



# Comparative life cycle assessment (LCA) of pork using different protein sources in pig feed

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**Abstract.** Feed production is the main contributor to a subset of environmental impacts of pork production. In this context, this study is concerned with the substitution of soy products in pig diets in order to reduce these impacts. The aim of this study was to assess three alternative diets in gestating and lactating sows as well as growing and finishing pigs in order to reduce the amount of soy products used as ingredients. In the three alternative scenarios soy proteins were compensated for by either using a combination of different feedstuffs (e.g. rapeseed meal, fava beans, and synthetic amino acids) (LOW), maximising the use of legumes (mainly fava beans) (LEG) and increasing the amount of synthetic amino acids (AA). These alternative scenarios were compared with standard diets (ST) and formulated in order to reduce the crude-protein content of the diet while maintaining the same performance of the pigs. Each of the resulting 16 diets was then assessed with respect to global warming, eutrophication, acidification, and land use, both when accounting and not accounting for emissions due to land use change. The analysis per kilogram of feed showed that the ST diets performed best with regard to global warming, eutrophication, and acidification. When emissions from land use and land use change were added, ST and AA diets appeared to have the least impact. In contrast, the assessment of scenarios per kilogram of pork highlighted that the AA scenario contributed the least in all impact categories. In conclusion, it is possible to partly replace soybean products by using synthetic amino acids in order to minimise the environmental impacts of the pork supply chain.

## 1 Introduction

Feed production has contributed to the environmental impacts of pork production in Europe (Basset-Mens and van der Werf, 2005; Dalgaard et al., 2007; Nguyen et al., 2011; Reckmann et al., 2013), causing the majority of emissions. Thus, it is important to improve the feeding stage in order to reduce environmental emissions from the production of pork (van der Werf et al., 2005). Despite several mitigation strategies suggested in different studies (Cederberg et al., 2005; de Boer et al., 2011; Nemecek et al., 2008), the substitution of soybean products in animal feed seems to have the greatest potential for minimising the environmental impact (Hörtenhuber et al., 2011; Lehuger et al., 2009; Eriksson et al., 2005;

van der Werf et al., 2005; Weightman et al., 2011). A large share of greenhouse gas emissions from using soybean products is related to crop production, transport, and land use change (LUC) (Meul et al., 2012). LUC refers to the conversion of land used, for example the transformation of land from forest or pasture land into agricultural land for the cultivation of crops used as ingredients in livestock feed manufacturing. Land is a limited resource already being put under great pressure (Flysjö et al., 2012), whereas the global livestock sector occupies 75 % of the world's agricultural land (Foley et al., 2011). One third of this proportion is used for crop production intended for livestock feed production. The cultivation of soybeans for livestock feed manufacturing has expanded rapidly in recent years so that taking emissions

from LUC into account is important. Therefore, improving feed production in the livestock supply chain has a great potential to minimise impacts related to LUC. Recent studies indicated that LUC contributes 9% of total anthropogenic CO<sub>2</sub> emissions (Peters et al., 2012), indicating the dire need to reduce the emissions. Generally, emissions from LUC are divided into emissions related to direct LUC (dLUC) and indirect LUC (iLUC). Alternatively, it is assumed that any occupation of land is responsible for deforestation, independently of where in the world it takes place, resulting in iLUC (Audsley et al., 2009; Schmidt et al., 2011). However, it is difficult to account for emissions related to LUC because there is no consensus on how to address these emissions. Flysjö (2012) and Meul et al. (2012) criticised the difficulties of choosing a method and highlighted that several studies investigating the environmental effects of substituting soybean products in pig feed did not come up with a consistent conclusion in terms of diet formulation. Accordingly, variations in environmental assessments of alternative diets have been observed among different studies, mainly due to the methodological choices for the inclusion of LUC emissions being incompatible.

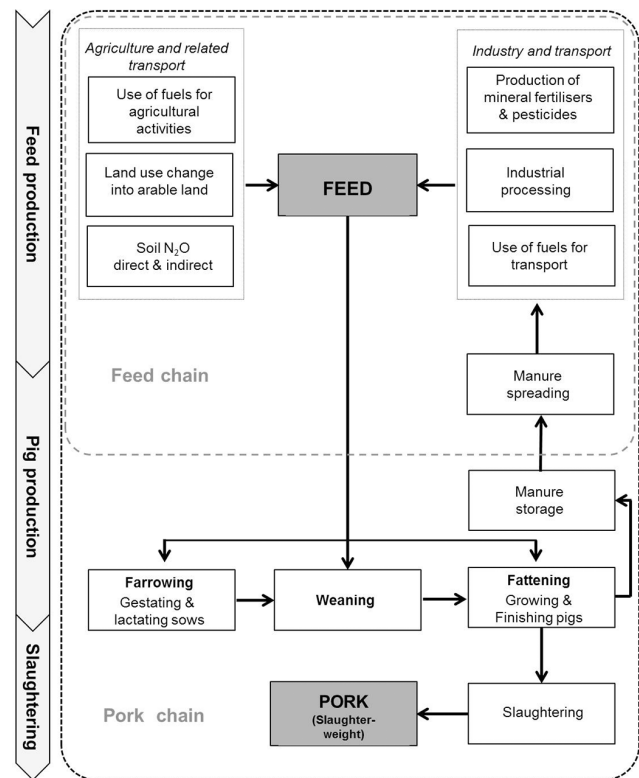
The aim of this study was to assess the environmental implications of reduced soy products used in the diets of farrowing and fattening pigs. Thus, a life cycle assessment (LCA) of alternative scenarios of reduced soy content in the diets of sows and fattening pigs was performed, focusing on providing feed recommendations for commercial farm conditions. Hitherto, all studies dealing with an LCA of pig feed set their system boundary at the gate of the feed company. In order to come up with comprehensive conclusions considering the whole pork supply chain, the present study additionally accounted for downstream processes as far as the gate of the slaughterhouse, to identify processes (e.g. manure composition) which might be influenced by the different pig diets.

## 2 Materials and methods

An LCA of pig diets was conducted, using four different diet compositions each in the farrowing and fattening stages. Results were calculated both per kilogram of feed and per kilogram of pork applying three different LUC accounting methods: LUC not included; dLUC emissions included; total direct and indirect LUC emissions included. A schematic overview of the considered systems within the system boundaries chosen is illustrated in Fig. 1.

### 2.1 Pig diets

Environmental impact assessments of standard diets (ST) for gestating and lactating sows (GE and LA, respectively) as well as for growing (GRO) (30–70 kg) and finishing (FI) (70–120 kg) pigs were performed using an attributional LCA approach, which aims at understanding the magnitude of different life cycle stages. Details on the methodology and its



**Figure 1.** Pork supply chain within the system boundaries chosen. The feed chain within the dashed grey line is considered when results are expressed per kilogram of feed. The pork chain within the dotted black line is considered when the outcome is related to the production of pork.

application to pork production are described in Reckmann et al. (2012). Three different pig feed scenarios were modelled, each with a different partial substitution of soybean feed composition compared to that of ST (Table 1). All diets were formulated with respect to the currently accepted limits of maximum inclusion levels for different feed ingredients, as described below.

- Scenario LOW: this alternative scenario involved a combination of various feedstuffs, e.g. rapeseed meal, fava beans, and wheat distillers' dried grains with soluble (DDGS), which were identified in previous studies as having low environmental impacts (Meul et al., 2012; van der Werf et al., 2005).
- Scenario LEG: this scenario involved the maximum use of legumes in the diets, considering recommendations of the association for nutritional physiology (GfE, 2006). Legumes have high protein contents and a reduced need for N fertilisation due to the atmospheric N fixation of the crops (Lehuger et al., 2009).
- Scenario AA: in this scenario, synthetic amino acids were used intensively to reduce the crude-protein content of the diets. The reduced crude-protein content was

**Table 1.** Ingredients of standard (ST) and alternative (LOW, LEG, AA) diets for sows and fattening pigs.

Ingredients (%)	Gestating sows				Lactating sows				Growing pigs				Finishing pigs			
	ST	LOW	LEG	AA	ST	LOW	LEG	AA	ST	LOW	LEG	AA	ST	LOW	LEG	AA
Wheat	26.0	26.0	26.0	26.0	40.0	40.0	40.0	40.0	40.0	39.9	38.4	48.5	36.0	40.1	33.1	46.0
Barley	37.0	37.0	37.0	40.0	30.0	30.0	30.0	37.2	37.0	37.0	37.0	37.0	45.0	39.0	45.0	45.0
SBM <sup>a</sup>	6.0	0	1.0	3.0	18.0	3.0	9.0	10.0	20.0	3.0	5.0	11.0	16.5	0	3.0	6.0
RSM <sup>b</sup>	0	2.0	0	0	0	5.0	0	0	0	5.0	0	0	0	5.5	0	0
DDGS <sup>c</sup>	0	2.0	0	0	0	4.6	0	0	0	5.0	0	0	0	5.5	0	0
Fava beans	0	2.0	5.0	0	0	5.0	14.0	0	0	5.0	15.0	0	0	5.5	15.0	0
Wheat bran	17.0	17.0	17.0	17.0	5.5	4.6	0.4	5.5	0	0	0	0	0	0	0	0
Beet pulp	10.0	10.0	10.0	10.0	2.0	2.0	2.0	2.0	0	0	0	0	0	0	0	0
RSO <sup>d</sup>	1.0	1.0	1.0	1.0	1.5	3.0	1.5	2.0	0	1.5	1.0	0	0	1.5	1.0	0
Lysine	0	0.05	0	0.05	0	0.25	0.05	0.20	0	0.35	0.25	0.3	0	0.35	0.20	0.35
Threonine	0	0	0	0	0	0.10	0.05	0.05	0	0.15	0.15	0.15	0	0.10	0.10	0.15
Methionine	0	0	0	0	0	0.05	0.05	0.05	0	0.05	0.15	0.10	0	0	0.10	0.05

<sup>a</sup> SBM: soybean meal; <sup>b</sup> RSM: rapeseed meal; <sup>c</sup> DDGS: distillers' dried grains with solubles; <sup>d</sup> RSO: rapeseed oil.

expected to reduce the N excretion of pigs, thus influencing the results when assessing the whole pork supply chain.

Overall, 16 different diets were assessed and compared (each scenario – ST, LOW, LEG, and AA – for each animal category – GE, LA, GRO, and FI).

### Feed ingredients and compositions

Feed ingredients of the different pig diets are listed in Table 1; chemical compositions are shown in Table S2 in the Supplement. All diets were formulated with regard to nutritional requirements recommended by the association for nutritional physiology (GfE, 2006). It was assumed that the performance of pigs was not influenced by the different diets since nutritional requirements were fully met. In addition, a diet for piglets (8–30 kg) was included in the overall assessment but was not varied in terms of soybean inputs. Previous analyses (Reckmann et al., 2013) showed that the piglet stage did not contribute considerably to the overall impacts of pork production; thus, it is not mentioned further.

For sow diets, energy content was fixed at 11.8–12.2 MJ of metabolisable energy (ME) for gestation and 13.0–13.4 MJ ME for lactation. Lysine content for gestating sows was set at a minimum of 6 g kg<sup>-1</sup> with an assumed ideal protein pattern of lys:met + cys:thr:try of 1:0.55:0.65:0.18, while for lactating sows lysine content was set at 9.5 g kg<sup>-1</sup> with an assumed ideal amino acid pattern of 1:0.6:0.65:0.2. Digestible P content was 2.2 g kg<sup>-1</sup> for gestating and 3.3 g kg<sup>-1</sup> for lactating sows. The mineral vitamin mix used contained additional amino acids and 500 units of phytase. All alternative diets were supplemented with synthetic amino acids in order to meet amino acid requirements. Diets for growing and finishing pigs contained about 13 MJ ME. Amino acid content was balanced according to an ideal amino acid pattern of 1:0.55:0.65:0.18. The minimum lysine content of the diets was 10.5 g kg<sup>-1</sup> for growing and 9.0 g kg<sup>-1</sup> for finishing pigs. Digestible phosphorus content was set to meet or ex-

ceed 2.5 g kg<sup>-1</sup> for growing and 2.1 g kg<sup>-1</sup> for finisher pigs. All diets were supplemented with a mineral vitamin mix containing additional amino acids and 500 units of phytase per kilogram of diet. There are limited environmental data available for mineral feed and vitamins added. Since the amount of these additives is comparable in the different diets (2.5–3.0 %), we did not consider their environmental impacts. Additionally, all diets were formulated with respect to the currently accepted limits of maximum inclusion levels for different feed ingredients due to antinutritive factors (Meul et al., 2012; van der Werf et al., 2005) using a feed optimising software tool (Zifo WIN v1.5). Thus, maximum inclusion rates (Hoffmann and Steinhöfel, 2010) were set for rapeseed meal (5–10 %), DDGS (20 %), beet pulp (10 %), wheat bran (20 %), and fava beans (15–20 %). However, it has to be noted that these maximum inclusion rates are not fixed values.

## 2.2 Life cycle assessment (LCA) methodology

### 2.2.1 Data inventory

Figure 1 shows a schematic overview of the pork supply chain within the system boundaries chosen. The feed chain encompassed the production of pre-products (e.g. fertilisers and pesticides), the use of fuels for transport and agricultural activities, land use activities, and the processing into feedstuffs (kilogram of feed). The pork chain encompassed all processes within the feed chain, and, in addition, it included pig housing, manure management, and slaughtering. The final product was pork as slaughter weight. According to the PAS 2050 (British Standard Institution, 2008), production processes which play a minor role (e.g. chemicals and buildings) were excluded from the system. A data inventory for both systems is presented in the following.

### Feed chain

The data inventories of wheat, barley, and fava beans were based on the Ecoinvent database v2.1 (2009) but modified in terms of current crop yields and fertiliser use in Germany. Data for the rapeseed production originated from Schmidt (2007), whereas the processing was similar to that in Jungbluth et al. (2007). It was assumed that the soybeans (Ecoinvent, 2009) were produced in Brazil. The transformation of soybeans and rapeseed into meal is associated with the co-production of soybean oil and rapeseed oil. Due to the attributional LCA applied in the current study, an allocation was necessary (Nguyen et al., 2011; Reckmann et al., 2012), and economic allocation was applied in this study. In the case of soybeans, we used the economic allocation as described in Nguyen et al. (2011), resulting in allocation factors of 66.3 % for soybean meal and 33.7 % for soybean oil. Rapeseed was allocated according to Schmidt (2010), resulting in factors of 27 % for rapeseed meal and 73 % for rapeseed oil. ‘With regard to the production of wheat bran, 73.9 % of production was allocated to flour, 24.2 % to bran and 1.9 % to residues (Zygouras et al., 2005). Beet pulp was also economically allocated, resulting in factors of 91.7 % for sugar, 4.5 % for molasses and 3.8 % for beet pulps (Jungbluth et al., 2007). Processing emissions were added, and the drying of sugar beet pulp caused 692 g CO<sub>2</sub>-eq kg<sup>-1</sup> beet pulp (Ecoinvent, 2009; Meul et al., 2012). Allocation factors of DDGS were gathered from Jungbluth et al. (2007). The production of amino acids is assumed to proceed as described in Mosnier et al. (2011), who include data due to fermentation and chemical synthesis of products. Since the content of the mineral composition in the feed did not differ between various scenarios of the pig group, it was not considered in the LCA and the comparison was considered the same across the groups.

Data regarding the processes to transform feed ingredients into feedstuffs were provided by a feed company in Germany. The manufacturing of 1 t feed is connected with an energy use of 3.9 kWh, a heat (oil) use of 57.6 MJ, a water use of 0.02 m<sup>3</sup>, and the emission of 80 g particulates. Additional information is given in the Supplement.

### Pork chain

Since feed production is part of the pork supply chain as indicated in Fig. 1, the data inventory of the pork chain started with the processes described above. It continued with the amount of feed needed to raise the pigs. It also included pig housing as well as the slaughtering of the animals. A detailed description of the assumptions for the LCA of pork is given in the Supplement, and basic essentials are described in the following. To represent the pig farm, we used a pig farm model as specified in Reckmann and Krieter (2014). We thereby focused on the gestating, farrowing, weaning (8–30 kg), and finishing (30–120 kg) stages while using the most recent data available for northern Germany, mainly from the

**Table 2.** Main farm performance parameters of the average pig production in northern Germany in the marketing year 2011/2012.

	Parameter	Value	Unit
Piglet production	Sows per farm	270	no.
	Replacement rate	45	%
	Live-born piglets per sow and year	32.4	no.
	Weaned piglets per sow and year	27.7	no.
	Litters per sow and year	2.3	no.
	Piglet losses	14.6	%
Weaning	Daily weight gain	460	g
	Piglet losses	2.4	%
Finishing	Fattening pigs per farm	1399	no.
	Final fattening weight	120	kg
	Carcass yield	78.9	%
	Daily weight gain	806	g
	Feed conversion ratio 1	2.84	kg
	Lean-meat content	57.2	%
	Animal losses	3.1	%

marketing year 2011/2012 (SSB, 2012). The main performance parameters of average pig production are listed in Table 2, remaining the same throughout all analyses. Electricity, heat, and water were needed for the rearing of the pigs. The excreta of the animals were stored as slurry in the pit beneath the slats for around 1 month. After this period, manure was pumped to an external storage tank outside the stable, where it developed a natural crust. After 6 months of prescribed storage, the manure was ready for field application, thereby replacing synthetic fertilisers in the cultivation of crops. The average distance to the field was 10 km, while the application of the manure consumed 21 MJ t<sup>-1</sup> slurry ex-storage (Dalgaard et al., 2001). The substitution of artificial fertiliser was regarded as a positive effect since it avoided fertiliser production using related resources (e.g. 0.4 MJ kg<sup>-1</sup> fertiliser N; Dalgaard et al., 2001) and emissions. All impacts related to the non-application of synthetic fertilisers were deducted from the system. In contrast, the spreading of manure occurred along with emission of pollutants, which could be rated as a negative effect. Overall, the N in the pig manure substituted 75 % of synthetic N fertiliser (Nguyen et al., 2011); the substitution rate of P was 97 % (Dalgaard et al., 2006). According to Sommer et al. (2008), the substitution rate of K in manure was 100 %. All environmental impacts related to manure management, including in-house storage, outside storage, and field application, were allocated to pork production. Details of the manure characteristic calculations can be found in Nguyen et al. (2011) and in Fig. S1 in the Supplement.

At a final live weight of 120 kg, the animals were transported 350 km from the farm to the slaughterhouse (Dreier, 2012). The final product was pork as slaughter weight, whereas the slaughter weight of the finishing pigs averaged

**Table 3.** Global warming potential (GWP), eutrophication potential (EP), acidification potential (AP), and land use (LU) of feed ingredients (per kilogram of ingredient). GWP originating from direct (dLUC) and total (total LUC) land use change is listed separately.

Feed ingredient	GWP (g CO <sub>2</sub> -eq)	EP (g PO <sub>4</sub> -eq)	AP (g SO <sub>2</sub> -eq)	LU (m <sup>2</sup> yr <sup>-1</sup> )	GWP from dLUC (g CO <sub>2</sub> -eq)	GWP from total LUC (g CO <sub>2</sub> -eq)
Wheat	547	2.8	2.6	1.55	0	222
Barley	442	8.2	3.6	1.34	0	192
Soybean meal	480	1.6	1.2	1.76	520	252
Rapeseed meal	451	1.9	2.5	2.90	0	415
Rapeseed oil	2008	8.9	9.6	5.47	0	782
DDGS	914	0.3	2.0	0.03	0	5
Fava beans	989	6.4	3.0	2.91	0	416
Beet pulp	704	0.1	0.1	0.10	0	14
Wheat bran	782	6.4	6.4	1.30	0	186
Lysine	4940	10.1	14.9	0.20	0	29
Threonine	4940	10.1	14.9	0.20	0	29
Methionine	2890	2.0	7.4	0.01	0	1

95 kg. The slaughtering process consumed heat, electricity, water, and energy for transportation and produced emissions to air and water. Primary data were supplied by a slaughterhouse, and the inventory data are presented in Table S2.

### 2.2.2 System boundaries and impact categories

Results given as two different functional units: kilogram of feed and kilogram of pork. An LCA for each of the scenarios was performed, considering a simultaneous change in farrowing and fattening diets. Only diets of the same scenario were included in the different stages; no combination of different scenarios across diets took place.

The outcomes of the LCA were expressed in impact categories of global warming potential (GWP), eutrophication potential (EP), acidification potential (AP), and land use (LU). Results of the first three categories were calculated using the CML 2 Baseline method v2.05 (CML, 2009), whereas the IMPACT 2002+ method v2.10 (Jolliet et al., 2003) was used for the calculation of LU. Equivalence factors were defined according to the IPCC guidelines (IPCC, 2006), using a 100-year time horizon for the GWP. All calculations were performed in SimaPro 7.3.3 (Pré Consultants, 2009).

#### Emissions related to land use change

Direct LUC relates to the conversion of land directly attributed to the production of one or more feed ingredients (i.e. soybeans). In contrast, iLUC attributes conversion of land induced by changes in the production of or demand for feed ingredients (Schmidt et al., 2011). Since there is no consensus about the method to calculate LUC emissions (Flysjö, 2012; van Middelaar et al., 2013) and LUC emissions are non-recurrent in contrast to other emissions which recur

annually (van Middelaar et al., 2013), LUC emissions were presented separately from other emissions.

#### Taking direct LUC (dLUC) into account

Since the EU demand for soybeans is responsible for tropical forest conversion and due to the methodology of dLUC, LUC emissions were related to the use of soybean products. As recommended in the “EU product environmental footprint (PEF) guide” (European Commission, 2013), dLUC emissions were allocated to feed for 20 years. Data from Jungbluth et al. (2007) were used stating that 3.2 % of total soybeans in Brazil originated from tropical forest. Furthermore, 5.2 % were converted from shrubland. Default values from the IPCC (2006) were used for carbon stocks in above- and below-ground biomass, dead organic matter, and soil for tropical forest, shrubland, and cropland. This procedure resulted in 2081 kg CO<sub>2</sub>-eq ha<sup>-1</sup> soybeans, being equivalent to 784 kg CO<sub>2</sub>-eq t<sup>-1</sup> soybeans. These values were adapted from Meul et al. (2012). Considering the allocation factor of 66.3 % for soybean meal, the emissions from dLUC resulted in 520 kg CO<sub>2</sub>-eq t<sup>-1</sup> soybean meal.

#### Taking total LUC risk into account

Due to the attributional LCA applied, total LUC risk (dLUC and iLUC) was calculated for each diet and each scenario based on historical and current deforestation rates (Audsley et al., 2009; Lange, 2011; Meul et al., 2012). The same value as proposed by Audsley et al. (2009) and Meul et al. (2012) was used, assuming a total LUC risk of 1430 kg CO<sub>2</sub>-eq ha<sup>-1</sup> of agricultural land use associated with each diet.

**Table 4.** Global warming (GWP), GWP including direct (GWP incl. dLUC) and total (LUC incl. total LUC) land use change, eutrophication (EP), acidification (AP), and land use (LU) for different pig diets (standard diet: ST; mix of low environmental impact ingredients: LOW; maximum use of legumes: LEG; and increased use of amino acids: AA) per kilogram of feed.

Pig diets		GWP (g CO <sub>2</sub> -eq)	GWP incl. dLUC (g CO <sub>2</sub> -eq)	GWP incl. total LUC (g CO <sub>2</sub> -eq)	EP (g PO <sub>4</sub> -eq)	AP (g SO <sub>2</sub> -eq)	LU (m <sup>2</sup> yr <sup>-1</sup> )
Gestating sows	ST	467.3	498.5	641.9	4.56	2.93	1.21
	LOW	486.3	486.3	660.8	4.64	3.00	1.22
	LEG	488.3	493.5	669.9	4.79	2.30	1.27
	AA	456.9	472.5	627.1	4.72	2.30	1.19
Lactating sows	ST	499.0	592.6	704.9	3.99	2.74	1.44
	LOW	586.2	601.8	807.9	4.34	3.13	1.55
	LEG	548.3	595.1	781.4	4.41	2.75	1.63
	AA	512.1	564.1	715.2	4.44	2.98	1.42
Growing pigs	ST	451.7	555.7	651.9	3.95	2.48	1.40
	LOW	546.9	562.5	760.0	4.34	2.93	1.49
	LEG	555.3	581.3	787.0	4.79	2.86	1.62
	AA	480.2	537.4	679.0	4.10	2.67	1.39
Finishing pigs	ST	479.2	565.0	695.1	5.38	2.77	1.51
	LOW	547.5	547.5	760.6	4.47	2.98	1.49
	LEG	538.3	553.9	765.7	5.14	2.92	1.59
	AA	471.4	502.6	665.9	4.50	2.80	1.36

### 3 Results

#### 3.1 LCA of feed chain

##### 3.1.1 LCA of different feed ingredients

LCA results of different feed ingredients with respect to the impact categories assessed are listed in Table 3. The GWP ranged from 442 (barley) to 2008 g (rapeseed oil) CO<sub>2</sub>-eq kg<sup>-1</sup> ingredient. The amino acids lysine, threonine, and methionine showed higher values. The EP ranged from 0.1 (beet pulp) to 8.9 (rapeseed oil) g PO<sub>4</sub>-eq kg<sup>-1</sup> ingredient, whereas the AP showed comparable values. The highest land use was caused by the production of 1 kg rapeseed oil (5.47 m<sup>2</sup> yr<sup>-1</sup>). The inclusion of dLUC emissions would only affect the GWP of soybean meal. By contrast, the GWP related to total LUC risk varied from 1 (for methionine) to 782 (for rapeseed oil) g CO<sub>2</sub>-eq kg<sup>-1</sup> ingredient.

##### 3.1.2 LCA of different scenarios using varying pig diets

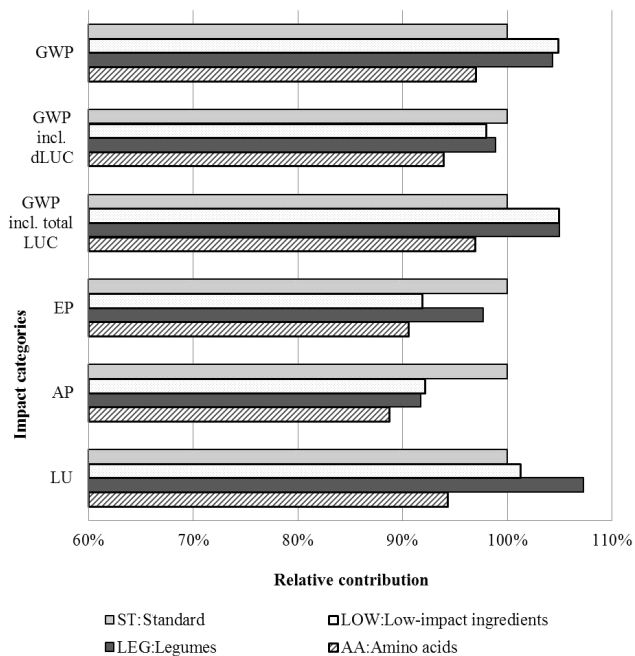
Table 4 summarises the results of all diets assessed. The standard diet for gestating sows showed the least values for all impact categories assessed. It resulted in a GWP of 467.3 g CO<sub>2</sub>-eq kg<sup>-1</sup> feed. Considering LUC emissions increased the GWP by 6.7 % (dLUC) and 37.4 % (total LUC risk), respectively. The GWP increased by up to 4.5 % (LEG), when alternative diets were compared to ST (see Table 4). The estimation of EP resulted in values of 4.56 (ST) to 4.79 (LEG) g PO<sub>4</sub>-eq kg<sup>-1</sup> feed for alternative diets. The AP of LEG and AA diets was lower compared to ST, whereas

the value increased slightly by 2.4 % for the LOW diet. Of the alternative diets, AA used the least land (1.19 m<sup>2</sup> yr<sup>-1</sup>).

The results of diets for lactating sows illustrated that the inclusion of dLUC emissions increased the GWP by 2.6 % (LOW) to 15.8 % (ST). Accounting for total LUC risk resulted in a 37.8 % (LOW) to 42.5 % (LEG) increased GWP. The resulting EP was 3.99 g PO<sub>4</sub>-eq kg<sup>-1</sup> ST feed (Table 4), whereas it increased only slightly (8.8–11.3 %) when assessing alternative diets. See Table 4 for AP and LU.

When dLUC emissions were added to the GWP results of the diets of growing pigs, values increased by 2.8 % (LOW) to 18.7 % (ST). The EP of diets for growing pigs ranged from 3.95 (ST) to 4.79 (LEG) g PO<sub>4</sub>-eq kg<sup>-1</sup> feed, whereas the AP showed values of 2.48 (ST) to 2.93 (LOW) g SO<sub>2</sub>-eq kg<sup>-1</sup> feed. The LU varied within a small range of 1.39 (AA) and 1.62 (LEG) m<sup>2</sup> yr<sup>-1</sup> kg<sup>-1</sup> feed.

The assessment of diets for finishing pigs resulted in a GWP of 479.2 g CO<sub>2</sub>-eq kg<sup>-1</sup> standard diet (Table 4). When dLUC emissions were included, values increased by 15.2 % (ST), 0 % (LOW), 2.8 % (LEG), and 6.2 % (AA). By contrast, the resulting increase in total LUC risk ranged from 38.9 % (LOW) to 45.1 % (ST). The least impactful finishing diet in terms of EP was LOW (4.47 g PO<sub>4</sub>-eq kg<sup>-1</sup> feed). The AP ranged from 2.77 (ST) to 2.98 (LOW) g SO<sub>2</sub>-eq kg<sup>-1</sup> feed. Most land was needed for the production of LEG (1.59 m<sup>2</sup> yr<sup>-1</sup> kg<sup>-1</sup> feed), whereas other diets decreased LU by up to 14.5 % (AA).



**Figure 2.** Contribution of different scenarios to global warming with emissions from direct (GWP incl. dLUC), total (GWP incl. total LUC), and no land use change (GWP), eutrophication (EP), acidification (AP), and land use (LU) in relation to the standard scenario. The assessment was performed per kilogram of pork considering the whole pork supply chain.

### 3.2 LCA of pork chain

The assessment of the pork supply chain resulted in a GWP of  $3.01 \text{ kg CO}_2\text{-eq kg}^{-1}$  pork considering the standard diet. The inclusion of dLUC caused a GWP of  $3.33 \text{ kg CO}_2\text{-eq kg}^{-1}$  pork. Accounting for total LUC risk resulted in a GWP of  $3.77 \text{ kg CO}_2\text{-eq kg}^{-1}$  pork. The EP was estimated at  $28.4 \text{ g PO}_4\text{-eq}$ , the AP reached  $57.2 \text{ g SO}_2\text{-eq kg}^{-1}$  pork, and LU showed a value of  $5.21 \text{ m}^2 \text{ yr}^{-1}$ . Figure 2 illustrates that the LOW scenario resulted in highest GWP, directly followed by LEG. The outcome of AA was reduced by 3% compared to ST. When including dLUC emissions, the ST scenario appeared most impactful; the GWP of AA, in contrast, decreased by 6%. The inclusion of total LUC risk highlighted LEG and LOW as having the highest GWP. The GWP of AA was reduced by 3% compared to ST, as demonstrated in Fig. 2. EP ranged from 25.8 (AA) to 27.8 (LEG)  $\text{g PO}_4\text{-eq kg}^{-1}$  pork. Results of the AP illustrated that ST had the highest values, whereas a maximum reduction was achieved via the feeding of AA diets (−11%). In terms of LU, AA performed best, resulting in  $4.92 \text{ m}^2$  land used per year for the production of 1 kg pork. Using LEG diets to produce pork increased LU by 12%. Overall, Fig. 2 highlights that the AA scenario performed best in all impact categories assessed. All impacts were reduced by 3 to 11% compared to the ST scenario.

## 4 Discussion

Since the agricultural expansion and the resulting LUC emissions are responsible for a considerable share of global greenhouse gas emissions, it is important to account for them in LCAs of food products. There is no consensus about the method to calculate LUC emissions (Flysjö et al., 2012; van Middelaar et al., 2013), and LUC emissions are non-recurrent in contrast to other emissions which occur annually (van Middelaar et al., 2013). Thus, in this study LUC emissions were presented separately from other emissions and were considered in GWP. The comparative results showed GWP increased considerably when including dLUC of feed manufacturing in all feed alternative scenarios, except in LOW diets of gestating sows and finishing pigs, where it remained the same since no soybean meal was included. Despite the methodological limitations it was decided to use the same dLUC values as calculated by Meul et al. (2012) because this approach showed more comprehensive assumptions. In contrast, Flysjö et al. (2012) summarised several dLUC factors from different studies resulting in different values. These different factors have some influence on the results of this study, but the variation is not considerable enough to change the overall conclusion.

The main advantage of the dLUC method is that it addresses the major drivers of deforestation (Gerber et al., 2010; Leip et al., 2010), namely the cultivation of soybeans from South America. On the other hand, it does not consider land as a limited resource and that land use elsewhere can also affect LUC indirectly (Flysjö et al., 2012). Therefore, Schmidt et al. (2011) recommended the inclusion of total LUC risk (direct and indirect) in assessments, with the consideration that all occupation of land contributes to some LUC. When including emissions from total LUC risk, GWP results per kilogram of pork increased by 24.0 to 25.5% as compared to emissions without LUC. Similarly, Audsley et al. (2009) argue that total LUC risk should be included because all demand for agricultural land influences global markets and thereby contributes to LUC. Thus, it is important to consider LUC in GWP studies of food and feed production (van Middelaar et al., 2013).

As observed from the scenario analyses, the level of soybean meal replacement varied among the different diets and scenarios. For example, the replacement of soybean meal in GE ranged from 50% for AA to 100% for LOW as compared to ST. In comparison, the reduction level was lower in LA diets, while in GRO diets it was up to 75% for LOW and LEG scenarios. Similarly, soybean meal could be replaced completely in some FI diets. These values indicate that soybean replacement in AA diets was the least, whereas the LOW diet representing relatively lower impacting ingredients resulted in an almost 100% replacement.

This is similar to the results in Meul et al. (2012), who reached a higher level of reduction in soybean products in fattening diets, although the complete replacement of soy-

beans was not considered in all their scenarios. On the other hand, discussions with various feed experts indicate that the amino acid composition of soybean products remains a limiting factor in the replacement.

Most of the LCA outcomes of feed ingredients in this study are in line with recent studies in the literature (Flysjö et al., 2012; Hörtenhuber et al., 2011; Meul et al., 2012; van der Werf et al., 2005). Nevertheless, results of some feed ingredients differ from those of other studies. For example, GWP and LU of DDGS did not comply with previous studies (Meul et al., 2012; Hörtenhuber et al., 2011), where 38.5 % higher and 7.4 % lower variations were observed, respectively. Additionally, the GWP in the present study increased more than 2-fold compared to the results of Hörtenhuber et al. (2011). On the other hand, the GWP impacts of beet pulp presented in this study were lower (−16.8 %) as compared to those from Meul et al. (2012). These differences might be due to varying energy use, differences in processing techniques, crop yields, or fertiliser use. Potential variation might be dependent on the databases used; feed ingredients presented in this study were analysed based on Ecoinvent database (2009). Uncertainties in the results were dealt with by using values from the literature, to see if errors in the ingredients could potentially affect the final ranking of the various scenarios. However, the use of literature values did not affect our conclusion for beet pulp because the content within pig groups remained the same over the various scenarios. By contrast, the inclusion of literature values in the cases of DDGS and fava beans slightly affected the results of the LOW and LEG diet scenarios. However, the overall conclusion remained the same because ST and AA scenarios were not affected due to the absence of DDGS and fava beans in the respective diets.

Assessments of the AA scenario by reducing crude-protein content had been expected to influence the N excreted by pigs (Portejoie et al., 2004). As expected, the different diets have resulted in a reduction in protein content value of 7.9 % in GE, 15.4 % in LA, 15.0 % in GRO, and 19.4 % in FI diets. The main parameters of the pork supply chain influenced by this change were N content of manure, emission from manure and replaced fertiliser use. It is assumed that pig performance was not affected. Thus, the N content of manure could be reduced by 14.7 % as compared to ST, which in turn, affected the emissions of CH<sub>4</sub>, direct N<sub>2</sub>O, and NH<sub>3</sub> from pig production in a similar manner. Consequently, results of the various scenarios were influenced by these interactions.

Overall, the AA scenario was identified as having the least impacts in all categories assessed. However, it was assumed that the inclusion of synthetic amino acids in pig diets does not have any side effects. Hitherto, studies dealing with an LCA of alternative pig diets have set the system boundary at the gate of the feed company, thereby choosing feed as a functional unit (Meul et al., 2012; van der Werf et al., 2005; van Middelaar et al., 2013). This study is unique in that it presents, for the first time, an assessment of alternative pig

diets per kilogram of pork. In this study, the whole pork supply chain was included by using an actual pig farm model (Reckmann and Krieter, 2014; see also the Supplement) to account for downstream processes which are influenced by different diet compositions, e.g. N excretion of pigs. The results indicated that replacement of soybeans with synthetic amino acids resulted in relatively better environmental performance. Hence, it is recommended that AA-replaced diets be used in pork production, but their applicability within an actual farm situation should be verified to avoid any possible side effects of using synthetic amino acids. Therefore, further research is required to determine the effects of using synthetic amino acids in the diets of pig when replacing soybeans in order to reduce the environmental impact of pork production.

## 5 Conclusions

The LCA of alternative diets in pig housing showed that the scenario with an increased use of amino acids performed best in terms of all the impact categories assessed when analysing the whole pork supply chain. This may be due to the reduction in crude-protein content of the diets that consequently lowered N and CH<sub>4</sub> excretion of pigs. Thus, when considering the whole pork supply chain, it can be recommended to partly substitute soybean products in pig diets with amino acids to minimise the environmental impacts of pig feed.

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