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LIVESTOCK RESEARCH
WAGENINGEN UR

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Lelystad, November 2014

Livestock Research Report 819

Boer, H.C. de, M.M. van Krimpen, H. Blonk, M. Tyszler, 2014. *Replacement of soybean meal in compound feed by European protein sources- Effects on carbon footprint.* Wageningen, Wageningen UR (University & Research centre) Livestock Research, Livestock Research Report 819.

Samenvatting NL
Er is een studie uitgevoerd naar de duurzaamheid van enkele Europese eiwitbronnen ter vervanging van sojaschroot van Zuid-Amerikaanse herkomst. Op basis van data uit de literatuur en de systematiek van het programma FeedPrint zijn de nutritionele waarde en de carbon footprint (CFP) van deze eiwitbronnen vastgesteld. Deze eiwitbronnen zijn ingerekend in een startvoer voor vleesvarkens, zonder dat de nutritionele waarde van het startvoer veranderde. Vervolgens is de CFP van het startvoer vastgesteld. De resultaten en conclusies worden in dit rapport besproken.

Summary UK
The overall aim was to investigate if soybean products from South American can be replaced by protein sources produced in Europe in a sustainable way. Based on data from literature, and based on the systematics of the FeedPrint programme, the nutritional value and the carbon footprint (CFP) of these protein sources is determined. These protein sources are used in feed optimizations of a starter diet for pigs, thereby maintaining the nutritional value of the diet. Subsequently, the CFP of the grower diet is calculated. The results and conclusions will be discussed in this report.

The picture on the front side shows the harvest of soybeans in the Netherlands. The picture was made available by Agrifirm Plant, Apeldoorn, The Netherlands.

Livestock Research Report 819

Table of contents

Samenvatting

Geïmporteerde sojaschroot uit Zuid-Amerika is momenteel een van de belangrijkste eiwitbronnen in diervoeders. Om de Europese mineralenkringloop te sluiten en minder afhankelijk te zijn van Zuid Amerika, neemt de vraag naar eiwitbronnen van Europese herkomst toe. Voorwaarde is wel dat deze eiwitbronnen op zijn minst even duurzaam zijn als geïmporteerde sojaschroot. Daarom is een studie uitgevoerd naar de duurzaamheid van enkele Europese eiwitbronnen. Dit onderzoek is uitgevoerd door Wageningen UR in het kader van de PPS Feed4Foodure, in samenwerking met Stichting Natuur & Milieu, Uitvoeringsagenda Duurzame Veehouderij en Nevedi.

In overleg met het veevoerbedrijfsleven en de Stichting Natuur en Milieu zijn voor deze studie de volgende grondstoffen geselecteerd: sojaschroot geteeld in Nederland en in de Oekraïne, zonnebloemzaadschroot, pluimveevleesmeel, DDGS, meelwormen, algeneiwit en single cell proteins. Op basis van data uit de literatuur en de systematiek van het programma FeedPrint zijn de nutritionele waarde en de carbon footprint (CFP) vastgesteld. Deze eiwitbronnen zijn ingerekend in een startvoer voor vleesvarkens, zonder dat de nutritionele waarde van het startvoer veranderde. Vervolgens is de CFP van het startvoer vastgesteld, zowel met als zonder de bijdrage van "land use and land use change" (Luluc). Startvoer met Zuid-Amerikaanse sojaschroot gold hier als referentie. Deze scenario's zijn doorgerekend volgens de principes van de zogenaamde 'attributional LCA benadering', waarbij geen rekening is gehouden met mogelijke verdringingseffecten.
Aanvullend zijn in samenwerking met Blonk Consultants drie scenario's uitgewerkt volgens het principe van een consequential LCA, waarbij mogelijke verdringingseffecten wel zijn meegenomen. De scenario's waren: i) het gebruik van processed animal protein (PAP) als grondstof voor een vleeskuikenvoer, in plaats van te gebruiken als kunstmest, ii) het grootschalig telen en processen van sojabonen in Europa in plaats van in Zuid Amerika en iii) het gebruik van toenemende hoeveelheden tarwe DDGS, dat vrijkomt als co-product bij de productie van ethanol als biobrandstof.

De belangrijkste conclusies van deze studie zijn:

Gebaseerd op de attributional LCA benadering

- Er is slechts een beperkt aantal opties beschikbaar om sojaschroot van Zuid-Amerikaanse herkomst in startvoer voor vleesvarkens te vervangen door eiwitbronnen van Europese herkomst, zonder toename van de CFP;
- Vervanging van 12% Zuid-Amerikaanse sojaschroot door 12% Nederlandse of Oekraïense sojaschroot in het voer resulteert in een beperkte afname van de CFP van 595 naar respectievelijk 580 en 592 g CO_2-eq. per kg mengvoer. Deze afname wordt met name veroorzaakt door een afname in transportafstand;
- Vervanging van 12% Zuid-Amerikaanse sojaschroot door 2.5% pluimveevleesmeel resulteert in een beperkte afname van de CFP van 595 naar 591 g CO_2-eq. per kg mengvoer. Het hoge fosforgehalte van pluimveevleesmeel is een belangrijke reden voor het lage inmengingspercentage in het voer; deze berekeningen zijn gebaseerd op erg gedateerde voedingswaarden en verteerbaar fosforgehalten van de pluimveevleesmelen; er is behoefte aan actualisatie van deze waarden;
- Als we het gehalte sojaschroot in het referentievoer terugbrengen van 12 naar 6%, stijgt de CFP van het voer enigszins, namelijk van 595 naar 606 g CO_2-eq. per kg voer;
- Vervanging van 12% Zuid-Amerikaanse sojaschroot door 6.1% insectenmeel (meelwormen) resulteert in een stijging van de CFP van 595 naar ten minste 717 g CO_2-eq. per kg mengvoer. Deze toename hangt onder andere samen met de hoge energiebehoefte voor het verwarmen van de meelwormenfaciliteit en voor het drogen van de wormen;
- Vervanging van 12% Zuid-Amerikaanse sojaschroot door 2.8% ontvet algenmeel resulteert in een beperkte stijging van de CFP van 595 naar ten minste 611 g CO_2-eq. per kg mengvoer. Deze CFP is berekend voor een optimistisch scenario, waarbij geen upstream CFP, die nodig was voor het

produceren van de biodiesel, is gealloceerd aan het algenmeel. Tevens is er uitgegaan van dat de algen een hoog vetgehalte hadden en dat een energie-efficiënte droogtechniek is toegepast;

- Alle andere berekende scenario's voor vervanging van Zuid-Amerikaanse sojaschroot resulteerden in een stijging van de CFP van het voer. Hieruit blijkt dat van de op dit moment wettelijk toegestane scenario's alleen het toepassen van sojaschroot vanuit Nederland of een ander Europees land resulteert in een verlaging van de CFP van het voer;
- Wanneer de CFP, samenhangend met landgebruik en verandering van landgebruik, wordt meegenomen in de berekening, dan blijkt dat de totale CFP van het voer bij alle berekende scenario's toeneemt, behalve als Zuid-Amerikaanse sojaschroot wordt vervangen door Europese of Oekraïense sojaschroot of door pluimveevleesmeel;
- De droogstap die nodig is om vochtrijke producten toe te voegen aan mengvoer zorgt voor een aanzienlijke verhoging van de CFP van het voer. Wanneer in plaats van droog voer brijvoer wordt verstrekt, is deze droogstap niet meer nodig, waardoor het gebruik van deze vochtrijke producten vanuit het oogpunt van duurzaamheid aantrekkelijker wordt;
- Het gebruik van meelwormen resulteert in een toename van de CFP van het voer. Het gebruik van insecten die een lagere energiebehoefte hebben, en die in staat zijn te groeien op laagwaardige reststromen in plaats van op grondstoffen die ook in de diervoeding gebruikt worden, kan de ecologische voetafdruk van insecten verlagen en daarmee verwerking van insecten in diervoeding aantrekkelijker maken. Er is behoefte aan meer LCA insectenstudies, zodat het inzicht hierin toeneemt;
- Het verhogen van het aandeel vrij lysine in het voer resulteerde in een afname van de kostprijs, maar – op basis van de waarden in FeedPrint - in een toename van de CFP. Er is behoefte aan meer onderzoek naar mogelijke neveneffecten van hogere aandelen vrije aminozuren op de prestaties en gezondheid van landbouwhuisdieren;
- Voor een juiste beoordeling van de duurzaamheidseffecten van vervanging van Zuid-Amerikaanse sojaschroot door alternatieve eiwitbronnen van Europese herkomst is het gewenst dat naast de 'attributionial LCA' benadering ook 'consequential LCA's, worden uitgevoerd. Consequential LCA's betrekken mogelijke verdringingseffecten van het op grote schaal produceren van deze eiwitbronnen bij de duurzaamheidsanalyse.

Gebaseerd op de consequential LCA benadering

Het gebruik van PAP in pluimveevoer in plaats van als kunstmest resulteerde in een besparing van ~1200 kg CO_2-equivalenten voor elke ton PAP verwerkt in voer in het geval dat KAS (kalkammonsalpeter) en TSP (Triple Super Phosphate) als vervangende kunstmestbronnen werden ingezet. De besparing was ongeveer 1550 kg CO_2-eq. als ureum en SSP (Single Super Phosphate) als vervangende kunstmestbronnen werden gekozen. Elk ton PAP die in voer werd verwerkt leverde een besparing van 0,5 ha land op. Hier tegenover stond dat per ton PAP in voer voor de productie van vervangende CAS en TSP ruim 5000 kg olie-equivalenten nodig was en voor de productie van ureum en SSP 6000 kg .

Het vervangen van 1 ton Amerikaanse soja voor 1 ton Europese soja leverde een besparing op van 126 kg CO_2-eq. Deze besparing was met name terug te voeren op het verplaatsen van de productie van mais en sojaolie crushing. Tegenover deze besparing stond het verbruik van extra fossiele energie.

De omzetting van tarwe in bio-ethanol als brandstof en DDGS als grondstof voor diervoeders had een gunstig effect op de CFP en het gebruik van fossiele energie. Bij een relatief laag verbruik van DDGS treedt er vervanging op van o.a. tarweglutenmeel, sojaschroot en zonnebloemzaadschroot en daalt het landgebruik. Bij een toenemend verbruik van DDGS vindt er echter een omslag plaats, waarbij ook het verbruik van tarweglutenmeel, sojaschroot en zonnebloemzaadschroot weer toeneemt. Hierdoor neemt p het moment dat er erg veel DDGS beschikbaar komt per saldo het landgebruik echter weer toe.

Om de carbon footprint van eiwithoudende gewassen verder te verlagen is het noodzakelijk dat de productie efficiënter wordt. In Europa zal meer aandacht besteed moeten worden aan de veredeling en verbetering van teeltomstandigheden van deze gewassen, zodat hogere opbrengsten per hectare gerealiseerd worden. Indien vochtrijke producten worden gedroogd (o.a. DDGS) is er behoefte aan toepassing van meer energiezuinige droogtechnieken, zodat de footprint daalt.

Summary

The aim of the current study was 1) to determine the environmental impact of several selected protein sources cultivated under European conditions, 2) to calculate the impact of these protein sources on the attributional LCA of a complete diet as compared to a reference diet including South American soybean meal, and 3) to describe the consequences of displacement of three selected changes in the feed system by use of the consequential LCA approach, to identify feasibility and limitations of the (explorative) consequential approach on climate change, land occupation, fossil depletion and an aggregate score (ReCiPe), which is an indicator of the damage of the ecosystem.
The overall aim was to investigate if soybean products from South American can be replaced by protein sources produced in Europe in a sustainable way. This study was performed within the framework of the social responsible research agenda of the Dutch research program Feed4Foodure, in cooperation with the Dutch feed industry (Nevedi) and Stichting Natuur & Milieu (a Dutch NGO).

In this study, it was investigated whether soybean meal of South-American origin (SBM-SA) in compound feed could be replaced by at least 50% high-protein feed ingredients of European origin, without negatively affecting the feed's carbon footprint (CFP). The selected EU protein sources were high protein sunflower seed meal, poultry meat and bone meal, DDGS, soybean meal cultivated in the Netherlands or in the Ukraine, insects (meal worms), defatted algae, and bacterial single cell protein. The effects of replacement were analysed, where a standard starting compound feed for fattening pigs was considered as the reference scenario. With a feed formulation programme, an optimal compound feed was formulated from ingredients, based on their nutritive value and cost price, taking restrictions, e.g. on minimum and maximum inclusion level of certain ingredients and nutrients into account. CFP of feed ingredients was calculated with FeedPrint (a database and calculation tool of the feed production chain, to calculate greenhouse gas emissions using the attributional LCA approach) or calculated/estimated separately when an ingredient was not available in FeedPrint. Moreover, in cooperation with Blonk Consultants, three consequential scenarios have been worked out. The selected scenarios were: i) the use of porcine PAP (Processed Animal Protein) as feed ingredient in a poultry diet instead of using it as fertilizer, ii) soybean cultivated and processed in Europe, and iii) extra supply of wheat DDGS as residual from ethanol production.

The most important conclusions from this study are:

Based on the attributional LCA approach

- There are limited options to replace SBM-SA in starting compound feed for fattening pigs by alternative (European) high-protein ingredients, without increasing its CFP
- Replacement of 12% SBM-SA by 12% SBM-NL or SBM-UA slightly decreased CFP from 595 to 580 and 592 g CO_2-eq. per kg of compound feed, respectively. This decrease is mainly caused by a decrease in transportation distance
- Replacement of 12% SBM-SA by 2.5% poultry meat (bone) meal slightly decreased CFP from 595 to 591 g CO_2-eq. per kg of compound feed. An important reason for the low replacement percentage is the high P content of meat (bone) meal; these calculations are based on outdated nutritional values and available phosphorus contents of the animal products, and it is recommended to update these values
- Restricting the inclusion level of SBM-SA from 12 to 6%, and replacing SBM-SA by other available (European) high-protein ingredients, slightly increased CFP from 595 to 606 g CO_2-eq. per kg of compound feed
- Replacement of 12% SBM-SA by 6.1% insects (mealworms) increased CFP from 595 to at least 717 g CO_2-eq. per kg of compound feed. This is partly caused by the large energy requirement for heating during the production phase and a drying step thereafter
- Replacement of 12% SBM-SA by 2.8% defatted algae slightly increased CFP from 595 to at least 611 g CO_2-eq. per kg of compound feed. This CFP was calculated for an optimistic case, with no allocation of upstream CFP, assuming a high oil content in the algae, assuming a

future high production level, and applying highly efficient drying techniques (with low energy requirement)

- Replacement of SBM-SA by the other high-protein feed ingredients of European origin resulted in an increased dietary CFP. This means that from the current legal scenario's only replacement of SA-SBM by EU-SBM results in a decrease of the CFP per kg of feed;
- When the CFP arising from land use and land use change during feed production is added to its CFP, total dietary CFP increases for all replacement options except for the meat (bone) meal, SBM-NL and SBM-UA scenarios
- The drying step, necessary for inclusion of a wet feed ingredient in compound feed, contributes considerably to the CFP of a compound feed. A change in feeding concept from dry to wet feeding may decrease this contribution and make several wet feed ingredients more attractive
- Mealworms seem to have little perspective for inclusion in compound feed, without increasing its CFP. The use of other insect species with low energy requirement during rearing, and rearing on waste products instead of feed ingredients, may increase the replacement potential of insects. To explore this potential, more insect LCA studies are required
- An increased inclusion level of free lysine in compound feed decreased its cost price, but – based on the values in FeedPrint - increased its CFP. Potential side-effects of this higher inclusion level require further research
- For an accurate assessment of the effects on CFP of replacing SBM-SA by high-protein ingredients of European origin, not only attributional effects (this study) but also global consequential effects have to be taken into account.

Based on the consequential LCA approach

The use of porcine processed animal protein (PAP) in poultry diets instead of applying PAP as fertilizer resulted in ~1,200 kg CO_2-eq savings per ton replaced PAP in case that CAN (Calcium Ammonium Nitrate) and TSP (Triple Super Phosphate) are used as replaced fertilizers, and ~1,550 kg CO_2-eq savings per ton replaced PAP in case that Urea and SSP (Single Super Phosphate) are used as replaced fertilizers. The use of 1 ton of PAP resulted in the saving of 0.5 ha of land use. Contrary to this savings, the production of additional fertilizer required a considerable extra amount of fossil energy. The production of CAN & TSP required more than 5000 kg oil-eq., whereas the production of Urea & SSP required 6000 kg oil-equivalents per ton replaced PAP.

Taking all described consequences into account, it can be concluded that replacing 1 ton of US/SA soybean by 1 ton of EU soybean saves 126 kg CO_2-eq./ton soybean replaced. These savings were mainly attributed to the replacement of maize production and soya oil crushing. Contrary to these savings, the shift from US/SA to EU soybean required a considerable extra amount of fossil energy.

Converting wheat into bio-ethanol as fuel source and into DDGS as feed source had beneficial environmental effects in terms of climate change, use of fossil energy, and ReCiPe points. At low levels of DDGS use, wheat gluten feed, soybean meal and maize gluten feed are replaced, resulting in a decrease in land use. Increasing the share of DDGS to levels above 1 Mton in the UK market, however, also increased the use of wheat gluten feed, soybean meal and maize gluten feed. As a consequence, more land use is required if the share is more than ~ 1 Mton DDGS in the UK market.

For further reducing the CFP of protein rich ingredients of European origin, it is necessary to increase the efficiency of the production of these ingredients. Therefore, more attention should be given to breeding and improving cultivation conditions of these protein sources, resulting in an increased yield per hectare. In case of drying wet by-products (e.g. DDGS), more energy-efficient drying techniques should be developed to reduce the CFP of these products.

List of abbreviations

AFD = Apparent faecal digestible
ARG = Arginine
CAN = Calcium Ammonium Nitrate
CF = Crude fibre
CFP = Carbon footprint
CH_4 = Methane
CO_2 = Carbon dioxide
CYS = Cysteine
CP = Crude protein
DDGS = Distillers Dried Grains with Solubles
DM = Dry matter
ETBE = Ethyl tert-butyl ether
Ha = Hectare
HIS = Histidine
HP = High protein
ILE = Isoleucine
K = Potassium
K_2O = Potassium oxide
KAS = Kalkammonsalpeter
kWh = kilo Watt hour
LCA = Lifecycle assessment
LCIA = Lifecycle impact assessment
LEU = Leucine
LULUC = Land use and land use change
LYS = Lysine
MET = Methionine
M+C = Methionine + cysteine
MJ = Mega joule
N = Nitrogen
P = Phosphorus
P_2O_5 = Phosphate
PAP = Processed animal protein
N_2O = Nitrous oxide
NGO = Non-governmental organisation
ReCiPe = Aggregated score as indicator of the damage of the ecosystem
SA = South America
SBM = Soybean meal
SCP = Single Cell Protein
SSM = Sunflower seed meal
SSP = Single Super Phosphate
THR = Threonine
TRP = Trypophan
TSP = Triple Super Phosphate
UA = Ukraine
US = United States of America
VAL = Valine

1 Introduction

The total EU protein crop production (e.g. legumes, soybeans) currently occupies only 3% of the EU's arable land (Euractiv, 2011). In 2012, 34 million tonnes of soybeans and soybean cakes, equivalent to 15.5 million ton protein, were imported in the EU (FEFAC, 2012). These protein sources mainly originated from South America. In terms of land use abroad, these imports represent 10% (20 million ha) of the EU's arable land (Euractiv, 2011).

Concerns, however, are increasing regarding the amount of imported feed proteins from outside the EU. The reasons of concern differ between stakeholders, e.g. governments, NGO's, and consumers. In 2011, The European Parliament adopted a resolution on 'the EU's protein deficit', putting forward a series of measures to reduce the dependency on imports of protein crops for animal feed, primarily from the US, Argentina, and Brazil (Euractiv, 2011). The European Parliament is concerned that such massive dependency on imports makes the EU livestock sector extremely vulnerable to price volatility and trade distortions, causing feed price to rise, thereby increasing farmers' production costs and reducing the sectors' profitability. A major concern of NGO's is the deforestation of tropical rain forest, to fulfil the need of arable land for soybean cultivation (WNF, 2011; Van Gelder and Kuepper, 2012). As a consequence of conversion of natural ecosystems into agriculture, the rate of biodiversity loss (proportion of extinct species) increases, whereas the current status has already more than ten times exceeded the proposed boundary (Rockström et al., 2009). Moreover, large scale soybean cultivation may increase water and soil pollution, and drive small farmers and the native population out of business (WNF, 2011).

It is expected that the mentioned concerns, related to the large amounts of imported feed proteins, might be reduced by increasing the European protein production. Besides reduction in dependency from South America and unbalanced use of resources in this area, enhancing the EU protein crop production might reduce sensibility for crop diseases (more crop rotation), stabilise farmers' income, and positively influence socially desirable crop cultivation (e.g. non-GMO soybean production) (Westhoek et al., 2011).

As a follow-up on a public debate regarding sustainable livestock production, a Dutch committee (Commissie Van Doorn, 2011) formulated the goal that in 2020 at least 50% of the Dutch protein-rich feed ingredients should originate from Europe (27% in 2011). According to this committee, however, this goal has to be fulfilled under the condition that it results in a more sustainable feed production compared to the current situation. This condition fits in the perception of Boggia et al. (2010), who stated that sustainability is becoming the most important driving force behind human actions. A sustainable economic development involves maximising the net benefits of economic development, thereby maintaining the services and quality of natural resources over time (Pearce et al., 1988). The livestock sector increasingly competes for scarce resources, such as land, water, and energy, and has a severe impact on air, water and soil quality because of its emissions. The world's livestock sector is responsible for 18% of the global emission of greenhouse gases. This contribution of 18% was explained by emission of carbon dioxide from fossil-fuel combustion and deforestation, emission of methane from manure and enteric fermentation by ruminants, and emission of nitrous oxide from application of fertilizer during cultivation (Steinfeld et al., 2006). The production of milk, meat, and eggs gives rise to an environmental impact in terms of:

- energy use
- eutrophication of waters
- contribution to global warming and acidification
- ecological toxification by use of pesticides
- soil erosion
- loss of biological diversity (Cederberg and Darelius, 2001).

LCA (life cycle assessment) is a method to evaluate the environmental impact of products, activities and services during their entire life cycle (Owens, 1997). In agriculture, and particularly in animal husbandry, the LCA approach is very useful, because it allows an overall view of the environmental impact, emissions and the consumption of resources involved in every step of the productive chain, from the cultivation of crops to their transformation into feed (Boggia et al., 2010). LCA can help in decision-making and may assist both in the definition of the problem and in the assessment of alternatives (Tillman, 2000).

In LCA studies, usually emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are quantified. Emissions of CO_2, CH_4 and N_2O can be summed up based on their equivalence factor in terms of CO_2-equivalents: 1 for CO_2, 21 for CH_4 and 310 for N_2O (de Vries and de Boer, 2010). Acidification potential usually is expressed in SO_2-equivalents and eutrophication potential in PO_4-equivalents. In LCA studies, five impact categories are evaluated: land use, primary energy use, climate change, eutrophication and acidification.

LCA studies can be attributional or consequential. Attributional LCA studies describe the current situation, mainly on an economic allocation basis. In these studies, it is assumed that certain parts are not fully linked and can move independently. The attributional approach is suitable for point estimates of the current situation, for comparison of existing systems, and for specific interventions not affecting the allocation to products. Consequential LCA studies describe the changes in situations, thereby trying to avoid allocation. Such studies assume that changes are directly linked and cannot move independently. Attributional LCA studies are suitable for improvement of estimates, comparison of existing with non-existing systems, and large scale interventions and interventions that change the system.

The aim of the current study was 1) to determine the environmental impact of several selected protein sources cultivated under European conditions, 2) to calculate the impact of these protein sources on the attributional LCA of a complete diet as compared to a reference diet including South American soybean meal, and 3) to describe the consequences of displacement of three selected changes in the feed system by use of the consequential LCA approach, to identify feasibility and limitations of the (explorative) consequential approach on climate change, land occupation, fossil depletion and an aggregate score (ReCiPe).

The overall aim was to investigate if soybean products from South America can be replaced by protein sources produced in Europe in a sustainable way. This study was performed within the framework of the social responsible research agenda of the Dutch research program Feed4Foodure, in cooperation with the Dutch feed industry (Nevedi) and Stichting Natuur & Milieu (a Dutch NGO).

2 Materials and methods

2.1 Scenario's attributional LCA

In this study, it was investigated whether soybean meal of South-American origin (SBM-SA) in compound feed can be replaced by at least 50% high-protein feed ingredients of European origin, without negatively affecting the feed's carbon footprint (CFP). CFP represents the greenhouse gas emissions during feed production, expressed in CO_2-equivalents, and is a measure for the impact of feed production on climate change.

The effects of replacement were analysed, where a standard starting compound feed for fattening pigs was considered as the reference scenario. This feed was formulated using a feed formulation programme (Libra 5, version 22.8). With this programme, an optimal compound feed was formulated from ingredients, based on their nutritive value and cost price, taking restrictions, e.g. on minimum and maximum inclusion level of certain ingredients and nutrients into account. In the reference scenario, the inclusion of SBM-SA was allowed to a relatively high level. In nine additional scenarios, the inclusion level of SBM-SA was restricted or SBM-SA was excluded from inclusion, and SBM-SA could be replaced by various alternative high-protein ingredients of European origin. This resulted in a total of ten scenarios:

- scenario 1: unrestricted inclusion level of SBM-SA (reference scenario)
- scenario 2: restriction of SBM-SA to ≤6%
- scenario 3: replacement of SBM-SA by high-protein sunflower seed meal
- scenario 4: replacement of SBM-SA by poultry meat and bone meal
- scenario 5: replacement of SBM-SA by DDGS (co-product of bio-ethanol production)
- scenario 6: replacement of SBM-SA by SBM from soybeans grown in the Netherlands
- scenario 7: replacement of SBM-SA by SBM from soybeans grown in Eastern-Europe
- scenario 8: replacement of SBM-SA by insects (mealworms)
- scenario 9: replacement of SBM-SA by defatted algae
- scenario 10: replacement of SBM-SA by bacterial single-cell protein

For each scenario, a description of the input data for compound feed formulation and calculation of CFP is given below. Nutritive values of feed ingredients were from CVB (2011) and cost prices of commonly used ingredients were equal to the prevailing market prices.
CFP of feed ingredients was calculated with FeedPrint or calculated/estimated separately when an ingredient was not available in FeedPrint. FeedPrint is a database and calculation tool of the feed production chain, to calculate greenhouse gas emissions using LCA. A description of the used principles is given in Vellinga et al. (2013), and the tool can be downloaded from the internet (http://webapplicaties.wur.nl/software/feedprint/). The FeedPrint version used was 2013.03. In FeedPrint, CFP due to land use is 110 kg C ha^{-1} and CFP due to land use change (from forest to agricultural land) is 1180 kg C ha^{-1}.
CFPs for scenario's 1 through 8 were calculated with FeedPrint; CFPs for scenario's 9 through 11 were calculated separately, using data from available literature and applying FeedPrint methodology when possible. Based on the CFP of feed ingredients and their percentage of inclusion in the formulated compound feed, CFP of compound feed was calculated for the compound feed leaving the feed mill gate (headed to a farm).

2.2 Scenario 1: unrestricted inclusion level of SBM-SA (reference scenario)

Input for compound feed formulation
In this reference scenario, the inclusion level of SBM-SA in compound feed was restricted to a maximum of 17%. The term 'unrestricted' is used because this maximum inclusion level is relatively

high. As a reference SBM, we used SBM with < 45 g kg^{-1} of crude fibre (CF) and < 480 g kg^{-1} of crude protein (CP) per kg of product. An overview of the minimum and maximum values for inclusion level of nutrients and feed ingredients used in the feed formulation programme is given in Table 1. An overview of the used cost prices for feed ingredients is given in Table 2.

Table 1

Minimum and maximum inclusion levels (g kg-1 of compound feed) for nutrients and feed ingredients used in the feed formulation programme for the reference scenario (scenario 1).

Nutrient/Ingredient	Unit	Minimum	Maximum
Moisture	g/kg		
Ash	g/kg		
Crude protein	g/kg		170
Crude fat	g/kg		55
Crude fibre	g/kg	40	50
Starch (amylase)	g/kg	340	
Total sugars	g/kg		
Net Energy (NE)	MJ/kg	9.67	9.67
Linoleic acid	g/kg	10	
Calcium	g/kg	7.0	8.0
Phosphorus	g/kg		5.0
Digestible phosphorus	g/kg	2.7	
Natuphos	FTU/kg	1,000	1,000
Electrolyte balance	mEq	180	
Sodium	g/kg	1.5	1.5
Potassium	g/kg		
Chloride	g/kg		
AFD LYS	g/kg	9.13	
AFD MET/AFD LYS	-	0.32	
AFD M+C/AFD LYS	-	0.59	
AFD THR/AFD LYS	-	0.60	
AFD TRP/AFD LYS	-	0.19	
AFD ILEU/AFD LYS	-	0.52	
AFD HIS/AFD LYS	-	0.34	
AFD LEU/AFD LYS	-	0.97	
AFD VAL/AFD LYS	-	0.64	
AFD ARG/AFD LYS	-		
Free LYS/AFD LYS	-		0.35
Wheat	%		40.0
Wheat middlings	%		7.5
Barley	%	25.0	35.0
Maize	%	5.0	20.0
Soy oil	%		2.0
Palm oil	%		3.0
Molasses	%	2.0	4.0
Soybean meal	%		17.5
Soy hulls	%		2.5
Sunflower seed meal	%		12.5
Rapeseed meal	%		7.5
Peas	%		7.5
Potato protein	%		5.0

Table 2

Overview of the cost prices of compound feed ingredients.

Ingredient description	Price (€ 100^{-1} kg)
Wheat	18.80
Wheat middlings	16.20
Barley	18.30
Maize	23.20
Palm oil	67.20
Soy oil	79.00
Molasses, sugarcane, sugar>475 g/kg	17.80
Soybean meal, CF<45 g/kg, CP>480 g/kg	52.50
Soybean meal, CF<45 g/kg, CP<480 g/kg	46.90
Soybean hulls, CF 320-360 g/kg	17.50
Sunflower seed meal, CF<160 g/kg, dehulled	26.00
Sunflower seed meal, CF>240 g/kg	21.00
Rapeseed meal, CP<380 g/kg	23.20
Peas, dry	31.50
Potato protein, Ash>10g/kg	130.00
L-Lysine HCl	129.00
DL-Methionine	276.00
L-Threonine	170.16
L-Tryptophan	1300.00
L-Valine	1100.00
Natuphos 1000 FTU	600.00
Chalk	3.50
Monocalcium phosphate	49.80
Sodium chloride	6.70
Sodium bicarbonate	29.00

CFP calculation

CFP of SBM-SA was calculated in FeedPrint. The sourcing of this SBM was different from the default sourcing in FeedPrint, and was based on the actual sourcing of SBM used in the Netherlands in 2012. Of this SBM-SA, 23% was grown and crushed in Argentine, 45% was grown in Brazil and crushed in the Netherlands, and 32% was grown in the US and crushed in the Netherlands. An overview of the sourcing of the other feed ingredients used is given in Table 3.

Table 3

(European) sourcing of regular protein feed ingredients used to formulate starting compound feed for fattening pigs.

Ingredient description	Sourcing (%)
Wheat	35% Germany, 30% France, 10% Netherlands, 25% UK
Barley	10% Belgium, 45% Germany, 45% France
Sunflower seed meal, CF<160 g/kg	100% Ukraine
Rapeseed extruded, CP<380 g/kg	100% Germany
Soybean meal, CF<45 g/kg, CP<480 g/kg	23% Argentine, 45% Brazil, 32% US
Maize	25% Germany, 75% France
Potato protein, ASH >10 g/kg	10% Germany, 90% The Netherlands
Soybean hulls, CF 320-360 g/kg	23% Argentine, 45% Brazil, 32% US
Wheat middlings	10% Germany, 10% Belgium, 80% Netherlands
Peas dry	20% Germany, 80% France
Sunflower seed meal, CF>240 g/kg	100% Ukraine

2.3 Scenario 2: restriction of SBM-SA to ≤ 6%

This scenario was similar to scenario 1, except that the inclusion level of SBM-SA in compound feed was restricted to a maximum of 6%. This restriction gives insight in which protein-rich feed ingredients replace SBM at this maximum inclusion level, and what the effect of this replacement is on CFP.

2.4 Scenario 3: replacement of SBM-SA by high-protein sunflower seed meal

Input for compound feed formulation
Scenario 3 is comparable to scenario 2, except that inclusion level of SBM-SA was not allowed. Instead, a new high-protein sunflower seed meal (HP-SSM) could be taken up to a maximum level of 12.5%. This product is not available on the marketplace, but was formulated based on the assumption that additional removal of fibre from SSM is possible and will result in a considerable higher CP of 46%, compared to a maximum of 38% for available SSM (CF<160 g/kg). The assumption was that this new product has more potential to replace SBM-SA. The theoretical nutritive value after the removal of extra fibre is given in Table 4. Cost price of this HP-SSM was set at 32 € 100^{-1} kg of product, based on the cost price of SSM (CF<160 g/kg) and on an estimation of the extra amount necessary because of processing.

Table 4
Nutritive value of SSM (CF 0-160 g kg-1) before and after removal of extra fibre.

Ingredient	Moisture	Ash	Crude protein	Crude fat	Crude fibre	Starch	Sugar	Rest	Total
SSM	109	66	382	18	148	8	53	216	1000
HP-SSM	120	80	460	22	65	10	63	180	1000

CFP calculation
CFP of HP-SSM was based on CFP of SSM (CF<160 g/kg), which was calculated in FeedPrint. Sourcing of this SSM in FeedPrint was set at 100% sourcing from the Ukraine, to represent 100% European sourcing (in the current version of FeedPrint, SSM can only be sourced from Argentine, Canada and the Ukraine). To account for the extra CFP of HP-SSM relative to regular SSM, CFP of regular SSM was increased by 21%, being the percentage of increase in ash content of HP-SSM relative to the regular SSM (which suggests that 1.21 unit of SSM is necessary to produce one unit of HP-SSM). CFP was therefore increased from 711 (SSM) to 860 g CO_2-eq. kg^{-1} of product (HP-SSM). Fibre removal will also result in a small additional CFP due to use of energy and equipment. This extra CFP was not known and could not easily be calculated, and was therefore not taken into account.

2.5 Scenario 4: replacement of SBM-SA by poultry meat and bone meal

Introduction
Animal meal (e.g. blood meal, bone meal, meat meal, meat and bone meal) used to be a valued protein-rich ingredient in animal feed, but was banned from use in the year 2000 because of increased incidences of 'mad cow disease' (*Bovine spongiform encephalopathy*). However, voices are heard in politics that, under limitations, the use of animal meal should be permitted again. Animal meal has a low CFP because no upstream CFP is allocated, due to its relatively low economic value. Therefore, the inclusion level of animal meal in compound feed could contribute to the replacement of SBM-SA by proteins from European origin, and potentially lower its CFP.

Input for compound feed formulation
In this scenario, the inclusion level of SBM-SA was not allowed and meat and bone meal could be included in the diet to a maximum of 3%. Because of the species to species ban, indicating that animals should be prevented to consume the remains of their own species, meat meal and meat and bone meal of poultry origin were used in this scenario. Because the inclusion level of poultry meat and

bone was very low, poultry meat meal was added later to see if this would increase the inclusion level. Poultry meat and bone meal 50 Sonac (Appendix 1) and poultry meal 63 Sonac were used as meat and bone meal and meat meal, respectively. Prices were set at 40 and 61 € 100^{-1} kg of product, respectively (based on information from Vionfood, Eindhoven, the Netherlands).

CFP calculation

The CFP of poultry meat and bone meal was calculated with FeedPrint. For this scenario, CFP of poultry meat and bone meal (Category 3 rendering) with a crude fat content of maximal 100 g kg^{-1} of product was used. This meal was sourced from the Netherlands (default FeedPrint sourcing).

2.6 Scenario 5: replacement of SBM-SA by DDGS (co-product of bio-ethanol production)

Input for compound feed formulation

In this scenario, inclusion level of SBM-SA was not allowed and DDGS (distiller's dried grains with solubles) could be taken up to a maximum of 7.5%. DDGS is a co-product of the bio-ethanol production. CFP of DDGS only consists of CFP due to drying of the wet product; no upstream CFP (from crop cultivation & processing) is credited to DDGS because of the low economic value of the wet product (Vellinga et al., 2013). Because of its relatively low CP content (≈ 25%), DDGS cannot replace SBM (≈ 46%) at a 1:1 basis in animal diets. A high variability in nutrient composition and quality of DDGS, as well as high fibre content, limits it inclusion in diets, with most commonly used levels around 10%. Cost price of maize-DDGS was based on the market price and set at €23.50 100^{-1} kg.

CFP calculation

DDGS can be produced during the bio-ethanol production from different grains, e.g. maize and wheat. In the present study, maize-DDGS is used to replace SBM-SA, because the CFP of this product is already calculated in FeedPrint. Sourcing of the maize used for bioethanol production was set at 50% from Germany and 50% from France, which differed from the default sourcing in FeedPrint (33% from Germany, 33% from France, 34% from the US), to represent a product of European origin.

2.7 Scenario 6: replacement of SBM-SA by SBM from soybeans grown in the Netherlands

Input for compound feed formulation

The input for this scenario was equal to the input for scenario 1. Because there are no indications that the nutritive value of SBM-NL is different from SBM-SA, the same nutritive value was used. Although the cost price of SBM-NL is currently higher than the cost price of SBM-SA, an equal cost price was assumed, to facilitate 1:1 replacement. The use of a higher cost price might limit the inclusion level of SBM-NL and obscure its replacement potential.

CFP calculation

The main difference between SBM-SA and SBM-NL is a much smaller transportation distance for SBM-NL. There are also differences in cultivation characteristics. In FeedPrint, a new entry was created for soybeans grown and processed in the Netherlands. Differences in transportation distance were taken into account by changing the country of cultivation in FeedPrint. Cultivation data in FeedPrint were adapted for the new entry to represent the characteristics of soybean cultivation in the Netherlands. Cultivation data were collected from large-scale field trials, carried out since 2012 by feed manufacturer Agrifirm in collaboration with a group of farmers and research institute PPO. An overview of differences in cultivation characteristics between soybeans grown in the Netherlands and Brazil is given in Table 5.

Table 5

Differences in FeedPrint input data for soy cultivation characteristics (averages) between Brazil and the Netherlands.

Cultivation characteristic	Country	
	Brazil[1)]	*Netherlands*[2)]
Seed used (kg ha^{-1})	70	120
Organic N fertilizer (kg ha^{-1})	41	60
Synthetic N fertilizer (kg ha^{-1})	3	0
Mineral P fertilizer (kg ha^{-1})	86	0
Mineral K fertilizer (kg ha^{-1})	30	0
Lime (kg $CaCO_3$ ha^{-1})	400	100
Pesticides, herbicides, fungicides (kg a. i. ha^{-1})	2.30	0.75
Yield (kg ha^{-1})	2571	2650

[1)] Input from FeedPrint

[2)] Input from soy field trials, discussed with researcher Ruud Timmer (PPO, Lelystad, the Netherlands)

[3)] average yield from 2005 through 2009

In the Netherlands, there is a surplus of animal manure, which makes this a preferred source of nutrients. Several Dutch farmers who currently grow soybeans use liquid cattle manure for fertilization. Therefore, liquid cattle manure was chosen as the main N, P and K fertilizer for soybeans in the Netherlands. With an average application rate of 60 kg N ha^{-1}, also 22 kg P_2O_5 ha^{-1} and 85 kg K_2O ha^{-1} is applied with liquid cattle manure (Adviesbasis, 2014). Using the average realized yield level in the Netherlands, and P and K concentration in soybeans (CVB, 2011), actual P and K uptake by the beans (straw is left as residue on the field) can be calculated at 32 kg P_2O_5 ha^{-1} and 56 kg K_2O ha^{-1}, respectively. This means that K fertilization with liquid cattle manure is more than enough to compensate uptake by the beans, whereas P fertilization is 10 kg below requirement. However, since most agricultural soils in the Netherlands have high P levels, additional P fertilization will in most cases not be necessary to realize maximal yield. P and K fertilization with mineral fertilizer were therefore set at 0. Lime application was set at 100 kg ha^{-1} $year^{-1}$, a level aimed at general maintenance of soil pH irrespective of crop type.

Application of active ingredients with pesticides, herbicides etc. for soy cultivation is in the Netherlands considerably lower than in Brazil. In the Netherlands, currently only herbicides are used. Yield level in the Netherlands is comparable to Brazil, but is expected to increase considerably to about 4.5 ton ha^{-1} in about ten years. This increase is expected to be realized due to improvement of cultivation practices and the availability of new soy cultivars adapted to growing conditions in the Netherlands (Heselmans, 2013). When yield levels increase, input levels will also increase, but relatively at a lower rate. This will result in a decrease in CFP per kg of harvested soybeans and per kg of SBM.

After input of cultivation characteristics in FeedPrint, CFP was calculated for soybeans grown in the Netherlands. Based on CFP of soybeans, CFP of SBM and other soy products were also calculated in FeedPrint. Because there are no indications that the nutritive value of SBM-NL is different from SBM-SA, the same nutritive value was used.

Cultivation of soybeans in the Netherlands resulted in a CFP of 499 g CO_2-eq. kg^{-1} of beans. This is higher than CFP of cultivation in Argentine, Brazil or the US (Table 6). The reason for this is mainly a higher CFP of electricity use in the Netherlands compared to these other countries. Part of the differences is also caused by differences in the use of organic manure and synthetic fertilizers. CFP of SBM-NL, grown and processed in the Netherlands, was 500 g CO_2-eq. kg^{-1} at compound feed level (leaving the feed mill gate), which was 122 CO_2-eq. kg^{-1} lower compared to SBM-SA.

Table 6

CFP (g CO_2-eq. kg-1) of soybean cultivation in several countries (FeedPrint 2013.03).

Country	CFP
Argentine	442
Brazil	491
Netherlands	499
Ukraine	542
US	452

2.8 Scenario 7: replacement of SBM-SA by SBM from soybeans grown in Eastern-Europe

Input for compound feed formulation

In this scenario, SBM-SA is replaced by SBM from soy grown in Eastern-Europe and crushed in the Netherlands. The Ukraine (UA), the largest soy-producing country in Eastern-Europe, was chosen as the country of cultivation. The input for this scenario was equal to the input for scenario 1. Because there are no indications that the nutritive value of SBM-UA is different from SBM-SA, the same nutritive value was used. Although the cost price of SBM-UA may be higher than the cost price of SBM-SA, an equal cost price was assumed, to facilitate 1:1 replacement. The use of a higher cost price might limit the inclusion level of SBM-UA and obscure its replacement potential.

CFP calculation

It was expected that the much smaller transportation distance between the Ukraine and the Netherlands, if compared to between South-America and the Netherlands, would have a larger potential to reduce the CFP of SBM than differences in crop cultivation. Therefore, the choice was made not to collect specific crop cultivation data for the Ukraine, but to focus on the impact of transportation.

In FeedPrint, a new entry was created for soybeans grown in the Ukraine and processed in the Netherlands. Differences in transportation distance were taken into account by changing the country of cultivation in FeedPrint. Cultivation data in FeedPrint for the Ukraine were chosen to be same as for cultivation in Brazil. Average soybean yield in the Ukraine (1.7 Ton ha^{-1}, 2008-2012 (FAOSTAT)) is considerably lower than average yield in Brazil (2.8 Ton ha^{-1}, 2008-2012 (FAOSTAT)). However, cultivation intensity is in the Ukraine likely also lower. Considering that crop productivity is usually correlated with cultivation intensity, it was assumed that yield level in the Ukraine will be comparable to yield level in Brazil, at the same level of cultivation intensity.

SBM-UA, grown in the Ukraine and processed in the Netherlands, had a CFP at compound feed level (leaving the feed mill gate) of 600 g CO_2-eq., which is lower than CFP of SBM-SA (622 g CO_2-eq.).The underlying CFP of crop cultivation was in the Ukraine 542 g CO_2-eq. kg^{-1} of soybeans, the highest of all countries in FeedPrint (Table 6). When compared to crop cultivation in Brazil, the higher CFP of cultivation in the Ukraine was realized by a higher input of artificial N fertilizer (1 g CO_2-eq.), a higher CFP of land work (12 g CO_2-eq.) and a higher CFP of storage (38 g CO_2-eq.). This higher CFP is mainly caused by a higher CFP of electricity production in the Ukraine compared to Brazil (481 vs. 108 g CO_2-eq. kWh^{-1} in Vellinga et al., 2013).

2.9 Scenario 8: replacement of SBM-SA by insects (mealworms)

Compound feed formulation input

In this scenario, protein from SBM is replaced by protein from insects. Published LCA-studies of insect production are scarce; only one study was found with an LCA of the production of mealworms for human consumption (Oonincx and de Boer, 2012). This study was considered to be useful for a first investigation of the potential of insects to replace SBM in compound feed. Fresh mealworms have a DM content of on average 41% (Oonincx and de Boer, 2012) and have to be dried to a DM content of 88% for replacement of SBM in compound feed. CP content of mealworms is on average 49% in DM, somewhat lower than CP content of SBM (53%). Considering that mealworm protein is of comparable or higher quality if compared to SBM (Veldkamp et al., 2012), the assumption was that dried mealworms can replace SBM on at least a 1:1 basis. Although the cost price of mealworms can be about 50 times higher than the cost price of SBM (Veldkamp et al., 2012), an equal cost price was assumed to facilitate 1:1 replacement. The use of a higher cost price might limit the inclusion level of mealworms and thus obscure its (technical) replacement potential. The nutritive value of mealworms as used in the present study is given in Appendix 1.

CFP calculation
The mealworms in the study of Oonincx and de Boer (2012) were fed a diet of carrots and mixed grains. Since these products are feed ingredients themselves, the calculated CFP by Oonincx and de Boer (2012) is relatively high compared to a preferred scenario when mealworms or other insects are grown on organic waste or by-products with low economic allocation. However, even when the diet contribution (1490 g CO_2-eq. kg^{-1}) is excluded, CFP of the fresh product (1160 g CO_2-eq.) is still about double the CFP of (dried) SBM used in the present study (622 g CO_2-eq. kg^{-1}). This part of the total CFP is almost completely caused by energy use. According to Oonincx and de Boer (2012): "Mealworms, being poikilothermic, depend on suitable ambient temperatures for growth and development. When ambient temperatures are low, heating is required, increasing energy use. Mitigation measures are being investigated: larger larvae in this system produce a surplus of metabolic heat, which could be used to heat the heat-demanding smaller larvae".

Drying the mealworms to a required DM content of 88% requires the removal of 1150 g of water (for 1 kg of dried mealworms, 2.15 kg of fresh mealworms is needed). Removal of this water by thermal drying involves an estimated energy use of 9.6 MJ per kg of evaporated water (Nemecek et al., 2003). Using natural gas for drying, with a CFP of 70 g CO_2-eq. MJ^{-1} (FeedPrint), drying results in an extra CFP of 770 g CO_2-eq. per kg of dried mealworms. Because 2.15 kg of fresh mealworms are necessary for 1 kg of dried mealworms, the CFP of fresh mealworms has also to be multiplied by 2.15 to 2490 g CO2-eq. kg^{-1}. This results in a total CFP of 3260 g CO_2-eq. per kg of dried mealworms, excluding diet contribution. Also the contribution of transportation to the feed mill and some processing at the mill (e.g. grinding) to the total CFP is excluded.

2.10 Scenario 9: replacement of SBM-SA by defatted algae

Compound feed formulation input
In this scenario, SBM is replaced by defatted algae, a co-product of the processing of algae for biodiesel production. Algae can contain up to 50% of CP in DM (Van Krimpen et al., 2013), depending on type (microalgae, macro algae, duckweed) and strain or species within type. The nutritive value of defatted algae as used in the present study is given in Appendix 1. Although the cost price of defatted algae is likely higher than the cost price of SBM-SA, an equal cost price was assumed, to facilitate 1:1 replacement. The use of a higher cost price might limit the inclusion of defatted algae and obscure its replacement potential.

CFP calculation
There are a great number of studies available on the (potential) productivity of algae, with different types of algae used under different conditions, and with different processing options. Numerous studies have used LCA to quantify the environmental performance of algal biofuels; yet there is no consensus of results. To reduce the dependency of conclusions on specific cases, we used the work of Sills et al. (2013). Sills et al. (2013 used a Monte Carlo approach to estimate ranges of expected values of LCA metrics by incorporating parameter variability with empirically specified distribution functions.

Algae can be primarily grown for animal feed, but the use of only the defatted rest product is much more interesting. Not only is the CP content after oil extraction higher, but, more importantly, all upstream CFP is usually credited to the biofuel production (Sills et al., 2013). Oil can be extracted from algae by wet or dry extraction. Wet extraction has the lowest CFP (Sills et al., 2013) and is therefore the extraction method of choice. Sills et al. (2013) estimated a CFP of about 88 g CO_2-eq. per MJ of biodiesel produced for the cultivation phase, and 8 g CO_2-eq. per MJ of biodiesel for the dewatering step that precedes wet extraction at 20% DM (CFPs derived from Figure 3 in Sills et al. (2013)). Based on an algal oil content of 34% in DM and an oil extraction efficiency of 80% (Sills et al., 2013), the extractable oil content is 27% of DM. With a higher heating value (HHV) per kg of biodiesel of 38 MJ (Sills et al., 2013), this corresponds to a biodiesel yield of 10.34 MJ per kg algal DM, and a corresponding CFP of 992 g CO_2-eq. per kg of algal DM, or 873 g CO_2-eq. at 88% of DM (Note: this is before oil extraction and with algal DM is still suspended in water at 20% DM). The content of extractable biodiesel assumed by Sills et al. (2013) seems rather high; Brune et al. (2009) states that oil extraction levels achieved in practice have never exceeded 20% of DM. In that case, CFP per kg of algal DM could be higher than derived from the data of Sills et al. (2013). In the scenario used by Sills et al. (2013), algae were produced at a large production facility (1210 ha) and base productivity was assumed to be 25 g ash-free DM m^{-2} day^{-1}. Base productivity may be achieved in the near-term; actually achieved productivity is much lower at 2.4 to 16 g ash-free DM m^{-2} day^{-1} (Sills et al., 2013).

Oil extraction at 27% of DM results in a decrease in DM content of fresh product from 20 to 15.4%. When all upstream CFP is allocated to the biodiesel production, CFP of defatted algae only consists of CFP of drying the product from 15.4 to 88% DM. This means that for 1 kg of dried defatted algae, 5.7 kg of wet biomass is needed and 4.7 kg of water has to be removed. Water removal by thermal drying, using natural gas as energy source, would result in an increase in CFP of 3161 g CO_2-eq. per kg of dried product (4.7 x 9.6 x 70). However, the contribution of drying to total CFP can be substantially reduced when thermal drying of the wet product is preceded by application of pre-drying/concentration techniques with much lower energy use, such as membrane filtration, mechanical vapour recompression or thermal vapour recompression (Van Zeist et al., 2012)[1]. Wet products can be pre-dried up to 60% of DM, with a typical energy use of on average 0.25 MJ of fuel and 0.10 kWh of electricity per kg of water removed (Van Zeist et al., 2012). Spray drying of wet products typically involves an energy use of 4.1 MJ of fuel and 0.106 kWh per kg of water removed (Van Zeist et al., 2012). Pre-drying from 15.4% to 60% involves the removal of 4.24 kg of water, and spray drying from 60 to 88% the removal of 0.47 kg of water per kg of dried product. Using natural gas as fuel, the CFP of drying is calculated at 544 g CO_2-eq. kg^{-1} of dried defatted product, using FeedPrint CFP-factors of 70 and 709 g CO_2-eq. per MJ and kWh (for the Netherlands), respectively.

Because it is likely that the economic value of algae is not only defined by the oil content, but also by the value of the protein, a split in allocation of upstream CFP based on economic value is reasonable. For soybean meal (CF<45, CP<480), in FeedPrint about 36% of upstream CFP (soybean production) is allocated to the soybean meal per kg of product. This allocation can be used to give a rough indication of the effect of allocation on CFP of defatted algae. Soybeans and soybean meal have approximately the same DM content. Roughly 1.37 kg of algal DM is necessary to produce 1 kg of defatted algal DM. With use of this data, contribution of upstream CFP can be calculated at (0.36 x 1.37 x 873 = 431 g CO_2-eq. per 0.88 kg of defatted algal DM, dissolved in water at 15.4% DM. Including the contribution of energy-efficient drying (544 g CO_2-eq.), total CFP is 975 g CO_2-eq. per kg of dried product. The percentage of allocation may be different for defatted algae compared to soybean meal, depending on differences in percentage of oil extraction, differences in economic value of biodiesel relative to defatted rest product versus economic value of soybean oil relative to soybean meal/hulls. A more detailed analysis is therefore necessary to calculate a reliable contribution of upstream CFP tot total CFP of defatted algae, in case economic allocation is applied. All CFP's calculated above exclude the contribution of transportation to the feed mill and some processing at the mill (e.g. grinding).

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[1] Not all products with low DM content are suitable for application of pre-drying/concentration techniques, only products which are dissolved or suspended in water. E.g. mealworms have a relatively low DM content (41%) but have to be dried thermally.

2.11 Scenario 10: replacement of SBM-SA by bacterial single-cell protein

Introduction
In this scenario, SBM-SA is replaced by bacterial single-cell proteins (SCP). SCP typically refers to sources of mixed protein, extracted from pure or mixed cultures of algae, yeasts, fungi or bacteria. These organisms are grown on e.g. agricultural wastes, by-products from oil refineries, or natural gas, and the produced SCP is used as a substitute for protein-rich foods in human and animal feeds. In the present study, the production of SCP from natural gas is chosen as case. This choice was made because the direct cultivation on natural gas seems an efficient way of production, the product is commercially available, and main input data are available (Huizing, 2005). The production of SCP from natural gas seems one of the most efficient ways, because 80% of the CFP of gas use is due to the conversion of CH_4 into CO_2; only 20% is upstream emission during gas production (Vellinga et al., 2013). The CFP due to conversion of C into CO_2 is also realized when microbes are grown on agricultural wastes, but it is likely that also a considerable amount of energy is required to extract the protein from these substrates. Also, additional greenhouse gas emissions may occur during the fermentation process, and hygienic issues may have to be considered.

Compound feed formulation input
The nutritive value of SCP as used in the present study is given in Appendix 1. When replacement of SBM by SCP is considered, it has to be taken into account that, from a nutritional point of view, nucleic acids content in SCP is one of the main factors hindering its utilization as food for animals with longer life-spans. Excessive intake of nucleic acids leads to uric acid precipitation, causing health disorders, such as gout or kidney stone formation. UniBio, a commercial producer of SCP (www.unibio.dk), expects to be able to reduce the nucleic acid content below critical levels. When replacement of SBM by SCP is considered, it has also to be taken into account that the price of SCP is usually higher than the price of SBM, and that the production of SCP for animal feed is most likely not profitable from an economic perspective (Huizing, 2005). Although the cost price of bacterial SCP is likely higher than the cost price of SBM-SA, an equal cost price was assumed in the present study, to facilitate 1:1 replacement. The use of a higher cost price might limit the inclusion level of SCP and obscure its replacement potential.

CFP calculation
One of the largest commercial producers of SCP from natural gas is UniBio (Denmark). A short and generalized description of their production process is given below. At UniBio, SCP is produced from natural gas during a continuous fermentation process, operated at 45ºC, and using the bacterium *Methylococcus capsulatus (Bath)*. The fermentation process is operated with 2 – 3% of DM (biomass) and a dilution rate of 0.20-0.25 h^{-1}. Apart from natural gas, the bacteria are also fed with oxygen, ammonia, and several mineral solutions (Table 7). At harvest, the bacterial biomass is concentrated up to 30% DM by centrifugation. The concentrated biomass is quickly heated to 140ºC for sterilisation, and then quickly cooled to 70ºC. During this process, the biomass is inactivated and cells undergo lysis, so the protein becomes more accessible. Finally, the biomass is dried in a spray dryer with an integrated fluid bed. This gives a non-dusty agglomerated product, with 94% DM and 71% CP in DM. More information on the production process and the protein composition can be found on the website of UniBio (www.unibio.dk), UniProtein (www.uniprotein.eu), or in Huizing (2005).

An LCA on the production of SCP from natural gas (or other energy sources) has not been published yet. Earlier, input data for SCP production at UniBio were collected by Huizing (2005). These data are useful to calculate the largest part of the CFP for the production of this type of SCP. An overview of the specific raw materials required to produce 1 ton of protein is given in Table 7.

Table 7

Specific process conditions and specific material use for the production of SCP from natural gas (parameters expressed in kg or per ton of protein) (Huizing, 2005).

Specific process conditions	Amount
Productivity (kg m^{-3}.hr)	4
Production days (days $year^{-1}$)	330
Extra installed volume (%)	25
Base capacity (ton $year^{-1}$)	40000
Protein content product (%)	92[1]
Specific investment (€ ton^{-1})	0.865
Specific gas use (drying) (Nm^3 ton^{-1})	0.669[2]
Specific electricity use (kWh ton^{-1})	1438

Specific raw material use	Amount
Natural gas (Nm^3 ton^{-1})	1700
H_2O (m^3 ton^{-1})	8.51
O_2 (Nm^3 ton^{-1})	2025
NH_3 (kg ton^{-1})	138
H_3PO_4 (kg ton^{-1})	42
$MgSO_4$ (kg ton^{-1})	18
$FeSO_4$ (kg ton^{-1})	1
$CuSO_4$ (kg ton^{-1})	1
KNO_3 (kg ton^{-1})	4

[1] Is likely not protein content, but DM content

[2] Value seems not correct, far too low

Natural gas is the most important input in terms of contribution to the CFP of SCP. During the SCP production, methane is converted into bacterial biomass and CO_2, according to the formula (www.unibio.dk): $1.00\ CH_4 + 1.454\ O_2 + 0.105\ NH_3 \rightarrow 0.520\ X$ (biomass) $+ 0.480\ CO_2 + 1.69\ H_2O$

Under standardized conditions (0ºC, 1 bar), an ideal gas has a molar volume of 22.414 L mol^{-1}. When 1700 Nm^{-3} is used to produce 1 ton of protein (Table 7), this means that 75845 moles of natural gas or CH_4 are required to produce 1 ton of protein, and that (75845 x 0.48 =) 36406 moles of CO_2 are produced in the process. This molar amount converts into 1602220 g CO_2, using the molar weight of CO_2 (44.01 g). The production of 1 kg of SCP-protein thus involves a CFP of 1602 g CO_2-eq. from the use of natural gas. For the production of 1 ton of SCP-protein, also 1438 kWh of electricity is used. This equals to a CFP of 1020 g CO_2-eq. per kg of SCP-protein, using the CFP for electricity production in the Netherlands (709 g CO_2-eq. kWh^{-1}; FeedPrint 2013.03). For the production of 1 ton of SCP-protein, also 138 kg of NH_3 is used. The production of 1 ton of NH_3 in Western-Europe requires an input of 35 GJ of natural gas (Vellinga et al., 2013). Energy use from natural gas is thus 4.83 MJ per kg of protein. This converts into a CFP of 338 g CO_2-eq. per kg of SCP-protein, using a CFP of natural gas of 70 (Vellinga et al, 2013). Taking into account these inputs, CFP adds up to 2961 g CO_2-eq. per kg of protein. Because the end product does not contain 100% CP but 71% CP in DM, this partial CFP is 1850 g CO_2-eq. per kg of end product at 88% DM (and 62% CP). This excludes the use of some other input material (Table 7) and some transportation. It also appears that the energy use for drying is not included in these figures. Huizing (2005) provides a specific gas use for drying of 0.669 MJ ton^{-1} (of protein?), which seems not correct (far too low). Using the ammonia input per ton of protein, and the production formula given above, it appears that the natural gas input is solely used for conversion of methane into protein, and not for drying. The electricity input also seems far too low to represent total energy input for drying. The contribution of the drying step is therefore calculated additionally. The wet product has to be dried from a DM content of 2-3% to a DM content of 88%. For 1 kg of dried end product at 88% DM, on average 35.2 kg of wet product (2.5% DM) is necessary, and 34.2 kg of water has to be removed.

The contribution of drying to total CFP can be substantially reduced when thermal drying of wet products is preceded by application of pre-drying/concentration techniques with much lower energy use, such as membrane filtration, mechanical vapour recompression or thermal vapour recompression (Van Zeist et al., 2012). Wet products can be pre-dried up to 60% of DM, with a typical energy use of on average 0.25 MJ of fuel and 0.10 kWh of electricity per kg of water removed (Van Zeist et al., 2012). Spray drying of wet products typically involves an energy use of 4.1 MJ of fuel and 0.106 kWh per kg of water removed (Van Zeist et al., 2012). Pre-drying from 2.5% to 60% involves the removal of 33.73 kg of water, and spray drying from 60 to 88% the removal of 0.47 kg of water per kg of dried product. Using natural gas as fuel, the CFP of drying (pre-drying and thermal drying) is calculated at 3151 g CO_2-eq. kg^{-1} of dried product at 88% DM, using FeedPrint CFP-factors of 70 and 709 g CO_2-eq. per MJ and kWh (the Netherlands), respectively. Including the contribution from production, partial CFP of SCP is then calculated at 5001 g CO_2-eq. per kg of dried product (88% DM). CFP will further increase when the use of other raw materials is taken into account. Because this information is not available, this contribution was not calculated. From the input data, it is not clear which energy source is used to maintain the process temperature at 45ºC. Possibly, this heat is largely generated during the fermentation process itself. In the calculated CFP, the contribution of transportation to the feed mill and some processing (e.g. grinding) is excluded.

2.12 Consequential LCA scenarios

Besides the ten attributional LCA scenarios, three explorative consequential scenarios have been worked out. The selected scenarios were:

- the use of porcine PAP (Processed Animal Protein) as feed ingredient in a poultry diet instead of using it as fertilizer
- soybean cultivated and processed in Europe
- extra supply of wheat DDGS as residual from ethanol production.

For each scenario, three environmental impact indicators (climate change, land occupation, fossil depletion) and one aggregate score of these three indicators (ReCiPe) were provided.

The background of the ReCiPe tool is explained in further detail here. Life cycle assessment (LCA) is a methodological tool used to quantitatively analyse the life cycle of products/activities within the context of environmental impact. However, LCA has been rapidly incorporated into higher strategic levels, including decision- and policy-making at the firm/corporate levels, and it now clearly extends beyond only an assessment of end products. It has been stated that LCA is goal- and scope-dependent, and this most certainly also applies to LCA methodologies. However, at the same time, the autonomous developments in LCA have sometimes led to discrepancies between methods that cannot be explained by necessity alone, and for which historical factors play an important role. One such example is the development of midpoint-oriented and endpoint-oriented methods for life cycle impact assessment (LCIA). A number of methods used for LCIA convert the emissions of hazardous substances and extractions of natural resources into impact category indicators at the midpoint level (such as acidification, climate change and ecotoxicity), while others employ impact category indicators at the endpoint level (such as damage to human health and damage to ecosystem quality). The ReCiPe tool is a life cycle impact assessment method, which comprises harmonised category indicators at the midpoint and the endpoint level (Goedkoop et al., 2013). Within the framework of our report, the ReCiPe method uses the midpoint level results of the LCA scenarios in terms of climate change, land occupation and fossil depletion as input values, where after the impact of these factors on the damage of the ecosystem as endpoint level indicator is calculated according to harmonised principles and procedures.

Addition of porcine Processed Animal Protein to a poultry diet.

As a consequence of adding pork meat meal (4.8%; Appendix 1) to a poultry diet, the wheat content increased from 21 to 28% and the potato protein content from 0.3 to 1.8%, whereas the content of palm oil decreased from 3.3 to 0.8%, and the soybean meal content from 29 to 19%. Currently, the low grade PAPs are used as fertilizer. Because of the use of pork meat meal in the diet, new fertilizer is needed to replace it. For each kg of pork meat meal 0.10 kg of N and 0.086 kg P2O5 as fertilizer are needed. It is assumed that the volume of production of PAP will not be affected by the change from fertilizer to feed application.

Besides the basal comparison of a diet with and without pork meat meal, two replacement scenarios for PAP as fertilizer were considered:

- a combination of CAN (Calcium Ammonium Nitrate) and TSP (Triple Super Phosphate)
- a combination of Urea and SSP (Single Super Phosphate).

It is assumed that the emissions of PAP and artificial fertilizer (CAN, TSP, and SSP) are similar. For urea, an additional fossil CO_2 emission is counted.

Soybean cultivated and processed in Europe

This scenario assumes that 1 million ha with EU maize cultivation is replaced by soybean cultivation. Based on a yield level of 2.700 kg per ha, this means about 2.7Mtons of soybean cultivated in Europe. Starting point was that the total market volume of soybean and maize did not change. Therefore, in this scenario it was assumed that less soybeans will be grown in North and South America, whereas more maize will be cultivated in North America (based on previous analysis/worksheet of M. Buijsse, Agrifirm, 2013). This also implied less crushing of soybean in North and South America, thereby replacing imports of processed soybean meal into Europe. Moreover, an excess of soybean oil is being produced in Europe, that needs to be potentially exported back to South America. Finally, maize starch facilities in Europe have less EU cultivated maize available for processing. This leads to imports of maize from North America to Europe. These changes are shown graphically in Figure 2.1.

Figure 2.1 *Changes in volumes of soybean and maize cultivation, soybean crushing, and soya oil in Europe (EUR), North America (NA) and South America (SA) as a result of the scenario that 1 million hectares of soybean are cultivated in Europe.*

Extra supply of wheat DDGS as residual from ethanol production

In this scenario, the environmental impact of the availability of 4 Mtons additional DDGS in Europe is investigated. For this scenario, an ICCT study was used as reference (Hazzledine et al., 2011) in which the replacement ratios of animal feed were estimated for 51 different diets. According to the study, the Great Britain market comprises a total of 13.165.200 ton of raw feed ingredients, whereas in the baseline scenario 275 kton of wheat DDGS is used.

In the replacement scenarios, the effect of increased supply of Wheat DDGS on the use of other dietary ingredients is investigated, whereas the ratio between barley and wheat is assumed to be constant (1 to 5).

Figure 2.2 provides a schematic overview of the petrol production, the wheat cultivation chain, and the relation with bio-ethanol and DDGS production.

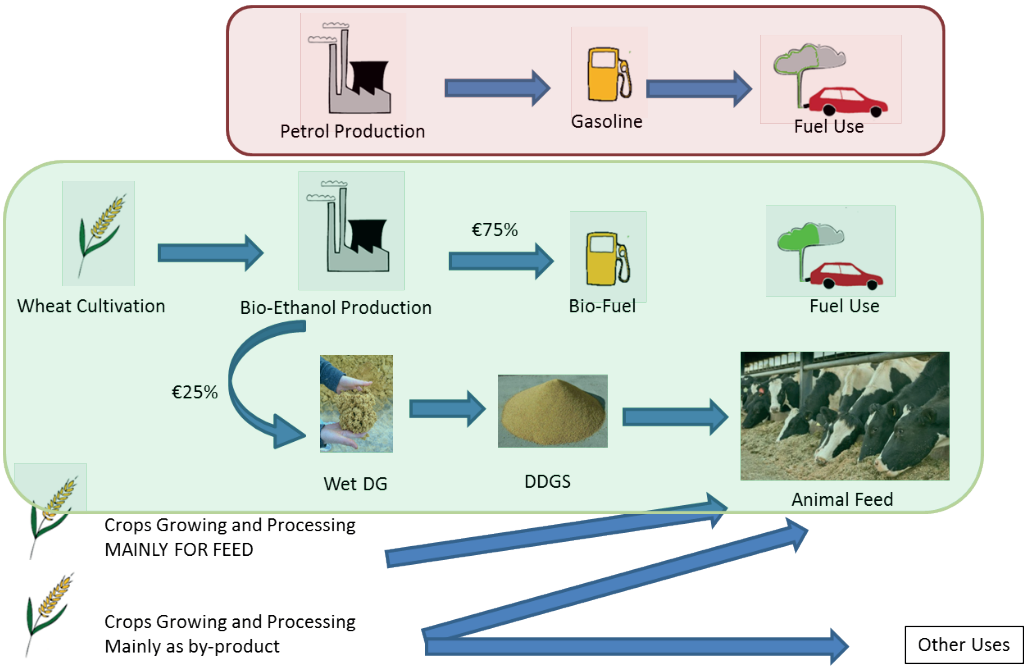

Figure 2.2 *Schematic overview of the petrol production, the wheat cultivation chain, and the relation with bio-ethanol and DDGS production.*

For ethanol production, the following inputs are necessary:
- 1 ton of wheat grain
- 1558.73 MJ of steam from natural gas
- 32.74 MJ from electricity.

Based on these inputs, the following outputs will be delivered:
- 285.80 kg ethanol
- 977.42 kg wheat distillers grains, wet.

The drying of DDGS requires:
- 1 ton of wheat distillers grains, wet
- 1909.29 MJ of steam from natural gas
- 38.45 kWh from electricity.

The drying of 1 ton of wet wheat distillers grains results in 333.33 kg of wheat DDGS.

The standard situation is based on a passenger car, that is using petrol fuel, 4% vol. ETBE (Ethyl tert-butyl ether) with an energy content of 47 MJ per kg of petrol. The petrol is replaced by bio-ethanol on a caloric basis. Ethanol is assumed to generate 29.7 MJ/kg.

Table 8 shows the effect of increasing amounts of DDGS available in the feed market on replacement of different dietary ingredients.

Table 8

Effect of increasing amounts of DDGS available in the feed market on replacement of different dietary ingredients.

Values in Mtons	Baseline	DDGS 0.43	DDGS 0.72	DDGS 0.99	DDGS 1.17	DDGS 1.36	DDGS 1.62
DDGS	275.00	430.00	720.00	990.00	1,170.00	1,360.00	1,620.00
Barley & Wheat grains	6,225.91	5,541.06	5,852.35	5,603.31	5,416.54	4,918.46	4,420.39
Wheat feed meal	825.42	586.05	685.10	709.86	726.37	742.88	759.39
Maize gluten feed	368.83	387.28	339.33	331.95	317.20	328.26	320.89
Soybean meal	934.56	448.59	542.04	588.77	607.46	607.46	635.50
Soybean hulls	66.19	64.20	64.20	64.20	64.87	65.53	66.19
Rapeseed meal	1,088.12	1,088.12	1,088.12	1,088.12	1,088.12	1,088.12	1,077.24
Sunflower meal	374.63	340.91	280.97	269.73	273.48	284.72	307.19
Sugar beet pulp	242.39	242.39	242.39	242.39	242.39	242.39	242.39
Palm kernels	360.06	367.26	367.26	360.06	338.45	316.85	316.85

Increasing the amount of DDGS resulted in a decreased use of barley and wheat, wheat feed meal, maize gluten feed, soybean meal, sunflower meal and palm kernels, whereas the use of soybean hulls, rapeseed meal and sugar beet pulp remained unchanged.

Within the DDGS case, the environmental impact of six different scenarios, differing in system borders, are calculated.

1. Environmental impact, not taking into account the ethanol production.
    - The case starts from the drying of wheat DDGS.
2. Environmental impact, taking into account 25% of the ethanol production.
    - Wheat DDGS contributes for 25% of the revenues, which is responsible for determining the economic viability of the bio-ethanol production.
3. Environmental impact, taking into account 100% of the Ethanol production.
4. Environmental impact, taking into account 100% of the Ethanol production with expansion (use).
    - Takes into account the replacement of petrol by bio-ethanol in the use phase.
5. Environmental impact, taking into account 100% of the Ethanol production with expansion (use + production).
    - Takes the production of petrol additionally into account.
6. Environmental impact, taking into account 100% of the ethanol production with expansion (use + production), as well as the alternative uses for palm kernels and wheat, which uses are not directly related to the feed sector. The use of soybean meal is also significantly reduced, but soybean meal is mainly a feed product, and one of the main reasons behind soy production is feed. So, it is assumed here that if there is less demand for soybean meal, the production might simply reduce.
    - This scenario is the most complete picture: it takes into account the replacement ratios in the feed market, and the benefits of the production and use of ethanol as a replacement for fossil petrol, as well as the replacement of other feed ingredients.

3 Results

3.1 CFP of single feed ingredients (attributional LCA)

The CFPs of the single feed ingredients, used to replace SBM-SA in the compound feed, calculated in FeedPrint or separately (applying FeedPrint methodology when possible), are given in Table 9. CFPs of other feed ingredients used in compound feed formulation (Table 2, Appendix 2) were taken from FeedPrint (version 2013.03) and are not reported here.

Table 9

CFP (g CO2-eq. kg-1 of product), DM and CP content (g kg-1 of product) of single feed ingredients used to replace SBM-SA in starting compound feed for fattening pigs.

Feed ingredient	CFP	DM	CP
SBM-SA	622	873	464
HP-SSM	860[1)]	880	460
Poultry meat and bone meal	326	957	461
Poultry meat meal	326	950	580
DDGS-maize	895	901	261
SBM-NL	500	873	464
SBM-UA	600	873	464
Mealworms	>3260[2)]	880	431
Defatted algae	>544 - 975[3)]	880	~ 460
Bacterial SCP	>1850 - 5001[4)]	880	625

[1)] Without contribution of extra processing (for extra fibre removal)

[2)] Without contribution of the mealworm diet

[3)] Depends on level of economic allocation; also based on optimistic assumptions (productivity, oil content, drying efficiency).

[4)] Not clear whether drying energy is included in the available input data (= 1850 g) or has to be calculated additionally (= 5001 g).

Based on their CFP (in relation to dry matter and crude protein content), it can already be concluded that HP-SSM, DDGS-maize, mealworms and bacterial SCP are not suitable to replace SBM-SA in compound feed, because this would result in a considerable increase in CFP of the compound feed, and thus in environmental impact.

3.2 CFP of alternative compound feeds (attributional LCA)

The CFP and cost price of the reference and alternative compound feeds are given in Table 10. A more detailed composition of the formulated compound feeds is for each scenario given in Appendix 2. The increase in CFP, relative to CFP of the reference, of the formulated alternative compound feeds with HP-SSM, DDGS-maize, mealworms and bacterial SCP confirmed that these ingredients are not suitable to replace SBM-SA. DDGS was not included at all during compound feed formulation, possibly because cost price was too high relative to other high-protein ingredients.

Table 10

Inclusion level (%) of the (alternative) high-protein ingredient, CFP (g CO_2-eq. kg-1 of the diet) and cost price (€ 100-1 kg of diet) for alternative starting compound feeds for fattening pigs, with replacement of SBM-SA by high-protein ingredients of European origin.

Replacement scenario	Inclusion level (%)	CFP	Cost price
1. Reference, with SBM-SA	12.0	595	25.30
2. SBM-SA ≤ 6%	6.0	606	25.81
3. HP-SSM	1.1	627	26.84$^{1)}$
4. Poultry meat (bone) meal	2.5	591	26.46
5. DDGS (maize)	0.0	626	26.84
6. SBM-NL	12.0	580	25.30$^{2)}$
7. SBM-UA	12.0	592	25.30
8. Insects (mealworms)	6.1	>717	25.77$^{2)}$
9. Defatted algae	2.8	>608-626	26.35$^{2)}$
10. Bacterial SCP	3.0	>644-739	26.17$^{2)}$

1) Cost price is (a little) too low, because cost of extra fibre extraction was not taken into account

2) Cost price is (far) too low, because cost price of the replacement is supposed to be similar to cost price of SBM-SA, whereas in practice it will be much higher

CFP of the compound feed also increased for (partial) replacement of SBM-SA by defatted algae, or in case of restriction of the inclusion level of SBM-SA to a maximum of 6%. CFP of compound feed is unchanged when a small amount of SBM-SA is replaced by poultry meat (bone) meal. CFP of compound feed is slightly lower when SBM-SA is replaced by SBM-NL and of comparable level when replaced by SBM-UA.

All alternative compound feeds had a higher cost price than the reference feed, except for the feed with replacement of SBM-SA by SBM-NL or SBM-UA. The price of alternative compound feeds with replacement of SMB-SA by mealworms, defatted algae or SCP were also higher, despite the fact that the cost price of the alternative ingredient was assumed to be equal to SBM-SA. A main reason for this is that the digestible amino acid profile and contents of SBM-SA better met the requirements of the starter diet compared to the other ingredients. Therefore, SBM-SA was only partially replaced by the alternative ingredients; the remaining part was replaced by other regular ingredients with higher cost prices. Although the alternative compound feeds with SBM-NL and SBM-UA have an assumed similar cost price in the present study, the market price can be higher for SBM-UA and will the coming years certainly be higher for SBM-NL. It can therefore be concluded that replacement of SBM-SA by alternative high-protein ingredients of European origin in case of the present study led to higher cost prices.

3.3 Porcine Processed Animal Protein as feed ingredient in a poultry diet (consequential LCA)

Figure 3.1 shows the impact of the use of porcine processed animal protein in a poultry diet on the savings in climate change. In this figure, the climate change is expressed in kg CO_2-equivalents per ton replaced processed animal protein.

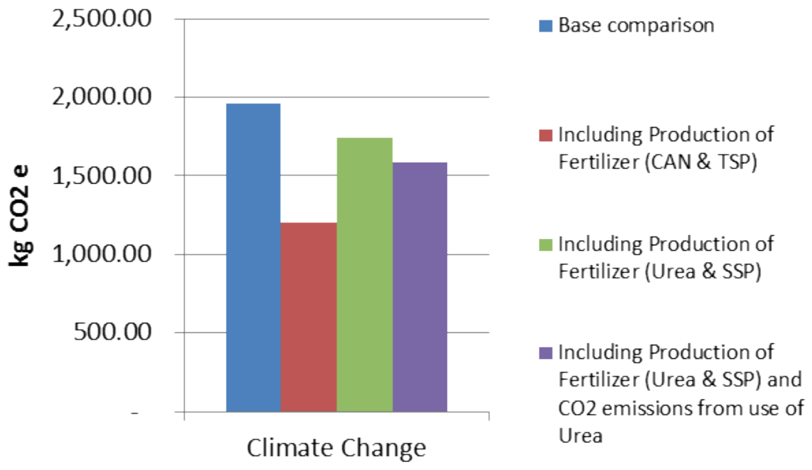

Figure 3.1 *Impact of the use of porcine processed animal protein in a poultry diet on the savings in climate change (kg CO_2-equivalents per ton replaced processed animal protein).*

Replacement of soybean meal and palm oil by PAP, wheat, and potato protein resulted in a saving of about 2,000 kg CO_2-eq per ton replaced PAP. The reduction of the dietary palm oil content largely contributed to this saving. Taking into account the production of additional fertilizer, the savings are about 1,200 kg CO_2-eq per ton replaced PAP in case that CAN & TSP are used, and about 1,700 kg CO_2-eq per ton replaced PAP in case that Urea & SSP are used. After correction for the CO_2-emissions from Urea, the savings are about 1,550 kg CO_2-eq per ton replaced PAP. The use of 1 ton of PAP resulted in the saving of 0.5 ha of land use.

Contrary to this savings, the production of additional fertilizer required a considerable extra amount of fossil energy. The production of CAN & TSP required more than 5000 kg oil-eq., whereas the production of Urea & SSP required 6000 kg oil-equivalents per ton replaced PAP. Figure 3.2 shows the aggregated effect (ReCiPe) of the savings of the different scenario's, taking into account the environmental impact of climate change, land use, and the use of fossil energy.

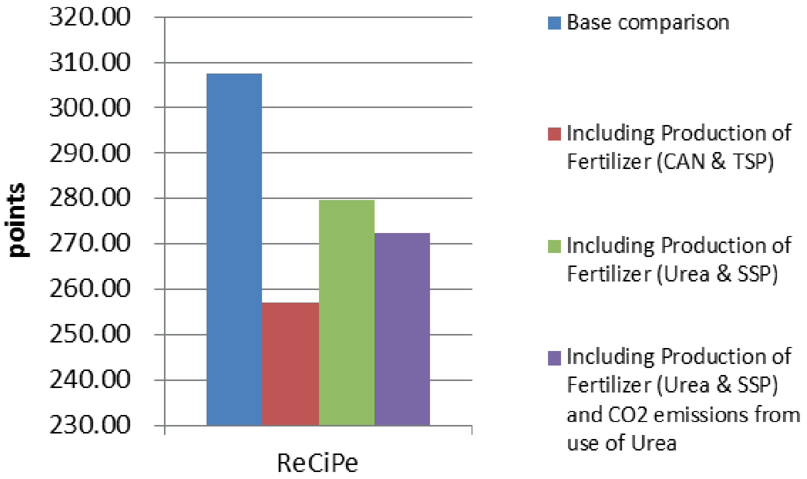

Figure 3.2 *The aggregated effect (ReCiPe, expressed in points) of the savings of the different scenario's, taking into account the environmental impact of climate change, land use, and the use of fossil energy.*

The aggregated saving of replacing 1 ton PAP was ~260 points in case using CAN and TSP as fertilizers, and ~ 270 points in case of using urea and SSP as fertilizers.

3.4 Soybean cultivated and processed in Europe (consequential LCA)

Soybean cultivation:
The impact of the cultivation of soybean in Europe on climate change is assumed to be similar to the cultivation in the US and South America.

Transport:
The local transport and energy efficiency in Europe are better developed in Europe than in the US, while there parameters in turn are better developed in the US compared to South America. As a consequence, crushing in Europe (extra 117 kg CO_2-eq./ton soybean crushed) is more efficient than crushing in the US (extra 178 kg CO_2-eq./ton soybean crushed), which in turn is more efficient than crushing in South America (extra 210 kg CO_2-eq./ton soybean crushed). The net savings (weight averages from US and SA of the cradle to gate) are about 69 kg CO_2-eq./ ton soybean replaced.

Crushing:
Crushing of 2.7Mton of soybean in Europe saves about 1.95 Mton (~72%) of soybean meal imports, resulting in less transportation of processed products. This brings the total savings to about 107 kg CO2 e/ton soybean replaced. Crushing of 2.7 Mton of soybean in Europe requires about 0.54 Mton (~20%) of soybean oil export to South America. This brings the total savings back to about 95 kg CO_2-eq./ton soybean replaced.

Maize cultivation:
Cultivation of 2.7 Mton of soybean in Europe implies 8.7 Mton of Maize that will not grow in Europe, which are assumed to be grown in the US. The cultivation of maize in the US has a slightly higher yield than in Europe (9.1 ton/ha vs 8.4 ton/ha). Moreover, mainly due to fertilizer and manure application, the cultivation of maize in the US has a lower environmental impact: ~458 kg CO_2-eq./ton in Europe vs ~350kg CO_2-eq./ton in the US. After taking into account the cultivation of maize in the US, the total savings become now 427 kg CO_2-eq./ton of soybean replaced.

Import of maize:
Because 8.7 Mton of maize is not cultivated in Europe, this will be compensated by importing 8.7 Mton maize from the US, at about 95 kg CO_2-eq./ton maize.

All consequences
Taking all described consequences into account, it can be concluded that replacing 1 ton of US/SA soybean by 1 ton of EU soybean saves 126 kg CO_2-eq./ton soybean replaced, as shown in Figure 5 Contrary to this savings, the shift from US/SA to EU soybean required a considerable extra amount of fossil energy, as shown in Figure 3.3.

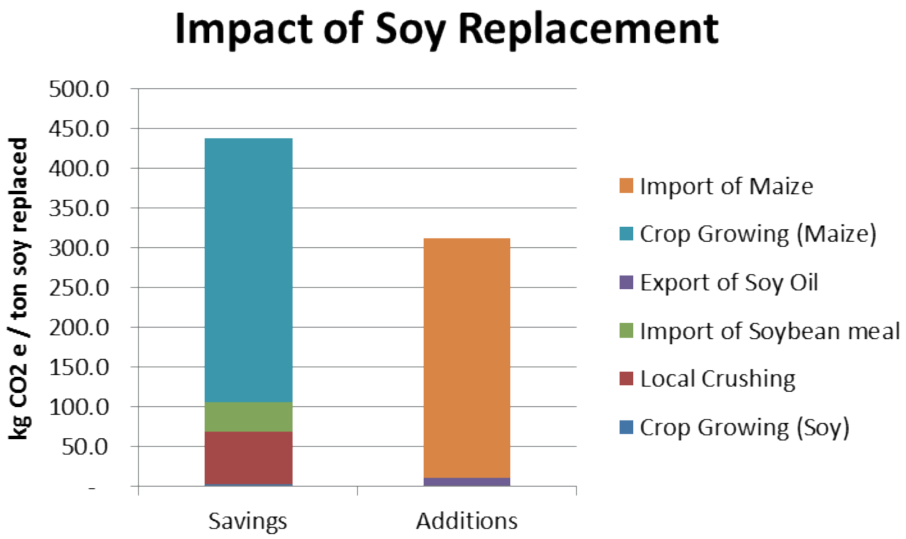

Figure 3.3 *Consequential effects of replacement of soybean from the US and South America by European soybean (savings and additions) on the climate change expressed in kg CO2-eq. per ton soybean replaced.*

Figure 3.4 shows the aggregated effect (ReCiPe, expressed in points) of the savings and additions of the replacement of maize by soybean, taking into account the environmental impact of climate change, land use, and the use of fossil energy.

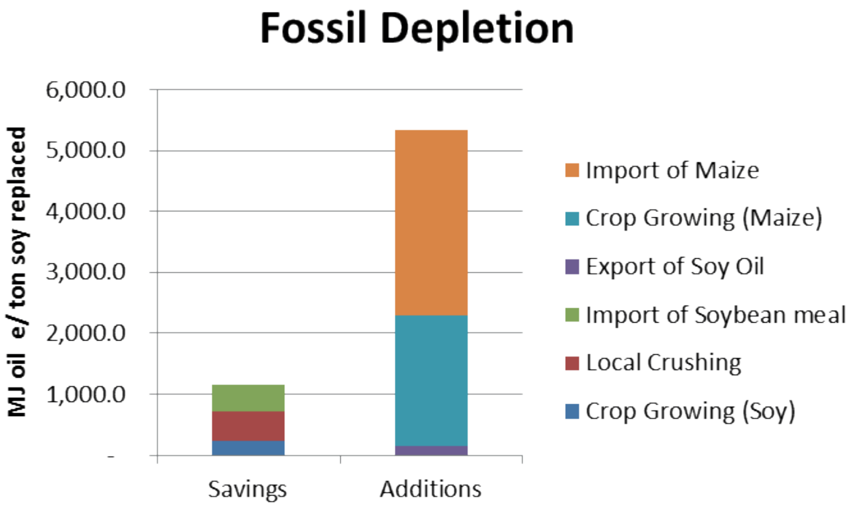

Figure 3.4 *Consequential effects of replacement of soybean from the US and South America by European soybean (savings and additions) on the use of fossil energy expressed in MJ oil-eq. per ton soybean replaced.*

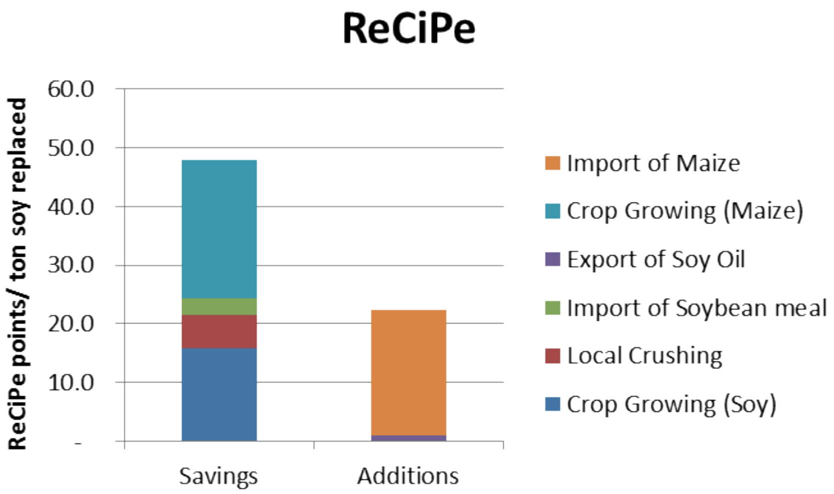

Figure 3.5 *The aggregated effect (ReCiPe, expressed in points) of the savings and additions of the replacement of maize by soybean, taking into account the environmental impact of climate change, land use, and the use of fossil energy.*

The aggregated savings are ~50 points per ton soybean replaced, whereas the aggregated additions were ~20 points per ton soybean replaced.

3.5 Extra supply of wheat DDGS as residual from ethanol production (consequential LCA)

The environmental impact of introducing wheat DDGS as a co-product from the ethanol production largely depends on the system borders that are taken into account. In this consequential LCA approach we distinguished five different systems:

- Representing the environmental impact of only the feed market (dark blue line in Figures 3.6-3.9)
- Representing the environmental impact of feed market, and 27 or 100% of the ethanol production (red and green lines, respectively, in Figures 3.6-3.9)
- Representing the environmental impact of the feed market, the ethanol production, and the use of ethanol instead of petrol (light blue lines in Figures 3.6-3.9)
- Representing the environmental impact of the feed market, the ethanol production, the use of ethanol instead of petrol, and the production of petrol (purple lines in Figures3.6-3.9)
- Representing the environmental impact of the feed market, the ethanol production, the use of ethanol instead of petrol, and the production of petrol, and alternative uses for palm kernel and wheat (orange lines in the Figures 3.6-3.9).

In Figures 8 to 11, the X-axis represents the simulated amount of DDGS (in Mton) in the UK coming available on the feed market. The Y-axis provides the savings in CO_2-eq (Figure 3.6), oil-eq. (Figure 3.7), land use (Figure 3.8), and ReCiPe (Figure 3.9, indicator of damage of the ecosystem).

If the environmental impact of only the feed market was taking into account, it can be concluded that providing wheat DDGS up to 1.62 Mton to the UK market saved 230 – 600 Kton CO_2-eq, mostly due to the replacement of soybean meal and cereals. The savings in terms of land use amounted ~ 210.000 (0.72 Kton DDGS) to 340.000 ha (1.62 Mton DDGS). Increasing the share of DDGs negatively affected the use of fossil energy. The savings in terms of oil use decreased from ~3000 Kton oil eq. (0.43 Mton DDGS) to ~ -3000 Kton oil eq. (1.62 Mton DDGS).
When incorporating 100% of the ethanol production into the system, all the benefits are cancelled, mainly due to the high energy demanded to produce the ethanol and the wet distillers‷ grain.
When also savings from the use of ethanol instead of petrol production are taken into account, the system showed again a number of savings. In terms of climate change, the savings amounted ~45 to ~500 Kton CO_2-eq., depending on the share of DDGS in the feed market. The savings in the use of fossil energy linearly increased from ~6,500 (0.43 Mton DDGS) to ~22,000 Kton oil-eq (1.62 Mton DDGS). This benefit is mainly from the gains from the reduced fossil depletion. From a DDGS share of 0.92 Mton or higher, no savings in land use were observed.

The scenario that took alternative uses for palm kernel and wheat into account followed the same pattern as the previous scenario, but all values were slightly improved.
The overall conclusion is that converting wheat into bio-ethanol as fuel source and into DDGS as feed source has beneficial environmental effects in terms of climate change, use of fossil energy and ReCiPe points, although more land use is required if the share is more than ~ 1 Kton DDGS in the UK market.

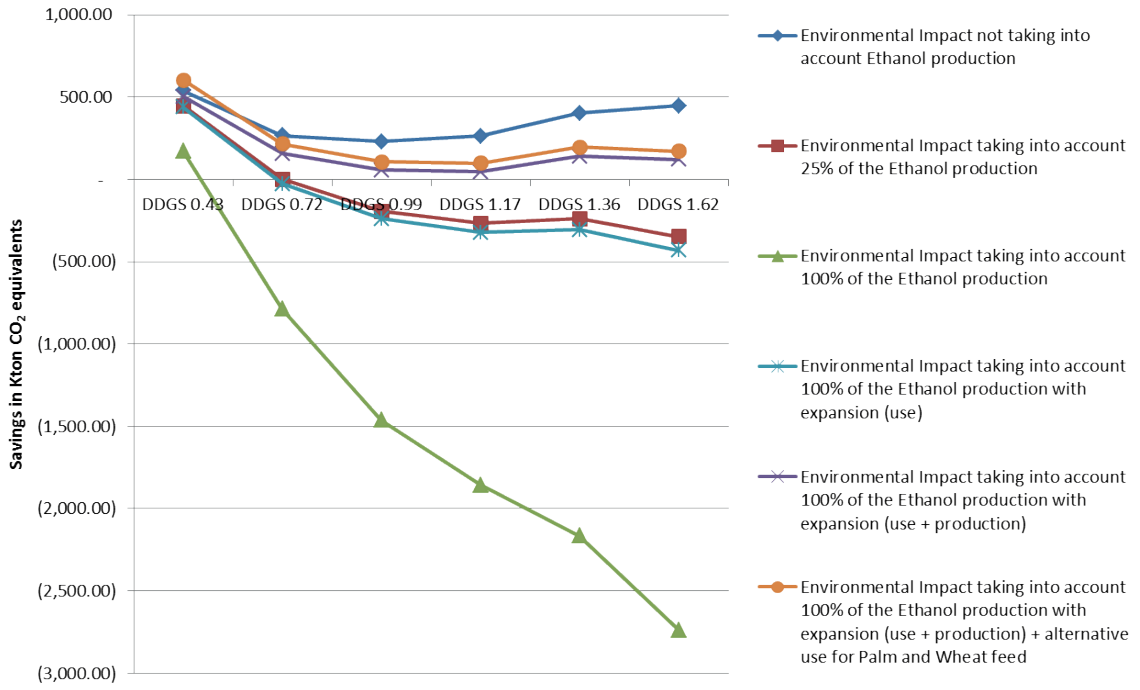

Figure 3.6 *Relation between the simulated amount of DDGS (in Mton) in the UK coming available on the feed market and the savings in Kton CO_2-eq. for the total market (13 Mton of feed).*

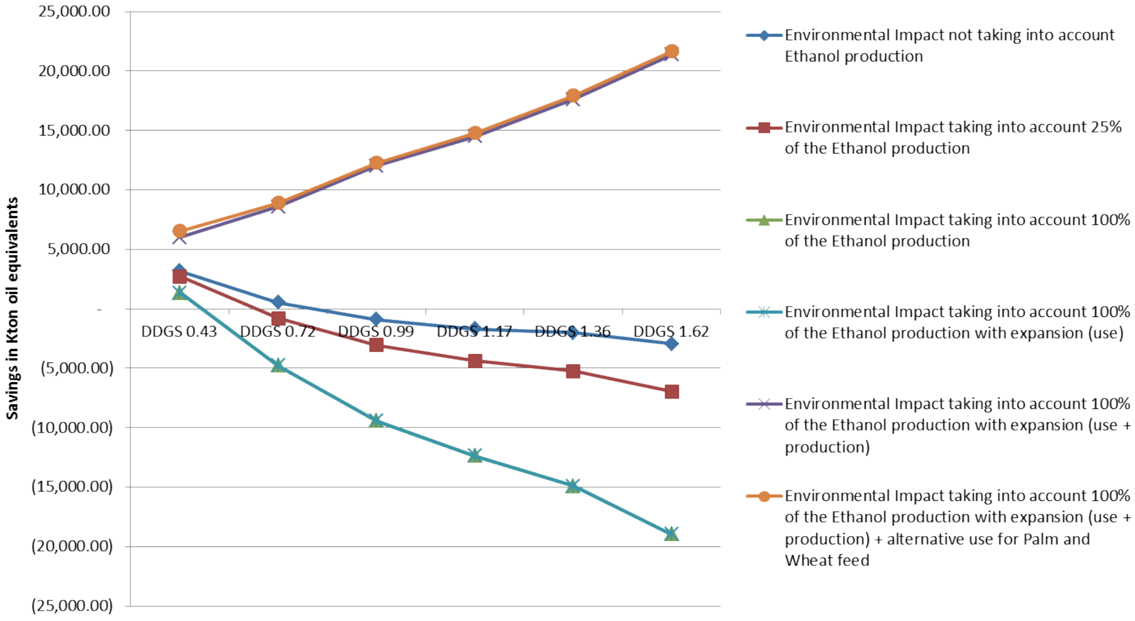

Figure 3.7 *Relation between the simulated amount of DDGS (in Mton) in the UK coming available on the feed market and the savings in Kton oil eq. for the total market (13 Mton of feed).*

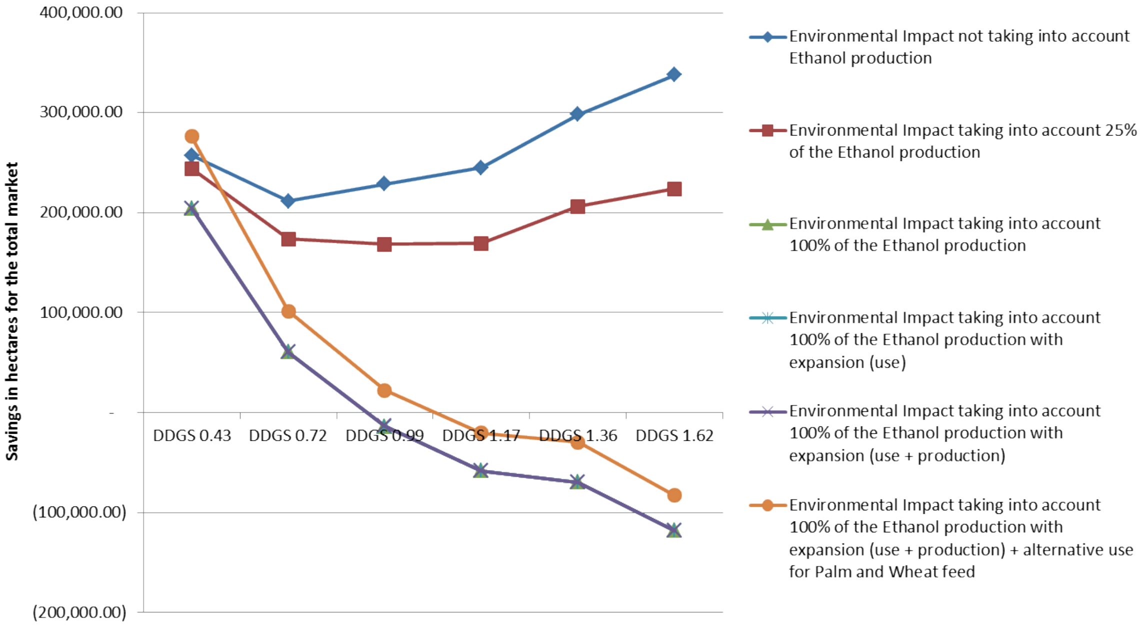

Figure 3.8 *Relation between the simulated amount of DDGS (in Mton) in the UK coming available on the feed market and the savings in land use (hectares) for the total market (13 Mton of feed).*

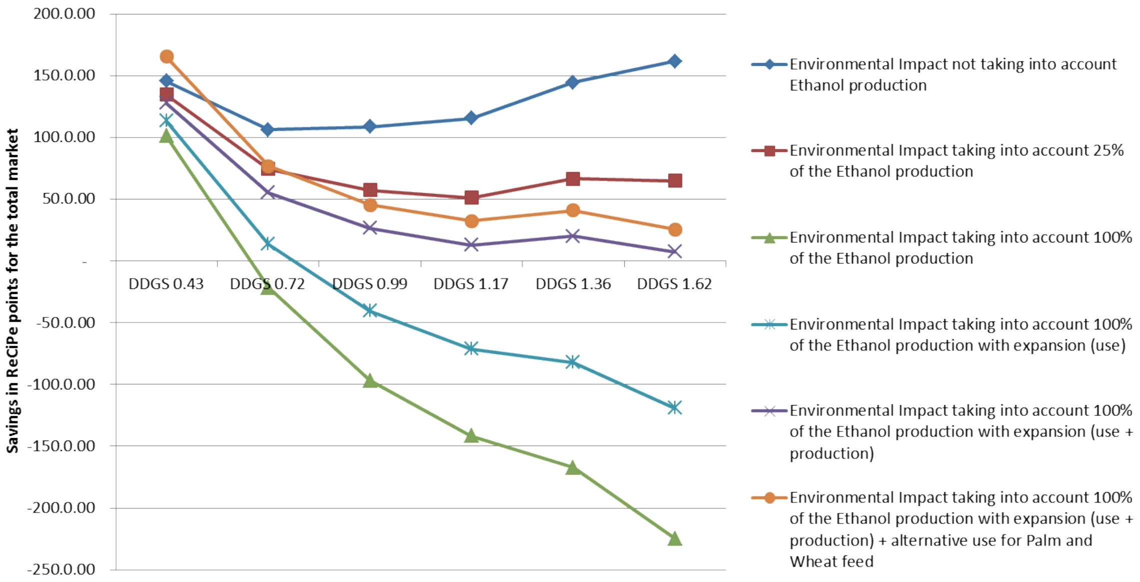

Figure 3.9 *Relation between the simulated amount of DDGS (in Mton) in the UK coming available on the feed market and the aggregated effect (ReCiPe, expressed in points) for the total market (13 Mton of feed).*

4 Discussion

4.1 Uncertainty range of CFP of compound feeds

The calculated CFP's of feed ingredients and compound feeds are subject to several types of uncertainty. When differences in CFP between ingredients or compound feeds are assessed, the ranges in uncertainty are important. FeedPrint offers the option to run a Monte-Carlo analysis on the level of average feed ration of fattening pigs. Using this analysis (with 150 simulations), the coefficient of variation for the default average feed ration is 2%. This coefficient can be used as a guideline to assess the reliability of differences between alternative compound feeds.

4.2 Impact of specific ingredient characteristics on potential replacement of SBM

Poultry meat and bone meal and poultry meat meal were only for 2.5% included in the diet, which was below the maximum inclusion level that was set at 3.0%. An important reason for this low inclusion level can be the high P concentration in both meal types, relative to P content in SBM (Table 11). Because P content of the compound feed was limited to a maximum of 5.0 g kg^{-1}, the inclusion of an ingredient with a P content of at least 35 g kg^{-1} may therefore be limited. Although increasing the maximum P boundary could enhance the inclusion level of these products, this simultaneously would result in an oversupply of P and an undesired increase in the phosphate excretion of the pigs. These calculations, however, are based on outdated digestibility coefficients of protein, fat and phosphorus of the animal products, and it is recommended to update these values.

Table 11

DM, P and CP content (g kg-1 of product) of SBM-SA and poultry meat (bone) meal.

Feed ingredient	DM	P	CP
SBM-SA	873	6.50	464
Poultry meat meal, CFAT < 100	950	35.3	580
Poultry meat and bone meal, CFAT < 100	957	69.7	461

The optimizations with maize-DDGS showed that not only the protein content but also the amino acid profile is affecting the inclusion level in the diet. Although the maximum boundary of maize-DDGS was set at 7.5% in this scenario, maize-DDGS was not selected at all. The digestible lysine content of maize-DDGS is relatively low. However, when higher inclusion levels of free lysine are allowed, maize-DDGS is included in the diet to the maximum level. Similarly, the inclusion level of HP-SSM increased if the inclusion level of free lysine was extended. In that case, the inclusion level of HP-SSM increased from 1.1% to 12.2%.

In this study, mealworms were used as a representative of the category of insects, because the paper of Oonincx and de Boer (2012) was the only available insect LCA study. Other types of insects, e.g. housefly and black soldier fly, seem from an animal nutrition point of view also to be perspective for use in compound feed. According to Van Zanten (2014) there is a need for more insect LCA studies, to increase our knowledge regarding the ecological feedprint of insects for use in feed.

In the studied scenario's, the inclusion level of free amino acids was restricted, in particular the ratio between free and apparent faecal digestible (AFD) lysine. This ratio was originally set at 0.35%. An increase in this ratio allows a higher inclusion level of free lysine and may result in replacement of SBM-SA by other ingredients. Therefore, the effect of this increased ratio on the composition of the reference diets was also determined. An increase in the allowed ratio from 0.35 to 1.00% resulted for scenario's 1 and 2 in a lower inclusion level of SBM-SA (Table 12). Inclusion levels decreased from

12.0 to 5.0% for scenario 1 and from 6.0 to 5.0% for scenario 2. This was partly compensated by an increase in the inclusion level of SSM (CF<160 g kg-1) from 0 to 12.5% for scenario 1 and from 5.9 to 12.5% for scenario 2 (with 12.5% being the maximal allowed inclusion level of SSM). An increase in the ratio free/ADF-lysine decreased compound feed cost price for all scenarios, on average from 26.0 to 24.6 € 100-1 kg of product (-5%). The effect of a higher ratio resulted in an increase of CFP for all scenarios except for scenario 8; CFP of this scenario decreased.

Table 12

Effect of an increase in ratio of free/ADF lysine from 0.35 to 1.00% on the inclusion level (%) of the alternative high-protein ingredient, CFP (g CO_2-eq. kg-1 of product) and cost price (€ 100-1 kg of product) of alternative starting compound feeds for fattening pigs, with replacement of SBM-SA by high-protein ingredients of European origin.

Replacement scenario	Inclusion level (%)		CFP		Cost price	
	0.35%	*1.00%*	*0.35%*	*1.00%*	*0.35%*	*1.00%*
1. Reference, with SBM-SA	12.0	5.0	595	627	25.30	24.49
2. SBM-SA ≤ 6%	6.0	5.0	606	627	25.81	24.49
3. HP-SSM	1.1	12.2	627	645	26.84	24.67
4. Meat (bone) meal (poultry)	2.5	2.0	591	611	26.46	25.01
5. DDGS (maize)	0.0	7.5	626	656	26.84	24.70
6. SBM-NL	12.0	5.0	580	621	25.30	24.49
7. SBM-UA	12.0	5.0	592	626	25.30	24.40
8. Insects (mealworms)	6.1	2.3	>717	>676	25.77	24.38
9. Defatted algae	2.8	2.8	>611-623	>618-630	26.35	24.70
10. Bacterial SCP	3.0	1.8	>644-739	>642-699	26.17	24.54

Apart from the effect on CFP, a higher inclusion level of free lysine can be attractive to realize lower inclusion levels of SBM-SA and also lowering cost price. The current boundaries for maximum inclusion levels of free amino acids are based on a mix of knowledge from scientific research and practical experiences. However, additional research is necessary to determine whether this higher inclusion level of free lysine will result in undesirable side-effects on animal performance and health. Although the ratio was allowed to increase to 1.0%, the average realized ratio increased only from 0.35 to 0.46%, with a maximal increase from 0.35 to 0.50%.

The CFP values of the different scenarios are based on the standard CFP values of free amino acids as used by FeedPrint. The standard CFP values of these free amino acids in FeedPrint, however, are rather high, compared to other references. To prevent confusion regarding the impact of free amino acids on the CFP of feed, it is desirable to harmonize these values.

4.3 Impact of drying wet products on CFP

Drying considerably contributes to the CFP of alternative compound feed ingredients. The contribution of drying to the total CFP varies between about 10% for SBM and SSM to 100% for poultry meat (bone) meal and DDGS. The use of another feeding concept (feeding of wet instead of dried feeds) could make some alternatives for SBM more attractive and is therefore a subject for further research.

Drying has a large contribution to the total CFP of defatted algae and bacterial SCP, despite the application of pre-drying/concentration techniques with low energy use. In practice, it may not be possible to fully apply those techniques, which could mean that in practice a considerable part of drying will still be by thermal drying. In that case, the calculated CFP of these feed ingredients and the compound feeds formulated with these ingredients, will be higher.

4.4 Impact of land use and land use change on CFP of SBM substitutes

CFP arising from land use and land use change (Luluc) can also be taken into account when calculating the CFP of feed ingredients. In FeedPrint, CFP due to land use is 110 kg C ha^{-1} and CFP due to land use change (from forest to agricultural land) is 1180 kg C ha^{-1}. When Luluc is taken into account, CFP of feed production in general increases, but differences between feed ingredients can change, making some ingredients more or less attractive. To gain insight into the impact of Luluc on CFP of feed ingredients and compound feed, CFP arising from Luluc was calculated for all feed ingredients and added to CFPs calculated earlier. Luluc for all regular feed ingredients and for feed ingredients SBM-SA, HP-SSM, poultry meat (bone) meal, DDGS, SBM-NL en SBM-UA were calculated in FeedPrint.

Luluc for the production of mealworms can be derived from data in Oonincx and de Boer (2012). Oonincx and de Boer (2012) reported a land use (Lu) of 3.56 m^2 per kg of fresh mealworms. For 1 kg of dried mealworms, Lu has to be multiplied by factor 2.15 (see section 2.9) and is 7.65 m^2. This area corresponds with a CFP of 84 g CO_2-eq. kg^{-1} for Lu and 903 g CO_2-eq. kg^{-1} for Luc, and a total of 987 g CO_2-eq. kg^{-1} for Luluc. More than 99% of this Luluc is associated with the diet fed to the mealworms; the direct contribution of land used for the production facility is 0.02 m^2 per kg of dried product (or 0.3% of total Lu), and therefore negligible.

For algae and SCP, the only land use (and associated land use change) is the land used for the production facility. As can be seen for the case of mealworm production, this land use is negligibly small. For algae, based on a production of 25 g ash-free DM m^{-2} day^{-1} (Sills et al., 2013), direct land use is roughly 0.1 m^2 per kg of dried algae (1/((25 x 365)/1000)). Land use for the production of SCP will be in the same order of magnitude. An overview of the Luluc for all alternative high-protein feed ingredients used to replace SBM-SA is given in Table 13.

Table 13

CFP (g CO_2-eq. kg-1 of product) associated with land use and land use change (Luluc) necessary for production of SBM-SA and alternative high-protein feed ingredients used to replace SBM-SA in starting compound feed for fattening pigs.

Feed ingredient	LuLuc
SBM-SA	390
HP-SSM	623$^{1)}$
Meat (bone) meal (poultry)	0
DDGS (maize)	0
SBM-NL	380
SBM-UA	404
Mealworms	987$^{2)}$
Defatted algae	~ 0
Bacterial SCP	~ 0

1) Luluc of SSM (CF<160 g kg^{-1}) in FeedPrint was used, increased with 21%, the percentage of increase in ash content of HP-SSM relative to SSM (see also paragraph 2.4).

2) When mealworm diet consists of feed ingredients as reported in Oonincx and de Boer (2012)

When the CFP of Luluc is included in CFP of feed production, CFP of all alternative compound feeds is higher than CFP of the reference feed, except for the alternative compound feed with replacement of SBM-SA by poultry meat (bone) meal, SBM-NL or SBM-UA (Table 14).

Table 14

CFP (g CO_2-eq. kg-1 of product) of alternative starting compound feeds for fattening pigs, with replacement of SBM-SA by alternative high-protein ingredients of European origin, including the impact of land use and land use change (Luluc).

Replacement scenario	CFP excl. Luluc	CFP incl. Luluc
1. Reference, with SBM-SA	595	783
2. SBM-SA ≤ 6%	606	807
3. HP-SSM	627	817
4. Meat and bone meal (poultry)	591	775
5. DDGS (maize)	626	819
6. SBM-NL	580	767
7. SBM-UA	592	782
8. Insects (mealworms)	>717	>946 1)
9. Defatted algae	>611-623	>795-807
10. Bacterial SCP	>644-739	>825-920

1) When mealworm diet consists of feed ingredients as reported in Oonincx and de Boer (2012)

The contribution of Luluc is for dried mealworms (Oonincx and de Boer, 2012) considerably higher than for SBM-SA. If mealworms (or other insects) can be reared on a diet with limited upstream CFP allocation (e.g. rest or waste products), Luluc of mealworm production can be lower. However, if contribution of the mealworm diet is excluded from calculations, CFP including Luluc is 886 g CO_2-eq. kg^{-1} for the alternative compound feed, still considerably larger compared to the reference compound feed (783 g CO_2-eq. kg^{-1}).

When agricultural land becomes scarce, a minimal land use for the production of feed ingredients may become much more important than its CFP. Under these conditions, feed ingredients with a minimal land use (insects, algae, SCP) can be very attractive.

4.5 Impact of consequential LCA

The present study focuses partly on the attributional impact of feed production on CFP, but considered the consequential impacts of some scenarios as well.

The use of porcine processed animal proteins (PAPs)
Including PAPs in a poultry diet resulted in considerable savings in climate change and land occupation. Contrary to these savings, the production of additional fertilizer required a serious amount of fossil energy, which is a disadvantage in terms of environmental impact.
By using PAP in the diet, the inclusion rates of palm oil and soybean meal decreased. In this study, however, we did not consider the environmental impacts of the additional amounts of these ingredients that came available.
In this study, we assumed that the efficacy of the N and P_2O_5 in PAP was similar to those nutrients in the artificial fertilizers. This assumption, however, can be discussed.

Soybean cultivated and processed in Europe
Based on this model, replacing US/SA by EU soybean seems to give a potential increase in environmental gains. These benefits are partly related to the higher efficiency in local transport energy in the EU. The import of maize almost offsets the gains. The current model calculated the environmental effects of importing whole maize. Probably, the import of processed goods might have beneficial environmental effects, although we did not calculate it.
We have to realize that the model is very simplistic in the economic matrix and changes. Price effects were not taken into account. The scenario of substitution of cultivation area and processing location were defined as fixed settings at the start of the calculations.
It is assumed that the soybean yield per hectare will be rather stable in the US/SA. Contrary to this, however, it is expected that the soybean yield in the EU will significantly increase in the coming years (from 2.7 to 4-5 ton/ha) because of the results of breeding programs and improvements in cultivation management. At such high yield level (4-5 ton/ha), EU soybean is a competitive crop for the farmer. At the current European yield of 2.7 ton/ha soybean, already some improvement in ecological

footprint is realised. An increase of the yield will further improve the environmental outcomes of this scenario.

Extra supply of wheat DDGS as residual from ethanol production
Although this scenario was treated as a consequential LCA approach, it has to be considered that still some weaknesses occurred. In this scenario, for instance, the price relations are not fully modelled, nor the complex economic connections between the different feed ingredients and fuels. Moreover, not all relations between co-production were taken into account. For example, wheat middlings is treated separately from wheat grain, but palm kernel extract was treated independently from palm oil. In this model, no cultivation area competition was included.
The ICCT study (Hazzledine et al., 2011) was developed for the UK context and is not supposed to be extrapolated to an European context.

Future perspectives
For further reducing the carbon footprint of EU protein sources, it is required that these crops will be produced more efficiently. Therefore, more attention should be given to breeding and improving of management conditions, resulting in a higher yield per hectare. The development of more efficient drying techniques is required, resulting in reduction of the carbon footprint of products that originates from wet processes (e.g. DDGS and aquatic proteins).

5 Conclusions

Based on the attributional LCA approach

- There are limited options to replace SBM-SA in starting compound feed for fattening pigs by alternative (European) high-protein ingredients, without increasing its CFP
- Replacement of 12% SBM-SA by 12% SBM-NL or SBM-UA slightly decreased CFP from 595 to 580 and 592 g CO_2-eq. per kg of compound feed, respectively. This decrease is mainly caused by a decrease in transportation distance
- Replacement of 12% SBM-SA by 2.5% poultry meat (bone) meal slightly decreased CFP from 595 to 591 g CO_2-eq. per kg of compound feed. An important reason for the low replacement percentage is the high P content of meat (bone) meal; these calculations are based on outdated nutritional values and available phosphorus contents of the animal products, and it is recommended to update these values
- Restricting the inclusion level of SBM-SA from 12 to 6%, and replacing SBM-SA by other available (European) high-protein ingredients, slightly increased CFP from 595 to 606 g CO_2-eq. per kg of compound feed
- Replacement of 12% SBM-SA by 6.1% insects (mealworms) increased CFP from 600 to at least 717 g CO_2-eq. per kg of compound feed. This is partly caused by the large energy requirement for heating during the production phase and a drying step thereafter
- Replacement of 12% SBM-SA by 2.8% defatted algae slightly increased CFP from 595 to at least 611 g CO_2-eq. per kg of compound feed. This CFP was calculated for an optimistic case, with no allocation of upstream CFP, assuming a high oil content in the algae, assuming a future high production level, and applying highly efficient drying techniques (with low energy requirement)
- Replacement of SBM-SA by other high-protein feed ingredients of European origin, while maintaining the same level of CFP, seems only possible for SBM grown in the Netherlands or another European country.
- When the CFP arising from land use and land use change during feed production is added to its CFP, total dietary CFP increases for all replacement options except for the meat (bone) meal, SBM-NL and SBM-UA scenarios
- The drying step, necessary for inclusion of a feed ingredient in compound feed, contributes considerably to the CFP of a compound feed. A change in feeding concept from dry to wet feeding may decrease this contribution and make several wet feed ingredients more attractive
- Mealworms seem to have little perspective for inclusion in compound feed, without increasing its CFP. The use of other insect species with low energy requirement during rearing, and rearing on waste products instead of feed ingredients, may increase the replacement potential of insects. To explore this potential, more insect LCA studies are required
- An increased inclusion level of free lysine in compound decreased its cost price, but – based on the values in FeedPrint - increased its CFP. Potential side-effects of this higher inclusion level require further research
- For an accurate assessment of the effects on CFP of replacing SBM-SA by high-protein ingredients of European origin, not only attributional effects (this study) but also global consequential effects have to be taken into account.

Based on the consequential LCA approach

- Taking all described consequences into account, it can be concluded that replacing 1 ton of US/SA soybean by 1 ton of EU soybean saves 126 kg CO_2-eq./ton soybean replaced. Contrary to this savings, the shift from US/SA to EU soybean required a considerable extra amount of fossil energy.

- The use of porcine processed animal protein (PAP) in poultry diets instead of applying PAP as fertilizer resulted in ~1,200 kg CO_2-eq savings per ton replaced PAP in case that CAN & TSP are used as replaced fertilizers, and ~1,550 kg CO_2-eq savings per ton replaced PAP in case that Urea & SSP are used as replaced fertilizers. The use of 1 ton of PAP resulted in the saving of 0.5 ha of land use. Contrary to this savings, the production of additional fertilizer required a considerable extra amount of fossil energy. The production of CAN & TSP required more than 5000 kg oil-eq., whereas the production of Urea & SSP required 6000 kg oil-equivalents per ton replaced PAP.

- Converting wheat into bio-ethanol as fuel source and into DDGS as feed source had beneficial environmental effects in terms of CFP and use of fossil energy. At low levels of DDGS use, wheat gluten feed, soybean meal and maize gluten feed are replaced, resulting in a decrease in land use. Increasing the share of DDGS to levels above 1 Mton in the UK market, also results, however, in an increased use of wheat gluten feed, soybean meal and maize gluten feed. As a consequence, more land use is required if the share is more than ~ 1 Mton DDGS in the UK market.

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Appendices

Appendix 1.

Nutritive value of mealworms, defatted algae and SCP as used in the present study

Nutrient	Unit	Ingredient				
		Defatted algae	SCP	Mealworms	Poultry meat & bone meal	Pork meal
Soluble NSP	g	378	95.5	90.2		
Remaining carbohydrates	g	378	95.5	90.2		
Dry matter	g	930	900	880	982	968
Ash	g	54	67.5	38.8	361	230
Crude protein	g	487	630	433	503	630
Crude fat	g	11	81	318	108	0
Crude fat (after acid treatment)	g	11	107	318	108	0
Moisture	g	70	100	120	18	22
NSP (Non-Starch Polysaccharides)	g	378	95.5	90.2		
ALA	g	34.58	44.73	29.44	37.7	45.4
ARG	g	30.68	39.69	25.11	35.2	42.8
ASP	g	46.41	53.55	35.07	42.3	47.9
CYS	g	1.31	4.41	25.11	4.5	4.4
GLY	g	25.76	30.87	42.87	13.6	79.4
HIS	g	7.89	13.86	15.59	11.1	14.5
ILE	g	20.45	27.72	29.01	16.1	17.6
LEU	g	36.14	47.25	46.33	32.2	38.4
LYS	g	30.63	35.28	27.71	30.7	36.5
MET	g	7.35	16.38	9.09	9.1	9.5
M+C	g	8.66	20.79	34.2	13.6	13.9
PHE	g	23.47	26.46	23.38	18.1	21.4
PRO	g	36.38	23.94	32.91	37.7	56.1
SER	g	18.94	22.68	19.05	17.1	22.7
GLU	g	62.53	66.78	52.83	65.9	77.5
TYR	g	27.71	22.68	11.26	12.6	15.1
THR	g	21.53	27.09	22.08	18.1	20.2
TRP	g	8.43	13.86	6.93	5.0	4.4
VAL	g	31.17	36.54	35.51	21.6	25.8
Net Energy for pigs	MJ	7.9	10.05	14.34	9.65	8.41
Net Energy for pigs	Kcal	1889	2401	3428	2307	2013
AID ALA for pigs	g	28	36.37	21.94	28.9	26.5
AID ARG for pigs	g	26.64	34.58	18.74	29.6	25.1
AID ASP for pigs	g	36.96	42.78	25.97	23.3	27.7
AID CYS for pigs	g	0.52	2.23	18.9	2.3	1.7
AID GLU for pigs	g	51.25	54.84	39.12	48.8	44.8
AID GLY for pigs	g	19.2	23.21	31.79	42.1	46.4
AID HIS for pigs	g	6.34	11.27	11.69	8.8	8.4
AID ILE for pigs	g	16.3	22.23	21.72	12.2	10.1
AID LEU for pigs	g	28.98	38.04	34.8	24.0	22.4
AID LYS for pigs	g	25.52	29.46	20.72	22.0	23.3
AID M+C for pigs	g	6.58	15.86	25.71	9.0	6.6
AID MET for pigs	g	6.06	13.63	6.81	6.7	4.9
AID PHE for pigs	g	17.56	19.85	17.49	13.8	12.4
AID PRO for pigs	g	27.46	17.76	24.04	29.8	32.2
AID SER for pigs	g	13.24	15.99	13.91	11.8	12.8
AID THR for pigs	g	16.16	20.49	16.26	12.4	12.6
AID TRP for pigs	g	6.36	10.55	5.14	3.5	1.5
AID TYR for pigs	g	21.23	17.34	8.3	9.5	8.7
AID VAL for pigs	g	25.22	29.67	26.52	16.1	14.8
Ca	g	1	2.5	9.9	129	72
Cl	g	12	17	1.8	2.0	4.5
K	g	15	5.8	1.4	4.8	5.4
Na	g	14	2.6	1.95	4.9	10.0
P	g	10	15.7	5.0	61.0	38.0
Available P	g	7.7	12.1	3.7	41.0	31.5
Zn	kg	75	0.02	0.02		

Appendix 2. Detailed composition of formulated compound feeds for all scenario's

Ingredients	**Unit**	**Scenario**									
		1	2	3	4	5	6	7	8	9	10
Wheat	%	38.5	25.1	35.6	27.5	36.2	38.5	38.5	33.6	35.3	22.6
Wheat middlings	%			1.0							
Barley	%	25.3	34.1	25.0	35.0	25.0	25.3	25.3	25.0	25.0	35.0
Maize	%	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
DDGS, maize	%										
Palm oil	%	3.0	3.0	3.0	2.7	2.9	3.0	3.0	1.6	3.0	3.0
Soy oil	%	0.5	0.6	0.4	0.4	0.4	0.5	0.5		0.4	0.7
Molasses, sugar>475 g/kg;	%	2.0	2.0	2.0	2.0	2.0	2.0	2.0	4.0	2.1	4.0
Soybean meal, CF<45 g/kg, CP>480 g/kg	%										
Soybean meal, CF<45 g/kg, CP<480 g/kg	%	12.034	6				12.034	12.034			
Soybean hulls, RC 320-360 g/kg	%										1.4
Sunflower seed meal, new	%			1.1							
Sunflower seed meal, dehulled, RC<160 g/kg	%		5.911	6.1	4.3	7.6			2.6	5.3	5.9
Sunflower seed meal, dehulled, RC>240 g/kg	%	3.588			1.4		3.588	3.588	2.8	1.5	
Rapeseed meal, CP<380 g/kg	%	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Peas, dry	%		7.5	7.5	7.5	7.5			7.5	7.5	7.5
Poultry Meat and bone Meal 50 Sonac	%				1.5						
Poultry Meal 63 Sonac	%				1						
Defatted algae, dried	%									2.8	
SCP, dried	%										3
Mealworms, dried	%								6.1		
Potato protein, ASH>10g/kg	%		0.667	3.1	2.3	3.1			1.4	2.1	1.8
L-Lysin HCl	%	0.404	0.404	0.4	0.4	0.4	0.404	0.404	0.4	0.4	0.4
DL-Methionine	%	0.062	0.065	0.04	0.07	0.04	0.062	0.062	0.05	0.07	0.06
L-Threonine	%	0.11	0.11	0.09	0.1	0.09	0.11	0.11	0.09	0.1	0.1
L-Tryptophan	%	0.012	0.022	0.02	0.03	0.02	0.012	0.012	0.02	0.02	0.01
L-Valine	%										
Natuphos 1000 FTU	%	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Chalk	%	1.369	1.377	1.38	0.92	1.38	1.369	1.369	1.25	1.43	1.4
Mono calcium phosphate	%	0.251	0.244	0.3		0.29	0.251	0.251	0.21	0.19	0.12
Sodium chloride	%	0.21	0.161				0.21	0.21			
Sodium bicarbonate	%	0.193	0.263	0.49	0.45	0.49	0.193	0.193	0.44	0.34	0.46
Nutrients											
Moisture	g/kg	125.01	124.22	124	123	123	125.01	125.01	129	123	126
Ash	g/kg	48.29	48.44	47	46	47	48.29	48.29	46	46	49
Crude protein	g/kg	170	170	170	170	170	170	170	170	170	170
Crude fat	g/kg	50.611	51.43	50	50	49	50.611	50.611	55	50	55
Crude fibre	g/kg	40	40	40	40	41	40	40	40	41	42
Starch (amylase)	g/kg	373.959	371.11	386	388	388	373.959	373.959	373	383	361
Total sugars	g/kg	48.356	45.29	41	40	41	48.356	48.356	48	40	49
Net energy (NE)	MJ/kg	9.67	9.67	9.67	9.67	9.67	9.67	9.67	9.67	9.67	9.67
Linoleic acid	g/kg	10.759	10.92	10	10	10	10.759	10.759	10	10	12
Calcium	g/kg	7	7	7	7	7	7	7	7	7	7
Phosphorus	g/kg	4.649	4.7	4.6	5	4.7	4.649	4.649	4.5	4.6	4.54
Digestible phosphorus	g/kg	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Natuphos	FTU/kg	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Electrolyte balance	mEq	180	180	181	180	183	180	180	180	180	180
Sodium	g/kg	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Potassium	g/kg	7.771	7.54	6.5	6.6	6.6	7.771	7.771	6.9	6.8	7.4
Chloride	g/kg	2.998	2.78	1.8	1.9	1.8	2.998	2.998	2.2	2.2	2.7
AFD LYS	g/kg	9.13	9.13	9.13	9.13	9.13	9.13	9.13	9.13	9.13	9.13
AFD MET/AFD LYS	-	0.32	0.327	0.33	0.34	0.33	0.32	0.32	0.32	0.34	0.35
AFD M+C/AFD LYS	-	0.594	0.59	0.59	0.59	0.59	0.594	0.594	0.68	0.59	0.59
AFD THR/AFD LYS	-	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
AFD TRP/AFD LYS	-	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
AFD ILEU/AFD LYS	-	0.572	0.556	0.57	0.54	0.57	0.572	0.572	0.6	0.56	0.55
AFD HIS/AFD LYS	-	0.378	0.361	0.35	0.34	0.35	0.378	0.378	0.37	0.34	0.34
AFD LEU/AFD LYS	-	1.06	1.033	1.07	1.04	1.08	1.06	1.06	1.1	1.05	1.04
AFD VAL/AFD LYS	-	0.663	0.66	0.69	0.67	0.69	0.663	0.663	0.73	0.69	0.38
AFD ARG/AFD LYS	-	0.95	0.973	0.93	0.92	0.93	0.95	0.95	0.88	0.92	0.92
Free LYS/AFD LYS	-	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Free MET/AFD MET	-	0.21	0.218	0.14	0.21	0.14	0.21	0.21	0.17	0.22	0.2
Free THR/AFD THR	-	0.197	0.197	0.16	0.19	0.16	0.197	0.197	0.16	0.17	0.18

To explore
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improve the
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Livestock Research Rapport 819

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