Danish electricity. This means that not only does one hectare of early seeded winter wheat provide the same amount of feed as one hectare of spring barley. It also produces additional feed to replace international feed production and renewable fuels (from straw) to replace fossil fuel that is enough to more than offset the GHG emissions from the field and from upstream inputs (fertilizers, etc.).

Finally, we note that all systems with straw removal benefit from a substantial GHG credit (from replacement of gasoline, natural gas, and Danish grid electricity). In that sense, using straw for biorefining substantially reduces the GHG emissions from Danish feed production and thereby from Danish livestock production. The bioethanol results will be explored further in Section 4.4.

The results per Mg barley equivalent (level 3) are summarized in Table 9.

Table 9. GHG results (kg CO_2e) presented per Mg spring barley equivalent (85% dry matter)

Marginal DK power	LUC time perspective	Systems and main crops[a] 5: WW	2: SB	3: WW	4: WW	5: WW	6: WW
Renewable	20 y	590	440	470	270	35	270
	100 y	580	420	540	290	51	300
Coal-based	20 y	590	370	460	150	-120	140
	100 y	590	350	520	160	-100	180
Average grid mix	20 y	590	410	460	210	-42	200
	100 y	580	390	520	220	-26	240

[a] See footnotes in Table 8

4.2 GHG results with indirect land use change (ILUC)

As discussed in Section 3.4.11, the consequence of an increase in Danish grain supply is likely to be a change in crop production intensity and land use elsewhere – and potentially also a change in consumption in the short to medium term. As also mentioned , we consider the implications of indirect land use change (in this case, avoided land use conversion due to increased Danish grain yields) but cannot factor in the climate implications of an indirect change in crop production intensity – and potentially crop consumption. As already discussed, it would be double-counting to assume that increased Danish grain production would result in a one-to-one replacement of German wheat and, in addition, avoided land use change elsewhere. In Table 10, we therefore replace the impacts from German wheat with the estimated indirect land use change.

Table 10. GHG results (kg CO_2e) presented per Mg spring barley equivalent (85% dry matter)

Marginal DK power	LUC time perspective	Systems and main crops[a] 1: SB	2: SB	3: WW	4: WW	5: WW	6: WW
Renewable	20 y	590	440	570	380	170	370
	100 y	580	420	730	480	300	490
Coal-based	20 y	590	370	580	270	43	270
	100 y	590	350	740	380	170	390
Average grid mix	20 y	590	410	570	330	110	320
	100 y	580	390	730	430	240	440

[a] See footnotes in Table 8.

The GHG results in Table 10 have also been depicted in Figure 12. The main change (as compared to Figure 11) is that yield increases give a slightly smaller GHG credit with the ILUC approach (as compared to assuming direct one-to-one replacement of feed production elsewhere). This specifically has an impact when land use change emissions are annualized over 100 years instead of 20 years (thereby reducing the ILUC emissions to one-fifth as compared to a 20 year horizon). With this reduced 'yield increase credit', the high-yielding wheat systems perform relatively worse (especially in a 100 year perspective). Besides that, the conclusions remain more or less unchanged. System 5 (with early seeding of winter wheat) performs best, system 4 and 6 come next (roughly equaled by system 2 in a 100 year perspective with replacement of average or coal-based electricity) and then system 2. System 1 and 3 (respectively barley with oilseed radish and winter wheat, both with 100% straw incorporation) have the highest emissions, roughly equal in the 20 year perspective and highest for winter wheat (system 3) in the 100 year perspective (due to the reduced GHG credit for yield increase).

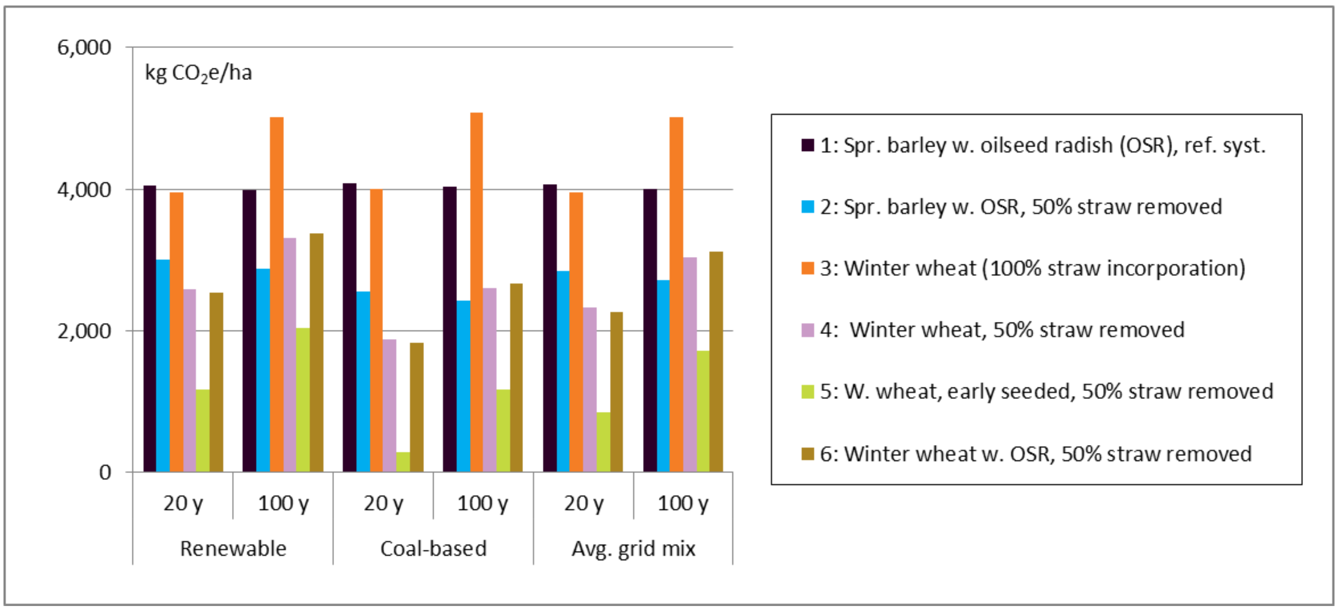

Figure 12. GHG results for different assumptions regarding marginal electricity and different LUC time perspectives (20 and 100 years) when changes in Danish grain production are assumed to cause indirect land use change.

4.3 Nutrient enrichment/Eutrophication

While losses of N to the aquatic environment may vary from year to year, the annual average is more or less constant over longer time periods (as opposed to the emissions of CO_2 from changes in SOC). Hence, nutrient enrichment results are not presented for multiple time perspectives but just based on annual averages (which is standard procedure in LCA). Results are summarized in Table 11.

Table 11. Eutrophication results assuming renewable marginal electricity

	Systems and main crops (kg PO_4^{3-}e/ha)[a]					
Breakdown	1: SB	2: SB	3: WW	4: WW	5: WW	6: WW
N field emissions	11.2	11.4	17.2	17.3	12.5	15.4
Fertilizer production	3.1	3.2	5.0	5.0	5.0	5.0
Field work	0.6	0.7	0.8	0.8	0.8	0.8
Seeds	1.2	1.2	1.5	1.5	1.2	1.6
Int'l feed production	0.0	0.0	-11.3	-11.4	-14.1	-11.3
Transport of straw	0.0	0.1	0.0	0.1	0.1	0.1
Biorefinery auxiliaries	0.0	1.1	0.0	1.7	2.0	1.7
Avoided gasoline	0.0	-0.3	0.0	-0.5	-0.6	-0.5
Avoided natural gas	0.0	-0.1	0.0	-0.1	-0.2	-0.1
Avoided electricity	0.0	-0.3	0.0	-0.4	-0.5	-0.4
Total	16.1	17.0	13.2	13.9	6.3	12.2

[a] See footnotes in Table 8.

The main source of nutrient enrichment in the reference system (system 1) is leaching and loss through the drains of N to the aquatic environment (cf. 'Output' in Table 2). This contribution designated as 'N field emissions' in Table 11 makes up more than 80% of the nutrient enrichment. The remaining part comes from N_2O emissions, which lead to atmospheric N deposition. The production of fertilizers (especially N fertilizers) also contributes to eutrophication through emissions to air, e.g. ammonia and nitrogen oxides (Table 11).

Considering winter wheat systems (system 3-6 in Table 11), it is clear that displaced international feed production also plays an important role. Keep in mind that the results for international feed production in Table 11 not only include field emissions but also all upstream emissions (fertilizer production, field work, etc.).

The transport of straw, the biorefinery auxiliaries, and the combustion of lignin also contribute significantly to eutrophication. Meanwhile, this is more than outbalanced by the resulting replacement of gasoline, natural gas, and grid electricity (even with the conservative assumption of renewable electricity replacement). Despite of this, the barley system with 50% straw removal (system 2) has a slightly higher contribution to eutrophication than the reference system (system 1). There are a number of reasons for this. First of all, the Daisy model predicts slightly higher N loss for system 2 as compared to system 1. The reason for this is that straw incorporation immobilizes N which is accumulated in the soil as organic N, which is not immediately prone to leaching. The difference is rather small however. Secondly, a little more P and K fertilizer is required in system 2 to compensate for straw removal (cf. Section 3.1). Furthermore, the application of biofertilizer in system 2 has a number of benefits (return of nutrients to the soil and thereby replacement of chemical fertilizers and savings of fossil fuel and resources) but it also increases nitrogen emissions slightly (cf. Section 3.4.8), i.e. there is a trade-off.

Table 12 shows the implications of changing the assumptions about which kind of electricity is replaced by the produced bioelectricity. As shown, all systems have lower contributions to eutrophication than the reference system if the bioelectricity is assumed to replace average or coal-based electricity. All the wheat systems (3-6) also have lower contributions to eutrophication if replaced electricity is assumed to be renewable. Thereby, system 2 (with assumed replacement of renewable electricity) is the only system where an increase in the contribution to eutrophication is observed.

Table 12. Eutrophication results for different assumptions regarding marginal electricity (level 2)

Marginal DK power	Breakdown	Systems and main crops (kg PO_4^{3-}e/ha)[a] 1: SB	2: SB	3: WW	4: WW	5: WW	6: WW
Renewable	N from field	11.2	11.4	17.2	17.3	12.5	15.4
	Fertilizers	3.1	3.2	5.0	5.0	5.0	5.0
	Int'l feed prod.	0.0	0.0	-11.3	-11.4	-14.1	-11.3
	Avoided DK power	0.0	-0.3	0.0	-0.4	-0.5	-0.4
	Other	1.8	2.6	2.3	3.5	3.4	3.6
	Total	16.1	17.0	13.2	13.9	6.3	12.2
Coal-based	N from field	11.2	11.4	17.2	17.3	12.5	15.4
	Fertilizers	3.2	3.3	5.1	5.2	5.2	5.2
	Int'l feed prod.	0.0	0.0	-11.9	-11.9	-14.7	-11.9
	Avoided DK power	0.0	-0.8	0.0	-1.2	-1.5	-1.2
	Other	1.9	2.6	2.3	3.5	3.4	3.6
	Total	16.2	16.6	12.7	12.7	4.8	11.0
Average grid mix	N from field	11.2	11.4	17.2	17.3	12.5	15.4
	Fertilizers	3.1	3.4	5.0	5.1	5.1	5.1
	Int'l feed prod.	0.0	0.0	-11.8	-11.8	-14.6	-11.7
	Avoided DK power	0.0	-1.3	0.0	-2.0	-2.4	-2.0
	Other	1.9	2.3	2.3	3.1	2.9	3.2
	Total	16.1	15.8	12.7	11.6	3.4	9.9

[a] See footnotes in Table 8

Finally, we present nutrient enrichment results per Mg spring barley equivalent (level 3) in Table 13.

Table 13. Eutrophication results for different assumptions regarding marginal electricity (level 3)

Marginal DK power	Systems and main crops (kg PO_4^{3-}e/Mg spring barley equivalent)[a] 1: SB	2: SB	3: WW	4: WW	5: WW	6: WW
Renewable	2.3	2.5	1.9	2.0	0.9	1.8
Coal-based	2.4	2.4	1.8	1.8	0.7	1.6
Average grid mix	2.3	2.3	1.9	1.7	0.5	1.4

[a] See footnotes in Table 8.

4.4 Bioethanol results

The previous analysis has compared cereal cropping systems with feed grain as the main output. In some of the systems, straw has been utilized to produce a range of products, which can replace gasoline, natural gas, electricity, and chemical fertilizers. These benefits were ascribed to the feed (as 'GHG credits' reflecting the replaced products) as it is standard procedure (system expansion) in consequential LCA.

In the present section, we consider the impacts of producing bioethanol from straw. We do so by comparing systems with full straw incorporation to systems (with the same type of crop) with 50% of the straw removed for ethanol production. That allows us to isolate the effects of the straw removal and its subsequent use for energy purposes. We consider ethanol as the main product and, hence, the co-production of biogas and bioelectricity (and the resulting replacement of natural gas and grid electricity) is assigned to the ethanol as 'co-product credits' (in line with the consequential system expansion methodology). In this analysis, the functional unit is 1 MJ of liquid transportation fuel. Note that any changes in the output of feed grain are still included by considering the impact on international feed production although these effects are almost negligible for the systems compared (because they have almost identical yields).

We make the following comparisons:

- System 2 vs. system 1: Ethanol from spring barley straw
- System 4 vs. system 3: Ethanol from winter wheat straw
- System 6 vs. system 3: Ethanol from winter wheat straw with intercropping of oilseed radish to mitigate loss of soil organic carbon (SOC) from straw removal

The current analysis of ethanol from straw is intended for further exploration and a more elaborate analysis will be submitted to a peer-reviewed journal. For this reason, the analysis addresses only a few selected GHG results.

4.4.1 GHG emissions from straw-based cellulosic ethanol

Figure 13 shows the GHG emissions associated with the production of 1 MJ bioethanol from straw (marginal Danish electricity assumed to be renewable and LUC emissions seen in a 20 year perspective). These results represent the difference in GHG emissions between a continuous cereal cropping system without straw removal (e.g. system 1) and the equivalent cropping system (same crop) with 50 % straw removal divided by the total ethanol output per hectare (12 GJ/ha in the case of system 2; Table 3). Ethanol from barley straw comes out most favorably with total GHG emissions of -3 g CO_2e/MJ (assuming bioelectricity replaces renewable electricity and applying a 20 year perspective for changes in SOC). It is important to notice that this is the C footprint of the ethanol before gasoline replacement. The negative number indicates that producing the ethanol itself leads to a reduction in GHG emissions (when taking into account the replacement of natural gas and electricity from the ethanol co-products).

The barley straw ethanol has lower SOC emissions than the wheat straw ethanol in system 4 but gets the same credit for reduced N_2O emissions caused by straw removal from the field (see also discussion in Section 3.1). The remaining GHG emissions are almost the same when comparing ethanol from barley straw and wheat straw.

Note that Figure 13 also shows estimated life cycle GHG emission from production and use of gasoline (average as well as marginal emissions).

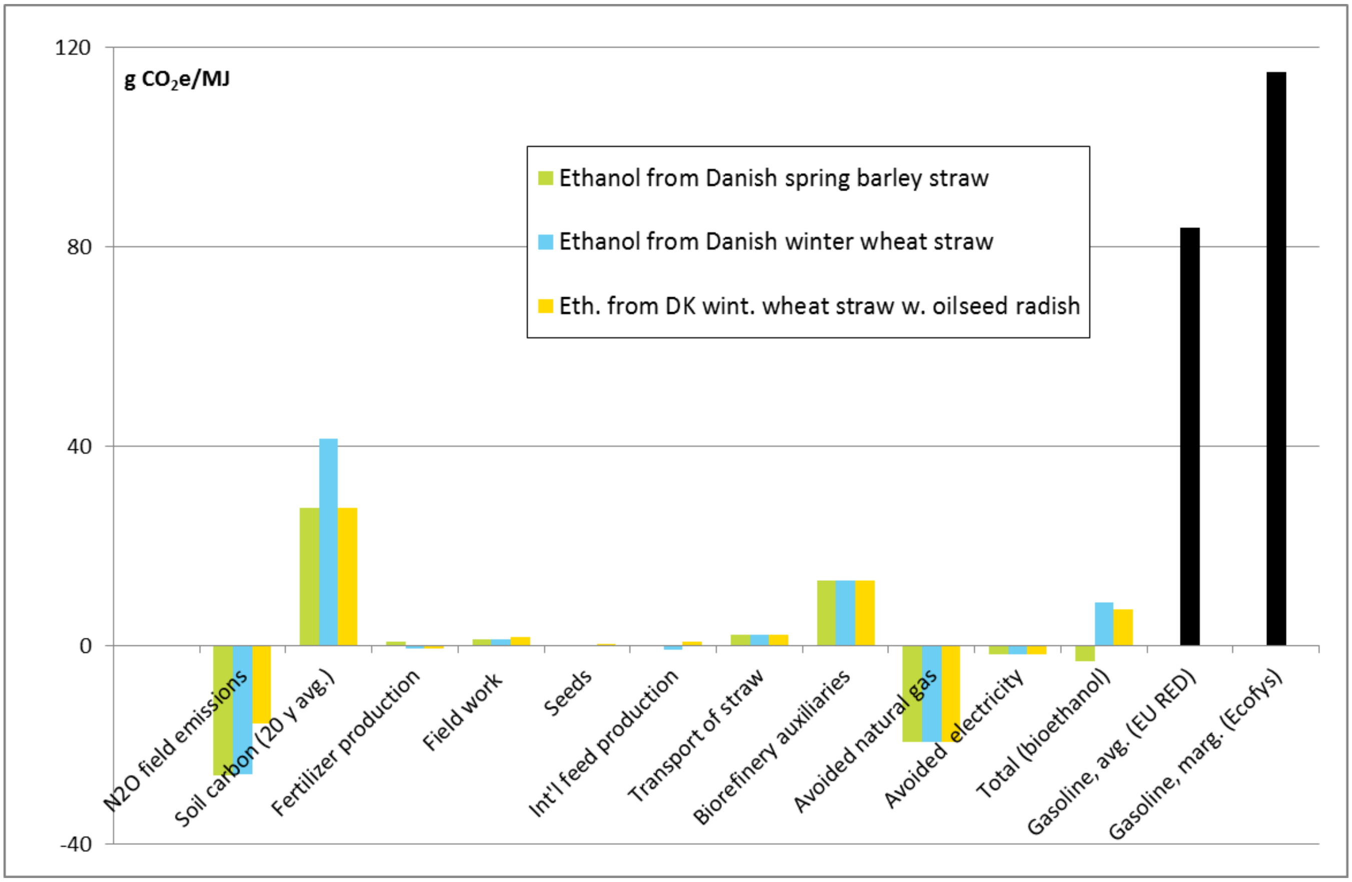

Figure 13. Breakdown of estimated GHG emissions from straw-based bioethanol (with SOC emissions seen in a 20 year time perspective and marginal Danish electricity assumed to come mainly from wind)

Figure 13 also shows that when wheat is produced with intercropping (oilseed radish), the loss of SOC is reduced (smaller soil CO_2 emissions). Meanwhile, this benefit comes at the expense of a smaller reduction in N_2O emissions.

5 Conclusions and Perspectives

We estimate that a Danish spring barley/oilseed radish cropping system (the reference system) results in GHG emissions of 590 kg CO_2e/Mg spring barley grain (ΔSOC averaged over 20 years) and a contribution to nutrient enrichment of 2.3 kg PO_4^{3-}e/Mg spring barley grain (~70% from the field). In the following, we seek to answer the five questions raised in Section 2.2.1.

1. When 50% of the straw is removed from the reference system to produce bioenergy in a biorefinery, some (additional) soil C is lost to the atmosphere (as CO_2). Meanwhile, this effect is more than counterbalanced by reductions in N_2O emissions from the field and from replacement of gasoline, natural gas, and grid electricity. The GHG savings per metric ton of spring barley vary between 25 and 40 percent depending on assumptions regarding electricity replacement (renewable, average, or coal-based).

   As for contributions to nutrient enrichment, the current study indicates a slight increase (<6%) as a result of residue utilization for bioenergy if the bioelectricity replaces other renewable energy technologies. If replacement of average or coal-based electricity is assumed, the contributions to nutrient enrichment are almost unchanged (±2%) seen in a full life cycle perspective.

2. If the reference system (spring barley and oilseed radish) is replaced with winter wheat, the output of feed grain is increased by more than one-third. This leads to replacement of feed production elsewhere and reduced pressure on global land resources. Quantification of the GHG impacts are challenging but we estimate that the 'yield effect' (i.e. avoided international feed production) reduces the GHG impact by roughly one-third (assuming one-to-one feed replacement) or somewhat less if only the effect on international land use change is considered with the market-based 'ILUC approach' (~16% and 3% in a 20 and 100 year perspective, respectively). In addition, there are impacts on SOC (more soil C storage with wheat) and other parameters. All in all, the continuous wheat system reduces the impact of feed grain production (as compared to the reference system) by roughly 20 and 10 percent when ΔSOC is seen over 20 and 100 years, respectively. Meanwhile, if the 'yield effect' is modeled solely as the indirect effect on global land use change (ignoring other market effects such intensification), there is only a minor GHG benefit in the short term (~2%) and actually a higher total emission from the wheat system as compared to the reference (spring barley system), mainly explained by a higher use of inputs (fertilizers, etc.) in the wheat system.

   As for contributions to nutrient enrichment, the wheat system has higher direct emission from the field and higher upstream emissions due to a higher use of N fertilizers. This is however counterbalanced if additional yield is assumed to replace international feed production (one-to-one). The wheat system thereby leads to a reduction (~20%) in the contribution to nutrient enrichment seen in a life cycle perspective (but the reduction takes place outside Denmark).

3. If the reference system is replaced with winter wheat and 50% straw is removed and used for bioethanol, the same yield benefit is obtained as in the wheat system with no straw removal (see discussion above). In addition, the co-products from the biorefinery replace gasoline, grid electricity, and natural gas while C sequestration on the field is reduced. All in all, GHG emissions from feed grain production are reduced in the order of 50-75% (assuming one-to-one replacement of international feed). The wide spread is explained by different assumptions regarding SOC (time horizon) and replaced grid electricity.

   As for contributions to nutrient enrichment, we observe an overall reduction compared to the reference system (assuming additional yield replaces international feed production one-to-one). This reduction is 10-30% depending on assumptions regarding replacement of grid electricity.

4. If the reference system is replaced by early sown winter wheat and 50% straw is removed and used for bioethanol, there is an even larger yield benefit (and associated GHG credit) than in the wheat system with normal seeding date and 50% straw utilization. At the same time, there is an even higher GHG benefit from straw utilization because the higher grain yield is accompanied by a higher straw yield. The GHG savings compared to the reference systems are 90-120% (assuming additional yield replaces international feed production one-to-one). The wide range of the savings is again explained by different assumptions regarding SOC (time horizon), replaced grid electricity, and replaced gasoline. Savings above 100% appear when bioelectricity is assumed to replace average or coal-based electricity. Savings above 100% indicate that the system itself is C negative, i.e. the GHG emissions from the field and the biorefinery (upstream, downstream, and direct) are lower than the GHG emissions from the feed and the energy carriers (e.g. gasoline) replaced.

   As for contributions to nutrient enrichment, we observe a substantial reduction compared to the reference system (assuming additional yield replaces international feed production one-to-one). This reduction is 60-80% depending on assumptions regarding replacement of grid electricity. One of the main reasons for these high savings is that the N field emissions are significantly reduced with early sown wheat (as compared to normal seeding date).

5. When the reference system is replaced with winter wheat intercropped with oilseed radish and 50% straw is removed and used for bioethanol, there is still a yield benefit (and associated GHG credit) similar to the other two wheat systems with normal seeding date (see previous discussion). As compared to the other system with wheat (normal seeding date) and 50% straw utilization, soil C sequestration

increases but so do N_2O emissions. Meanwhile, these two effects more or less cancel each other out. Hence, the GHG savings as compared to the reference system are also roughly 50-75% (assuming one-to-one replacement of international feed).

As for contributions to nutrient enrichment, the wheat system with intercropping of oilseed radish performs better than the other wheat systems with normal seeding and reduces emissions by 25-40% as compared to the reference (depending on assumptions regarding electricity replacement).

In general, the cropping systems studied can be ranked according to environmental performance as shown in Table 14. As indicated, system 5 (early sown wheat and straw utilization) is the best in terms of environmental performance. System 6 (wheat with intercrop and straw utilization) comes next, followed by system 4 (wheat and straw utilization). System 2 (spring barley with straw utilization) is ranked number 4 due to a better GHG performance (and despite a poorer nutrient enrichment score) than system 3 (winter wheat with 100% straw incorporation), which is ranked number 5. The reference system (spring barley with 100 % straw incorporation) comes out as the poorest performing system when seen in a full life cycle perspective.

Table 14. Ranking of cropping systems according to environmental performance with lowest score indicating best performance

Cropping system	Global warming	Nutrient enrichment	Combined
1 (spring barley, catch crop, 100% straw incorporation)	6	5	6
2 (spring barley, catch crop, 50% straw for biorefinery)	4	6	4[b]
3 (winter wheat, 100% straw incorporation)	5	3	5
4 (winter wheat, 50% straw for biorefinery)	3	4	3
5 (winter wheat, early seeded, 50% straw for biorefinery)	1	1	1
6 (winter wheat, intercrop, 50% straw for biorefinery)	2[a]	2	2

[a] GHG performance only slightly better (~2%) than system 4 (probably not statistically significant)
[b] GHG performance assigned higher weight than nutrient enrichment in the combined score

Based on the cropping system analysis, we derive the following general conclusions:

- Early seeding of winter wheat is environmentally beneficial if problems with higher risk of winter crop-kill, weed infestations, and fungal diseases are eliminated.
- Straw utilization for bioethanol and co-products improves the GHG profile of cropping systems.
- Seen in isolation, yield improvements on existing agricultural land also lead to a positive environmental impact due to replacement of grain production elsewhere. However, if only a very small credit is assigned (in terms of avoided GHG emissions and contributions to nutrient enrichment) the benefits of yield improvements may be outbalanced by the additional fertilizers and other inputs required.

- There is an inverse relationship between field N_2O emissions and CO_2 emissions from changes in SOC. In the long run, the N_2O effect however becomes dominating.
- Intercropping of oilseed radish in wheat production reduces contributions to nutrient enrichment.

As for the results related specifically to straw-based ethanol, we derive the following general conclusions:

- Very low or negative GHG emissions can be obtained for straw-based bioethanol even under conservative assumptions where bioelectricity co-produced with the ethanol is assumed to replace other renewable electricity technologies on the grid.
- We note that, in this perspective, it is much better to use straw for bioethanol than for power production (because straw-based electricity would only replace other renewable electricity whereas ethanol can replace fossil gasoline).
- The absolute GHG savings from straw-based ethanol depend not only on assumptions about replaced electricity on the grid but also on data for gasoline GHG emissions (marginal or average)

6 Recommendations

The present study illustrates the importance of looking beyond the field ('level 1') when assessing the environmental impacts of crop production and we recommend to apply a full life cycle perspective for this purpose ('level 2' and 'level 3'). While difficult to quantify, yield changes have important environmental implications and co-products such as bioenergy from straw can also significantly influence the environmental performance of a cropping system. We recommend that Danish regulation of crop production take these factors into account.

7 Future research

To further strengthening the present assessment, the following improvements could be added:

- Improve modeling of yield increase implications
  - Improve the consequential approach to modeling of the market-based response
  - Improve modeling of soybean meal
- Explore the fertilizer value of the biofertilizers further
- Explore the C sequestration potential of the biofertilizers
- Improve modeling of lignin combustion
- Consider potential fugitive emissions from biogas production and upgrade
- Expand modeling to include other environmental impact categories
- Include separate estimate for nutrient enrichment from marginal gasoline
- Include P emissions for the cropping systems studied

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DCA - National Centre for Food and Agriculture is the entrance to research in food and agriculture at Aarhus University (AU). The main tasks of the centre are knowledge exchange, advisory service and interaction with authorities, organisations and businesses.

The centre coordinates knowledge exchange and advice with regard to the departments that are heavily involved in food and agricultural science. They are:

Department of Animal Science
Department of Food Science
Department of Agroecology
Department of Engineering
Department of Molecular Biology and Genetics

DCA can also involve other units at AU that carry out research in the relevant areas.

SUMMARY

This report presents a comparative environmental assessment of six Danish cereal cropping systems with different straw removal rates using a life cycle assessment (LCA) approach. The assessment involves impacts of winter wheat seeding date and intercropping with oilseed radish between consecutive winter wheat crops. The report also works as documentation for a spreadsheet-based greenhouse gas (GHG) calculator that can be used to change assumptions and assess other cropping systems. The report represents a sub-component of the PlantePro project (Miljøsikret planteproduktion til foder og energi) co-funded by the Green Development and Demonstration Program (GUDP).