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Life cycle assessments of arable land use options and protein feeds

A comparative study investigating the climate impact from different scenarios in the agricultural sector

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Abstract

The aim of this study was to investigate and compare the climate impact from different arable land use options and protein feeds aimed for cattle. This has been made by executing two life cycle assessments (LCAs). The first LCA aimed to compare the following three arable land use options:

- Cultivation of wheat used for production of bioethanol, carbon dioxide and DDGS
- Cultivation of rapeseed used for production of RME, rapeseed meal and glycerine
- Fallow in the form of long-term grassland

The second LCA aimed to compare the three protein feeds DDGS, rapeseed meal and soybean meal. In the LCA of arable land, the functional unit *1 ha arable land during one year* was used and the LCA had a cradle-to-grave perspective. The LCA of protein feeds had the functional unit *100 kg digestible crude protein* and had a cradle-to-gate perspective, hence the use and disposal phases of the feeds were excluded.

Bioethanol, DDGS and carbon dioxide produced at Lantmännen Agroetanol, Norrköping, were investigated in this study. The production of RME, rapeseed meal and glycerine were considered to occur at a large-scale plant in Östergötland, but no site-specific data was used. Instead, general data of Swedish production was used in the assessment. The wheat and rapeseed cultivations were considered to take place at the same Swedish field as the fallow takes place.

The protein feed DDGS was produced at Lantmännen Agroetanol and the rapeseed meal was assumed to be produced at a general large-scale plant in Sweden. In the soybean meal scenario, a general case for the Brazilian state Mato Grosso was assumed and no specific production site was investigated. Data required for the LCAs was retrieved from literature, the LCI database Ecoinvent and from Lantmännen Agroetanol.

In the LCA of arable land use options, system expansion was used on all products produced to be able to compare the wheat and rapeseed scenarios with the fallow scenario. In the LCA of protein feeds, system expansion was used on co-products. The products in the arable land use options and the co-products in the protein feed scenarios are considered to replace the production and use of products on the market with the same function.

The result shows that the best arable land use option from a climate change perspective is to cultivate wheat and produce bioethanol, carbon dioxide and DDGS. This is since wheat cultivation has a higher yield per hectare compared to rapeseed and therefore a bigger amount of fossil products and feed ingredients can be substituted. To have the arable land in fallow is the worst option from a climate change perspective, since no products are produced that can substitute alternative products. Furthermore, the result shows that DDGS and rapeseed meal are to prefer before soybean meal from a climate change perspective, since soybean meal has a higher climate impact than DDGS and rapeseed meal. This can be explained by the smaller share of co-products produced in the soybean meal scenario compared to the DDGS and rapeseed meal scenarios. Since the production and use of co-products leads to avoided greenhouse gas emissions (since they substitute alternatives), the amount of co-products being produced is an important factor. A sensitivity analysis was also executed testing different system boundaries and variables critical for the result in both LCAs.

The conclusion of this study is that arable land should be used to cultivate wheat in order to reduce the total climate impact from arable land. Furthermore, it is favorable for the climate if DDGS or rapeseed meal are used as protein feeds instead of imported soybean meal.

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1. Introduction

The last three decades have been the warmest of the last 1400 years in the northern hemisphere. Human influence on the climate is clear and the on-going climate changes have had widespread impacts on the environment and the economy (IPCC, 2015). Agricultural activities are estimated to be responsible for one-third of climate change, partly because of deforestation and the use of fertilisers (Climate Institute, n.d.). The beef production is also a major contributor to climate change, and the beef consumption worldwide is increasing, raising the demand for animal feed (Dalgaard, et al., 2008). One of the reasons why the beef production has such a large environmental impact is the large area of arable land required in order to grow animal feed (Larsson, 2015). The population growth and the climate change will probably lead to a decrease in available arable land in parts of the world (Zhang & Cai, 2011), which means it is more important than ever to use the arable land existing today in the best possible way from a climate change perspective.

Biofuels, such as bioethanol and rape methyl ester (RME), are produced with the hope to reduce greenhouse gas emissions from a life cycle perspective, since biofuels can replace fossil fuels in the transportation sector. As the availability of arable land is limited, the greenhouse gas reduction per hectare of land and year is an important measure of sustainability when producing biofuels (Börjesson, et al., 2013). Lately, using arable land for biofuel production has been criticized for competing with food production and leading to indirect land use changes, i.e. the production of biofuels in Europe leading to changed land use and greenhouse gas emissions somewhere else in the world. At the same time, a significant part of the European arable land is used as fallow (Eriksson, 2013), land that could have been used to produce food or biofuels. These aspects opens up for a discussion – how should the arable land be used to contribute as little as possible to climate change?

When producing bioethanol from wheat and RME from rapeseed, the co-products Dried Distillers Grain with Solubles (DDGS) and rapeseed meal are also produced. These co-products can be used as protein sources in animal feed and substitute imported soybean meal, which means less land is required to grow soybeans (Börjesson, et al., 2010). However, different protein feeds have different protein content, and soybean meal contains more protein than DDGS and rapeseed meal which means a smaller amount of soybean meal is required to provide the animals with their daily protein intake compared to the two other protein feeds (Bernesson & Strid, 2011). The question remains which of the three protein feeds that contributes the least to climate change.

1.1 Aim

The aim of this study is to investigate the climate impact from arable land use options and protein feeds. This is made by calculating and comparing greenhouse gas emissions from the life cycle of 1 hectare arable land used for wheat cultivation, rapeseed cultivation and fallow. Furthermore, the protein feeds DDGS, rapeseed meal and soybean meal aimed for cattle are compared from a climate change perspective.

The three arable land use options investigated are:

- Cultivation of conventional wheat used for production of bioethanol, carbon dioxide and DDGS
- Cultivation of conventional rapeseed used for production of RME, rapeseed meal and glycerine

- Fallow in the form of long-term grassland[1]

The three protein feeds investigated are:

- DDGS
- Rapeseed meal
- Soybean meal

The result is presented in kg CO_2 eq/ha and kg CO_2 eq/100 kg digestible crude protein and two functional units are used; 1 hectare arable land during one year and 100 kg digestible crude protein.

1.2 Limitations

The report focuses on greenhouse gas emissions contributing to climate change. Other impact categories such as eutrophication, biodiversity, stratospheric ozone depletion and acidification were not considered in this report. Therefore no weighting between impact categories were executed. Only climate change was chosen to be investigated since it is more important than ever to take action and decrease greenhouse gas emissions if the global warming is to be limited below two degrees Celsius compared to pre-industrial levels, which is the target the EU members have agreed upon (Naturvårdsverket, 2015). Furthermore, climate change is the impact category the biofuel sector is focusing on today (Börjesson, et al., 2010). However, when only investigating climate change, other important environmental impacts are disregarded. This is addressed in the discussion chapter in the report.

In this study, the protein feeds are compared by digestible crude protein content. It is important to point out that the different protein feeds contain other elements besides protein that also are required by the animal, even though these elements were not accounted for in this study. Furthermore, protein from different sources contains a different amount of specific amino acids, and the proteins act different in the cow's digestion. Comparing the three different protein feeds only by digestible crude protein content is therefore a simplification.

Calculations of emissions from indirect land use change are not included in the result but a discussion of its consequences on climate change is included in the report. This is since there are large scientific uncertainties and no well-designed method to estimate the emissions caused by indirect land use change (Börjesson, et al., 2010).

The life cycle assessment (LCA) of protein feeds has a cradle-to-factory-gate perspective, which means that the use and disposal phases were not included. However, the LCA of arable land use options has a cradle-to-grave perspective. See chapter 3.1 for further explanation.

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[1] Long-term grassland fallows consist of conventional grassland mixtures, which can be kept in place for many years (Toivonen, et al., 2015).

2. Theoretical frame of reference

This chapter presents the theoretical frame of reference that forms the foundation of the report.

2.1 Structure of the chapter

In order to address the aim of the study, the theoretical frame of reference was structured in accordance with figure 1. Two different life cycle assessments with three scenarios in each assessment were executed. There are different life cycle assessment methods today that can be used in order to calculate the environmental impact. Therefore the chapter starts with a presentation of two common life cycle assessment methods describing their way of calculating the environmental impact. In order to verify that this study contributes with scientific results, previous studies on arable land use options and protein feeds are presented in the chapter. There is an existing gap in literature about climate impact from arable land use options and protein feeds and this will be explained further in chapter 2.3.

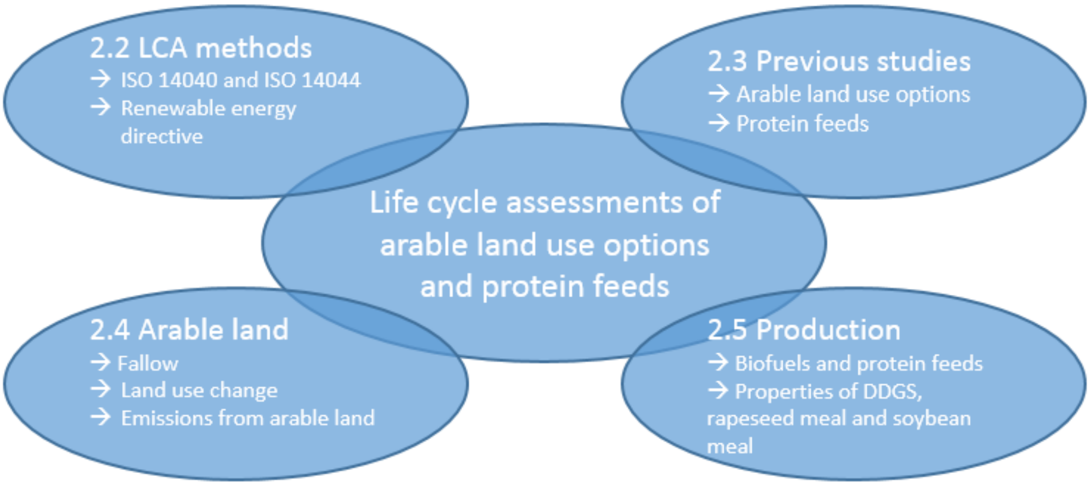

Figure 1: An illustration of the structure of the theoretical chapter.

When this theoretical knowledge is gathered, specific information of the studied scenarios are addressed. Information about fallow, which is the reference scenario for the arable land use options, is presented. Thereafter the problematics about land use change and greenhouse gas emissions from arable land are presented since these emissions can have a large climate impact. Through the cultivation on arable land, different products can be produced and these production processes are described further in chapter 2.5. In order to compare the protein feeds, properties of DDGS, rapeseed meal and soybean meal are also described in the chapter.

2.2 Life cycle assessment methods

The increased awareness of environmental impacts associated with products and services has created a demand of a method that addresses these impacts. Two of these methods are described below.

2.2.1 ISO 14040 together with ISO 14044

The International Organization for Standardization (ISO) has established two standards, ISO 14040:2006 together with ISO 14044:2006, which describe a method to address environmental impacts from products or services, called life cycle assessment (LCA). LCA addresses the environmental impacts throughout a product's life cycle from raw material procurement to final disposal, also called cradle-to-grave (ISO 14040:2006(en), 2006). An LCA can also be executed having a cradle-to-gate perspective where the usage and disposal phases are excluded (Flysjö, et al., 2008).

LCA can be helpful in several cases, for example when identifying the environmental impact of products at various points in their life cycle to improve the environmental performance or when comparing different products with the same function. It can also be helpful for the purpose of product design or for implementing an eco-labelling scheme (ISO 14040:2006(en), 2006).

An LCA study consist of four phases (ISO 14040:2006(en), 2006; ISO 14044:2006(en), 2006):

1. the goal and scope definition phase
2. the life cycle inventory analysis phase (LCI)
3. the life cycle impact assessment phase (LCIA)
4. the life cycle interpretation phase

The goal and scope definition phase specifies the problem and the system boundaries of the study. The second phase, the LCI, is an inventory of input/output data with regard to the system being studied. It consists of data collection necessary to meet the goals of the LCA study. The third phase, LCIA, provides additional information to better understand and evaluate the significance of the environmental impacts throughout the life cycle of the product. The final phase summarizes and discusses the LCI and LCIA results in relation to the defined goal and scope as a basis for conclusions and recommendations (ISO 14040:2006(en), 2006).

2.2.2 Renewable energy directive (RED)

To be able to evaluate the greenhouse gas performance of biofuels, the European Union has developed a simplified LCA-method described in the Renewable Energy Directive 2009/28/EG (RED). RED considers direct land use change associated with biofuels and last year (2015) new rules came into force in the EU with the aim to reduce indirect land use change and to facilitate the transition to advanced biofuels (European Comission, 2016).

Equation [1] below describes the formula used in RED to caclulate the greenhouse gas emissions from a fuel (European Parliament and the Council, 2009).

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} - e_{ee} \quad [1]$$

Where,
E is the total emissions from the use of the fuel and should be in the unit g CO_2 eq/MJ
e_{ec} is the emissons from the extraction or cultivation of raw materials
e_l is the emissions from carbon stock changes caused by land use change, where 2008 is a reference year
e_p is the emissions from processing
e_{td} is the emissons from transports and distribution
e_u is the emissions from the fuel in use and is considered to be zero for biofuels
e_{sca} is the emisson saving from carbon capture and geological storage
e_{ccs} is the emission saving from carbon capture and replacement
e_{ee} is the emission saving from exess electricity from cogeneration

Equation [1] includes carbon dioxide, methane and nitrous oxide emissions (European Parliament and the Council, 2009). According to RED, both glycerine and straw are considered to be residues and are considered to have greenhouse gas emissions equal to zero until the residues are collected. Furthermore, if an input is less than 0.005 g/MJ fuel, 0.2 kJ/MJ fuel, 0.3 kg/ha and year or 10 MJ/ha and year, the greenhouse gas emissions from the input can be excluded (Energimyndigheten, 2012). The emissions from production of machinery and equipment used during the life cycle of biofuels should not be considered in the life cycle assessment (European Parliament and the Council, 2009).

After the total emissions from the use of the biofuel is calculated, the greenhouse gas emission savings from using the biofuel instead of fossil fuels should be calculated using equation [2].

$$SAVING = (E_F - E_B)/E_F \quad [2]$$

Where,
E_F is the total emissions from the fossil fuel comparator
E_B is the total emissions from the biofuel.

2.2.3 Allocation and system expansion

A process or a production site can produce many different products. If the aim is to only investigate the environmental impact from one of these products, the emissions from the process or the production site must be divided by the different products. Allocation or system expansion can be used to divide the emissions to one specific product. (SLU, 2015)

According to RED, the greenhouse gas emissions should be allocated between the biofuel and co-products based on the products lower heating value (European Union, 2015). For example, when executing a lower heating value allocation, 64 % of the environmental impact from the co-production of rapeseed oil and rapeseed meal should be allocated to the rapeseed oil and 36 % of the impact should be allocated to the meal (Corré, et al., 2016). Besides energy content, allocations between co-products can be based on physical properties like mass or economic relations (SLU, 2015).

System expansion is when the system boundaries of the LCA are expanded to include co-products and what they substitute on the market. For example (see figure 2), if a production site produces product A and product B1, one can consider the total environmental impact from the production site. Then, an alternative system producing product B2 can be investigated. Product B2 has the same function as product B1, hence product B1 can substitute product B2 on the market. By knowing the environmental impact from the production of product B2 and then withdraw this impact from the investigated system, the resulting system will only include the environmental impact from product A. According to the ISO standard, system expansion is to be applied when possible, otherwise allocation methods are preferred (ISO 14040:2006(en), 2006).

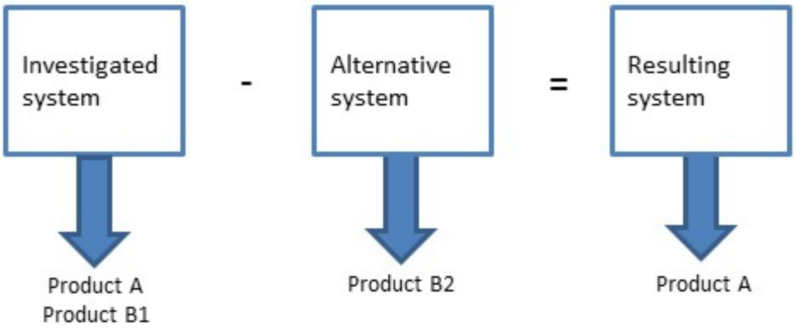

Figure 2: An illustration of system expansion.

2.3 Previous life cycle assessments

When searching for previous studies about arable land use options and protein feeds it became clear that there are gaps in these areas. During the literature search, no studies were found comparing greenhouse gas emissions from the total life cycle of different arable land use options. Land based functional units, such as 1 ha arable land, have not been frequently used in life cycle assessments since the use of land is not seen as a service with a productive function (González-García, et al., 2016). However, impacts from agricultural systems are connected to the amount of land used (González-García, et al., 2016), and to be able to make a comparison with land in fallow, the functional unit must be expressed as the amount of land used.

No studies have been found with the aim to compare the three protein feeds DDGS, rapeseed meal and soybean meal. Studies investigating one of the feeds alone or comparing complete feed rations including one or two of the protein feeds have been found (Lehuger, et al., 2009; Dalgaard, et al., 2008; Bernesson & Strid, 2011). A study calculating the total environmental impact from 1 kg of each protein feed was also found. However, the environmental impacts from the different feeds could not be compared with each other, since 1 kg of one feed cannot substitute 1 kg of another feed because of different properties of the feeds (Flysjö, et al., 2008).

2.3.1 Arable land use options

Several life cycle assessments have been executed on biofuels with protein sources as co-products (Börjesson, et al., 2010; Börjesson, et al., 2013; Corré, et al., 2016) and the use of the functional unit for biofuels per hectare and year is increasingly being advocated in the world of LCA (Börjesson, et al., 2010).

The study by Corré et al. (2016) shows that the method how and if the co-products are accounted for has a big impact on the result when performing life cycle assessments of biofuels. Hence, system-expansion is to prefer since it considers what really happens with the co-products. The assessment by Corré et al. (2016) shows it is the cultivation that contributes the most to climate change in the life cycle of one hectare rapeseed and soybean that are processed to biofuels and meals. One reason to this is the nitrous oxide emissions from the cultivation caused by fertilisers containing nitrogen. One hectare of rapeseed cultivation has a higher input of nitrogen fertiliser than one hectare soybean cultivation, why rapeseed has higher nitrous oxide emissions during the cultivation.

In the study by Börjesson et al. (2010), biofuels produced and used in Sweden today are investigated, such as bioethanol from wheat and RME from rapeseed. The calculations include greenhouse gas emissions from technical systems, e.g. energy input and biogenic emissions of nitrous oxide and carbon dioxide from direct land use changes. Impacts from indirect land use changes are also considered. In the study, the co-products DDGS and rapeseed meal replace the production of soybean meal (40 %) and barley (60 %). The results in the study are presented per MJ biofuel but also per hectare cropland. Börjesson et al. (2010) conclude that wheat-based ethanol and RME from rapeseed, when applying system expansion and using unfertilized grassland as a reference, lead to greenhouse gas emissions of 38.9 g CO_2 eq/MJ biofuel and 46.6 g CO_2 eq/MJ respectively. One important parameter that influences the climate benefit of RME is how much soybean meal that can be replaced by the co-product rapeseed meal. When the results are expressed per hectare and year, and land use change from grassland to arable land is assumed to occur on 25 % of the land, bioethanol from wheat and RME from rapeseed emitted around 3900 kg CO_2 eq/ha and year and 2700 kg CO_2 eq/ha and year respectively (Börjesson, et al., 2010). Hence, the climate impact from bioethanol and RME differs depending on which unit that is used.

2.3.2 Protein feeds

For animal feed, the greatest environmental impact comes from the protein source (Lehuger, et al., 2009) and life cycle assessments comparing different protein feeds have been made (Lehuger, et al., 2009; Samuel-Fitwi, et al., 2013). Consequential life cycle assessments focusing on a specific protein feed has also been made, e.g. for soybean meal (Dalgaard, et al., 2008). However, life cycle assessments with the aim to compare the three protein feeds soybean meal, rapeseed meal and DDGS have not been found during the literature search.

The study by González-García et al. (2016) contains a comparison of sorghum, oat and barley silage aimed for animal feed. González-García et al. have used several functional units, since the choice of functional unit has a large impact on the result. They use 1 tonne dry matter of silage for cattle feed as the base unit for comparison of the different feeds. This is since a mass-based functional unit is easy to comprehend. However, when comparing the silages by mass, the different qualities of the feeds will not be considered making the comparison unfair. Because of this, the functional units 1 ha and 1 tonne crude protein was also used in the study by González-García et al. (2016).

Since there is no easy way to compare protein feeds, performed life cycle assessments of protein sources in animal feed have used different functional units. Lehuger et al. (2009), which have executed a life cycle assessment of feed rations for dairy cows, use 1000 kg of feed designed with the exact same protein and energy content as functional unit. The feed contains a number of different ingredients, and all the different ingredients in the rations are included in the assessment. Samuel-Fitwi et al. (2013) have performed a life cycle assessment of different sources of protein in fish-meal, and they have used the functional unit 1 tonne of trout feed, which means that they also include all ingredients in the feed. Flysjö et al. (2008) use 1 kg of feed ingredient as functional unit. According to Flysjö et al. (2008), the investigated feed ingredients in their study (e.g. DDGS, rapeseed meal and soybean meal) cannot be assumed to substitute each other since they are different, but the study opens up for a comparison of similar feed ingredients. In the study by Lywood et al. (2009), DDGS and rapeseed meal are considered to substitute soybean meal and wheat in animal feed and the substitution ratios are based on equivalent digestible protein content and available energy content in the protein feeds.

To be able to get a complete picture of the environmental impact from different protein feeds, the methane emissions from the cow should also be included in the life cycle assessment according to Liljeholm et al. (2009). This is because the composition of the feed influences the amount of methane the cow emits (Liljeholm, et al., 2009).

In the feed industry, the view on how DDGS, rapeseed meal and soybean meal aimed for cattle should be compared differs. Some think that the best way is to compare the protein feeds by digestible crude protein content, since there are several different evaluation systems used on the protein feed market today, and the market have not agreed upon one single evaluation system (Erichsen, p.c., 2016). However, since the crude protein can have a different quality depending on which source it derives from (see chapter 2.5.4) other thinks that the comparison should be based on the AAT20 value used in the Nordic Feed Evaluation System (Lindberg, p.c., 2016). The AAT20 value is the amount of amino acids absorbed in the small intestine when 20 kg of the feed is eaten by the cow (Nordic Feed Evaluation System, 2005) and is further explained in chapter 2.5.4. Another view is that the optimal way to compare protein feeds would be to consider both protein content and protein quality when the comparison is made (Öhman, p.c., 2016).

The study by Lehuger et al. (2009) comparing soybean meal and rapeseed meal in complete feed rations shows that rations containing soybean meal contributes less to climate change than rations containing rapeseed meal. This is because the large amount of synthetic nitrogen fertilisers used in rapeseed cultivation and because of lower yields of rapeseed compared to soybean. The study also shows that the transport of soybean meal to Europe seems to have a small impact on the result.

The study by Flysjö et al. (2008) has calculated the climate impact from soybean meal, DDGS produced at Lantmännen Agroetanol and heat treated rapeseed meal (ExPro) with a cradle-to-feed-factory-gate perspective. The greenhouse gas emissions were calculated to 849.7, 308.3 and 460.6 g CO_2 eq/kg protein feed (dry matter) for soybean meal, DDGS and heat treated rapeseed meal respectively. However, these numbers cannot be compared with each other since 1 kg of one feed cannot substitute 1 kg of another feed (Flysjö, et al., 2008).

2.4 Arable land

During the 1910s the arable land area was at its largest in Sweden. Between 1951 and 2010 the arable land area in Sweden decreased with 1 million hectares and in Östergötland the decrease was nearly 20 percent (Statistiska centralbyrån, 2013).

Arable land is land that is used or can be used for crop production or pasture and is also suitable for ploughing (Skatteverket, n.d.). Fallow is when the arable land is out of production (Jordbruksverket, 2016) and is further described in chapter 2.4.1. When changing arable land from one form to another, for example from fallow to crop cultivation, land use changes takes place and this is further explained in chapter 2.4.2. The emissions from agriculture distinguish from emissions caused by other sectors in the society and is controlled by factors that can be difficult to control (Saxe, et al., 2013), such as oxygen deficiency in the soil which favours the formation of nitrous oxide emissions (Berglund & Wallman, 2011). In chapter 2.4.3 greenhouse gas emissions from arable land is described.

2.4.1 Arable land in fallow

Agricultural intensification has affected farmland biodiversity negatively across Europe. This has resulted in an increasing concern of the decline in biodiversity in the European Union, which has led to the introduction of agri-environmental schemes (AES). This means that farmers are paid subsidies for creating or managing areas that are not directly used for agricultural production, such as wildflower strips or fallow fields. (Toivonen, et al., 2015)

There are two general fallowing strategies for sown perennial fallows: *long-term grassland fallow* and *short-term meadow fallow*. Long-term grassland fallows consist of conventional grassland mixtures, which can be kept in place for many years, colonized by animals and wild plants (Toivonen, et al., 2015). This type of fallow is the most common one and constitutes 62 % of the total fallows in Sweden in 2012, which is an increase from 54 % in 2010 (Statistiska centralbyrån, 2013). Short-term meadow fallows contain flowering herbs and low competitive grasses and require, compared to long-term grassland fallows, re-establishment at regular intervals (Toivonen, et al., 2015). Both types of fallows are usually mowed once per season, commonly during the month of July (Statistiska centralbyrån, 2013). Mowing of vegetation is prohibited if there are animals and birds living on the fallow (Jordbruksverket, 2016). In the northern part of Götaland in Sweden, the share of long-term fallows and short-term fallows is 50 % each, but the share of long-term fallow increases further south in Götaland (Statistiska centralbyrån, 2013).

The basic rule for having land in fallow in Sweden is that the land must be out of production until July 15. Different subsidies can have specific rules stating that the land must be out of production for a longer period of time. Production on arable land includes harvesting, cultivation or livestock on farmland. It is however allowed to sow a suitable catch crop or other crops that promote biodiversity on the fallow. Soil and land improvement measures are permitted during the fallow period, for example drainage, liming and fertilising. (Jordbruksverket, 2016)

The total area of fallow in Sweden was 153 700 hectares in 2015 (see figure 3), an increase of 16 % compared to 2014. Since 2010, the area of fallow decreased with 23 100 hectares which corresponds to a reduction of 13 %. As seen in figure 3, the area of fallow decreased rapidly in 2008 due to the removal of the regulation that some percent of the land must lie in fallow. The increase between 2014 and 2015 may be due to the introduction of Ecological focus area[2] in the so-called Greening subsidy[3], where subsidies are given for arable land in fallow. In 2015, the total area in fallow represented 5.9 % of the Swedish arable land. (Jorbruksverket, n.d.)

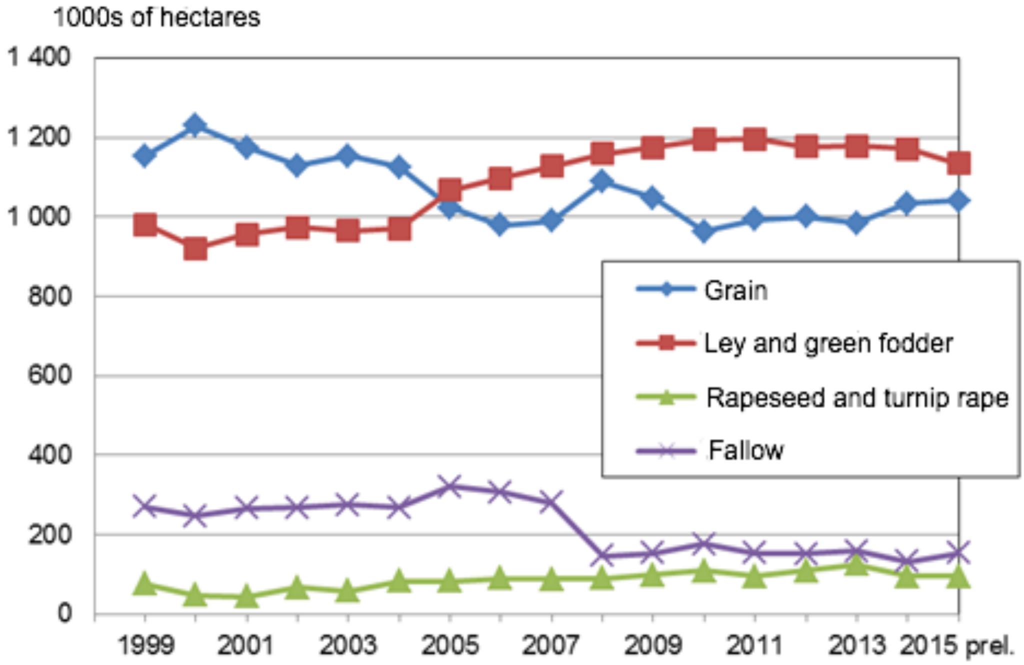

Figure 3: The change of arable land area for some crop groups in 1000s of hectares from 1999 to preliminary data for 2015 (Jorbruksverket, n.d.).

2.4.2 Land use change

If one category of land is turned into another, for example if a forest is cut down and turned into agricultural land, a land use change has occurred. Land use changes can be divided in two categories; direct land use change and in-direct land use change. Direct land use change occurs where the change happens, e.g. it occurs on the field where grassland is transformed into crop cultivation. Indirect land use change does not occur where the transformation occurs but somewhere else in the world. For example, if grain is used for biofuels instead of food in Europe, the supply of grain for food applications might decrease which can lead to increased crop cultivations somewhere else in the world. (Börjesson, et al., 2010)

A number of studies (Flysjö, et al., 2008; Börjesson, et al., 2010; Corré, et al., 2016) point out the uncertainties in estimating greenhouse gas emissions caused by land use change. Flysjö et al. (2008) argues that the lack of knowledge about emissions from indirect land use change made it impossible for them to consider these emissions in their study. According to Börjesson et al. (2010), indirect land use change should not be considered in LCAs of biofuels, since there are large scientific uncertainties and since there is no well-designed method to estimate the emissions caused by

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[2] In Swedish: ”Ekologisk fokusareal”.

[3] In Swedish: ”Förgröningsstödet”.

indirect land use change. Corré et al. (2016) have not considered direct or indirect land use changes, since there are not sufficient data on emissions caused by direct and indirect land use of individual crops.

Even though land use change is left out of the scope in many studies, scientists highlights the importance of the greenhouse gas emissions from land use change (Flysjö, et al., 2008; Börjesson, et al., 2010; Corré, et al., 2016). Flysjö et al. (2008) mean that in the future when the knowledge about land use change has been improved, emissions from deforestation should be considered in life cycle assessments of feed since they are very important and can change the result drastically, especially for soybean and palm oil. Despite the uncertainties, there have been studies trying to estimate land use changes (Mogensen, et al., 2015). If land use change is considered, it is important to be transparent when it comes to land use change calculations since different methods can give very different results (Mogensen, et al., 2015; Börjesson, et al., 2013).

Börjesson et al. (2010) assess several factors whether the production of biofuels from agricultural crops influence land use change or not. One of the factors is the proportion of arable land in use and in fallow. Another factor is whether there are surpluses of grains on the world market. A third factor is if the agricultural production is optimized or if changes can be made to improve the efficiency of the production. Since there is a certain amount of arable land not used today in Sweden and since there is capacity to increase the intensity of the agriculture, biofuels can be grown in Sweden without leading to negative indirect land use change (Börjesson, et al., 2010). The increased cultivation of biofuels in Sweden can result in a positive indirect land use change, since the co-products of biofuels can replace the cultivation of soybeans in tropical areas. Because of these reasons, Börjesson et al. (2010) made the assumption that Swedish biofuels do not contribute to indirect land use change.

However, Börjesson et al. (2010) include direct land use change in their study. Statistics from Jordbruksverket (2009) show that the total cropland area in Sweden has decreased with 200 000 hectares since 1990 and the area of grain has decreased with approximately 300 000 hectares. Börjesson et al. (2010) estimate that a certain proportion of the cultivation of wheat for production of ethanol and cultivation of rapeseed for production of RME is taking place on former grassland. Börjesson e al. (2010) are therefore making following assumption: "*it is assumed that on average ¼ of the cultivation of raw material is taking place on previous grassland while ¾ is assumed not to result in any direct carbon stock changes*" (Börjesson, et al., 2010, p. 16). There are uncertainties about the size of carbon stock changes when cultivation is made on previously grassland, since it depends on how long the ground has been grass-covered and if equilibrium in carbon stocks has been reached.

According to RED, land that has been used as arable land before 2008 and is registered as arable land when the harvest occurs is not considered to contribute to direct land use change (Energimyndigheten, 2012). Further, RED says fallows that are transformed into grain or oil crop cultivation are not considered to contribute to direct land use change (Börjesson, et al., 2010). Since the new EU-directive 2015/1513 took place, indirect land use change should be considered for biofuels made by grain, sugar and oil crops. If the production of biofuels leads to direct land use change, indirect land use change should not be considered (European Union, 2015).

2.4.3 Emissions from arable land

The predominant greenhouse gases in crop production are nitrous oxide (N_2O) and carbon dioxide (CO_2) (Berglund & Wallman, 2011). N_2O-emissions from agricultural soils have a considerable high impact on climate change and accounted for 46 % of the Swedish agricultural sector's greenhouse gas emissions in 2013 (Naturvårdsverket, 2015). Even though the emissions are typically only a few kg of N_2O per hectare and year, they are of great importance from a climate change perspective since N_2O contributes 265 times more to climate change than CO_2 (Berglund & Wallman, 2011). Methane (CH_4) is also a greenhouse gas, but since emissions of methane caused by land use are small, the climate impact from the emissions is generally small compared to the impact from N_2O and CO_2 emissions (Berglund & Wallman, 2011). The following section presents these emissions further.

Nitrous oxide emissions from soil

Nitrous oxide (N_2O) is produced as an intermediate product when nitrogen is converted by microorganisms in the soil, both in the denitrification process (conversion of NO_3^- into N_2) and in the nitrification process (conversion of NH_4^+ into NO_3^-). It is primarily factors favouring denitrification that increase the risk of N_2O-emissions from the soil since most of the N_2O is produced in denitrification. Denitrification occurs if the oxygen supply is poor and if the microorganisms use various nitrogen compounds instead of oxygen for their respiratory process. Complete denitrification to nitrogen takes place if anaerobic conditions occur. If completely anaerobic conditions do not occur, the denitrification process will stop at greater extent in the N_2O-step and the risk of N_2O emissions increases. Nitrification is an aerobic process and is a prerequisite for denitrification to occur, since there must be nitrate in the soil for denitrification to take place. In case of oxygen deficiency, the nitrification process is inhibited which increases the risk of N_2O emissions. The N_2O-emissions caused by the nitrification and denitrification processes are called direct emissions, since N_2O is emitted directly from the land surface to the atmosphere or leached directly to the ground water (Berglund & Wallman, 2011). In the case of indirect N_2O-emissions, nitrogen is first emitted as NO_3^- or NH_3 and subsequently converted to N_2O (Nemecek & Kägi, 2007).

Intensive agriculture with a high input of nitrogen fertiliser, lack of oxygen in the soil and easily degradable organic matter in the soil contributes to an increase in N_2O-emissions. Lack of oxygen in the soil can occur when the soil is saturated with water or at high microbial activity where large amounts of oxygen are consumed. N_2O measurements made in the field show that strong and relatively short-term emission peaks characterize N_2O-emissions. Such peaks can for example occur during heavily rainfall after fertilisation or when the ground thaws after the winter (Berglund & Wallman, 2011). The variations of N_2O-emissions caused by climatic factors make it difficult to predict emission rates from a single field at a specific nitrogen fertilisation rate and grazing intensity. Continuous field measurements over a long period of time are therefore needed to obtain reasonable results on N_2O-emissions from soil. Several European field studies within the framework of the European Union's GREENGRASS project have been performed for a 3-year period (2002-2004) at 10 grassland sites in eight European countries (Denmark, United Kingdom, France, Hungary, the Netherlands, Switzerland, Ireland and Italy). During the field studies, the soil to atmosphere fluxes of N_2O were monitored. The field studies showed a high variation of N_2O-emissions from site to site and from year to year due to differences in for example soil temperatures and moisture (Flechard, et al., 2007).

The Intergovernmental Panel on Climate Change (IPCC) has developed methods for estimating direct and indirect nitrous oxide emissions from arable land. In the method for estimating direct nitrous oxide emissions from the soil, 1 % of the added nitrogen (e.g. added as nitrogen fertiliser) is assumed to be emitted as nitrous oxide. Crop residues left on the field are also assumed to contribute to nitrous oxide emissions. (Ahlgren, et al., 2011)

Carbon dioxide emissions from soil

The ground contains large reserves of coal in the form of humus. In average, mineral soils in Sweden contains 2.5 % carbon in the topsoil, which is equivalent to 90 tonne carbon per hectare if the topsoil layer is 25 cm and the bulk density is 1.25 tonne per m^3. When land is used for agricultural activities, changes in the soil's carbon stock can occur. The soil can either release carbon in the form of CO_2-emissions (because of decomposition of organic material in the soil resulting in a decreased carbon content) or sequestrate carbon (the carbon content in the soil is increased due to added organic matter to the soil). Carbon losses in the soil usually occur if there are changes in land use, especially deforestation in the southern hemisphere. Sequestration of carbon usually occurs in permanent grasslands. (Berglund & Wallman, 2011)

Important to keep in mind is that changes in carbon stocks are hard to estimate and should be verified with long-term field trials according to Börjesson (1999). The carbon stock changes depend on several aspects, e.g. soil type, location and crop residue management (Börjesson, 1999).

Methane emissions from soil

Methane (CH_4) emissions can be formed from land that is flooded, for example in marshes and in rice cultivations. Bacteria in well-drained mineral soils can in contrast consume small amount of methane from the atmosphere or deeper soil layers (Berglund, et al., 2009). Methane emissions from Swedish agricultural land is usually not included in studies, which can be seen in the Swedish climate report from the Swedish Environmental Protection Agency where the methane emissions are neglected (Naturvårdsverket, 2015).

2.5 Production

In this subsection, the production processes where wheat, rapeseed and soybean are used as raw materials are explained. In order to compare the protein feeds, properties of DDGS, rapeseed meal and soybean meal are also described in this subsection.

2.5.1 Production of bioethanol, DDGS and carbon dioxide

The largest bioethanol producer in Sweden with a capacity of 230 000 m^3 bioethanol per year is Lantmännen Agroetanol, located in Norrköping (Lantmännen Agroetanol, 2016). Agroetanol uses wheat, triticale and barley as raw material and has a full capacity of 600 000 tonne grain yearly, which represents a grain cultivation with the size of 100 000 hectares (Lantmännen Agroetanol, 2016). This means that Agroetanol has the capacity to use 3.9 % of the total arable land in Sweden (Jorbruksverket, n.d.). This can be compared with the 5.9 % arable land being used as fallow (Jorbruksverket, n.d.). Agroetanol produces three products – bioethanol, which is sold and mainly blended with petrol, carbon dioxide, which is captured and used as carbonic acid in the food industry, and DDGS, which is used as animal feed (see figure 4) (Lantmännen Agroetanol, 2016).

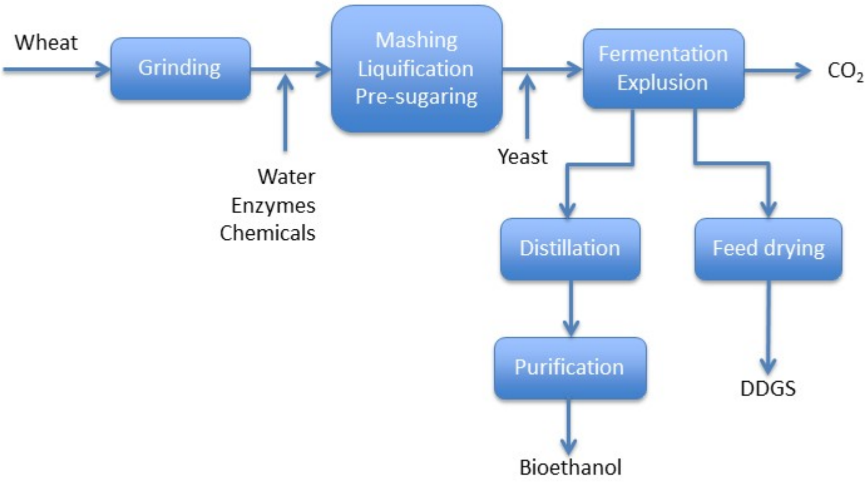

Figure 4: The manufacturing process in Lantmännen Agroetanol's factory where bioethanol, DDGS and carbon dioxide are produced from grain (Lantmännen Agroetanol, n.d.).

The first step in the bioethanol process is grinding, where the grain is split up to smaller particles. This step is important for the starch to dissolve in water. Water and enzymes are then added in the liquefaction step where the starch is decomposed to a sugar mixture. Yeast is added to the sugar mixture in the fermentation step, which convert the sugar to bioethanol and to carbon dioxide. The carbon dioxide is collected and sold, e.g. for soda manufacturing. The bioethanol is then separated from the mixture and dewatered in the distillation and dehydration step. The remaining parts in the mixture is called stillage, which is protein rich. The stillage is dried, pelletized and used as animal feed (Lantmännen Agroetanol, 2016). This pelletized material with a high protein content (30-35 %) is called DDGS and Agroetanol has the capacity to produce 180 000 tonne of DDGS per year (Lantmännen Agroetanol, 2016).

DDGS is suitable for most ruminants (e.g. beef cattle) and the protein in the feed is enough to cover the animal's protein requirements. The protein in DDGS is easily degradable, which means that the protein is degraded in the rumen. Dairy cows are also in need of hard degradable proteins, why feed aimed for dairy cows might also need to contain protein from soybean meal or rapeseed meal (Bernesson & Strid, 2011).

2.5.2 Production of RME, rapeseed meal and glycerine

Rape methyl ester (RME), also called biodiesel, is made of rapeseed oil and can be used in certain diesel engines. In an international perspective, the term biodiesel includes a larger number of fatty acids called FAME (Fatty Acid Methyl Ester) (JTI - Institutet för jordbruks- och miljöteknik, 2011). RME can be produced in different system scales. Large-scale systems have a higher extraction efficiency and more expensive process technologies compared to small-scale systems. However, large-scale systems have longer transport distances of raw material to the processing plant and of residual products back to the farm compared to small-scale systems where the transport distances are decreased or eliminated. Small-scale systems have been of great interest in Sweden due to the possibility to increase rural employment (Bernesson, et al., 2004). The first Swedish large-scale facility producing RME, Ecobränsle in Karlshamn, was inaugurated by Lantmännen in 2006 and another large-scale facility was opened by a chemical company, Perstorp in Stenungsund, in 2007 (JTI - Institutet för jordbruks- och miljöteknik, 2011).

The first step in the production of RME and its co-product rapeseed meal is to press the rapeseed in a mechanical press (see figure 5). This can be done during elevated temperature, where the seeds are heated to 80 °C, or through cold moulding, where the temperature usually is around 20 °C. An elevated temperature is used in large-scale processes and the cold moulding is used in small-scale processes (JTI - Institutet för jordbruks- och miljöteknik, 2009). After the mechanical press, the oil is separated from the residue called rapeseed cake. Hexane is then added to the rapeseed cake to extract even more rapeseed oil, and rapeseed meal is extracted as well (Flysjö, et al., 2008). The rapeseed meal is protein rich and mostly used as animal feed. After the extraction, the rapeseed oil is pre-treated before the transesterification, either through sedimentation, centrifugation or filtration. The rapeseed oil is then heated to 60 °C in a chemical process and methanol is added which splits the triglycerides to ester molecules. To speed up the process, a potassium or sodium hydroxide catalyst is added. RME and glycerine are now produced and due to the higher density of glycerine, it can be drained from the bottom of the vessel. The RME is then purified from excess of methanol. The last step in the production of RME is to neutralise, desalt and filter the RME before it is pumped into storage containers. The glycerine can be used in the manufacturing of soap, cosmetics and pharmaceuticals (JTI - Institutet för jordbruks- och miljöteknik, 2009). It can also be digested into biogas (Corré, et al., 2016).

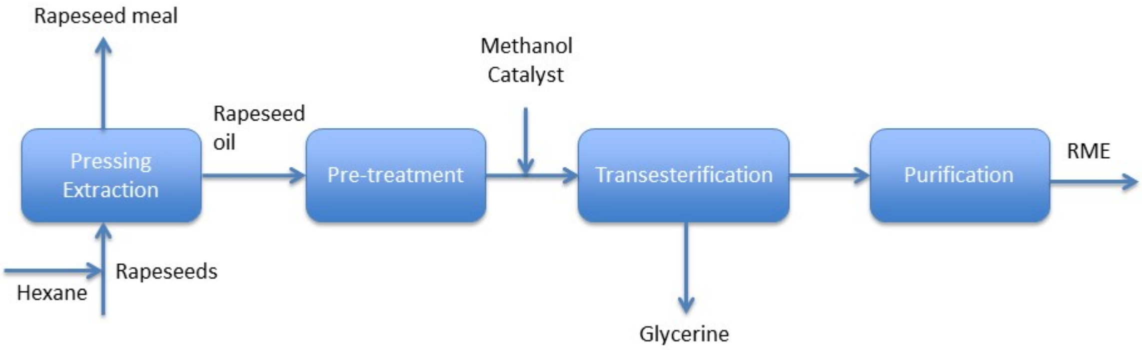

Figure 5: The production steps of RME, rapeseed meal and glycerine.

2.5.3 Production of soybean meal and soybean oil

The vegetable protein used in animal feed in Europe today mainly comes from imported soybeans. The soybean is the highest-yielding source of protein from vegetables (Dalgaard, et al., 2008). The first step in the life cycle of soybean meal is the cultivation of soybeans, which occurs in tropical climate. Hence, many European countries cannot grow soybeans themselves but must import from other countries. USA, Brazil and Argentina are the largest exporters of soybeans. After the cultivation of soybeans, the beans are cleaned, stored and dried (Taelman, et al., 2015). The soybeans then enter an oil mill where the beans are crushed and the oil is extracted by adding hexane (Dalgaard, et al., 2008). Around 80 % of the mass output is soybean meal and around 20 % is soybean oil (see figure 6). The soybean meal is protein rich and used in animal feed and the oil is sold and for example used in food (Taelman, et al., 2015). According to Dalgaard et al. (2008), which have made a consequential LCA of soybean meal, the hot spot in the soybean meal lifecycle when it comes to greenhouse gas emissions is soybean cultivation. The emissions from the cultivation mainly come from the degradation of crop residues and during biological nitrogen fixation when nitrous oxide is released. The amount of greenhouse gases being released during cultivation depends on which soil management practise that is used (Geraldes Castanheira & Freire, 2013).

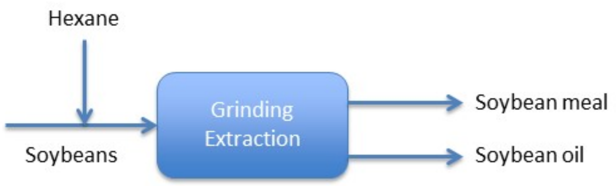

Figure 6: Production steps of soybean meal and soybean oil.

Lantmännen imports their soybean meal used for animal feed from Denofa, which is a Norwegian company that processes soybeans into soybean meal, soybean oil and lecithin (Denofa, 2016). Denofa imports most of their soybeans from Brazil, where they mostly are cultivated and harvested in the state of Mato Grosso (Denofa, 2016).

2.5.4 Properties of DDGS, rapeseed meal and soybean meal

The protein sources DDGS, rapeseed meal and soybean meal are often used in compound feeds, i.e. feeds that are a blend of different raw materials and ingredients. The target within the EU is that the feed should contain 15-30 % protein. The largest part of the feed consists of cereals, e.g. wheat or maize, which is often around 50 % of the feed. However, cereals only contain around 9-13 % protein. Hence, cereals and protein rich ingredients (e.g. DDGS, rapeseed meal or soybean meal) are blended to achieve the right protein content in the feed (Lywood, et al., 2009).

There is no easy way to compare different protein sources since different proteins have different quality. For ruminants, the quality of the protein depends on the amount of protein degraded in the rumen (the first stomach of a ruminant). The protein is considered to have an inferior quality if a large proportion of the protein is degraded in the rumen, and a better quality if the protein is stable in the rumen and later on degraded in the intestinal tract. From this point of view, soybean meal has a better protein quality compared to DDGS and rapeseed meal. If the degradation of protein is large in the rumen, digestible carbohydrates need to be added to the ruminant's diet. The carbohydrates provide the animal with energy, making the synthesis of microbial protein possible in the rumen. The microbial protein then goes to the intestinal tract where the protein can be digested. Hence, the microbial protein formed in the rumen by energy from carbohydrates makes up for the lack of good quality protein in the feed. (Johansson & Ullvén, 2015)

The protein value in the feed can be expressed in amino acids absorbed in the small intestine (AAT) and in protein balance in the rumen (PBV) (Nordic Feed Evaluation System, 2005). The cow's requirement of protein can be expressed in AAT and the cow requires between 350 and 500 AAT during one day (Gustafsson & Volden, 2007). The microbial protein produced in the rumen normally covers 60-80 % of the AAT requirements of the cow (Mehlqvist, et al., 2007). The AAT value varies with the amount of feed the animal eats (Nordic Feed Evaluation System, 2005). In table 1, the AAT20 values of the different protein feeds can be seen. AAT20 is the amount of amino acids absorbed in the small intestine when 20 kg of the feed is eaten by the cow. The AAT20 value is developed and described in *The Nordic Feed Evaluation system*, which is a model formulating feed rations and feed intake for cattle based on scientific methods (Volden, 2011).

The different content and nutrition values of DDGS, soybean meal and rapeseed meal can be seen in table 1. Even though soybean meal contains more protein with a different quality, soybean meal can be substituted by rapeseed meal and DDGS in feeds used for beef breeding (Sonesson, et al., 2009), but the quantity of different ingredients in the cows nutrition should then be changed as well.

Table 1: Nutrition values for DDGS, soybean meal and rapeseed meal.

	DDGS produced at Agroetanol	**Soybean meal**	**Rapeseed meal**
Crude fat [g/kg dry matter][1]	55.5[2]	29	45
Crude protein [g/kg dry matter][1]	341.5[2]	487	400
Digestible crude protein [g/kg dry matter][1,3]	272	469	343
Crude fibre [g/kg dry matter][1]	61[2]	74	123
Metabolisable energy ruminants [MJ/kg dry matter][1, 4]	13.5[2]	14.6	12.5
AAT20 [g/kg dry matter][5]	127	218	144
PBV [g/kg dry matter][6]	166	261	231

[1] (Bernesson & Strid, 2011)

[2] Mean values

[3] Digestible crude protein is the protein that can be digested by the ruminant. The value is for Agrodrank 90 (DDGS produced at Lantmännen Agroetanol).

[4] Metabolisable energy = gross energy - energy going out with the excrement and urine - the energy that is lost in the form of gases that the animal belches out or emits as intestinal gases (Bernesson & Strid, 2011)

[5] (Gustafsson, et al., 2014)

[6] (Liljeholm, et al., 2009)

3. Method

This chapter describes the method used to meet the aim of the report. It starts with a presentation of the LCA methodology used in this study. Subsequently a source criticism will be presented followed by a criticism against the method. The methodology is later described more in detail in chapter 4, e.g. how calculations have been executed.

3.1 Life cycle assessments

Two different life cycle assessments have been executed in order to compare the climate impacts from different arable land use options and protein feeds (see table 2). The method explained in ISO 14040:2006 together with ISO 14044:2006 was followed.

Table 2: The two life cycle assessments executed in this study with their three different scenarios. The produced products in the different scenarios are also presented in the table.

Life cycle assessment of 1 hectare arable land during one year	**Products**
Land use option: wheat	Bioethanol, DDGS and carbon dioxide
Land use option: rapeseed	RME, rapeseed meal and glycerine
Land use option: fallow of type long-term grassland	No products
Life cycle assessment of 100 kg digestible crude protein	**Products**
Protein feed: DDGS	DDGS Co-products: bioethanol and carbon dioxide
Protein feed: rapeseed meal	Rapeseed meal Co-product: rapeseed oil
Protein feed: soybean meal	Soybean meal Co-product: soybean oil

One life cycle assessment of three different arable land use options was performed and their climate impacts were compared with each other. The one hectare arable land was assumed to be located in Östergötland, Sweden. The other life cycle assessment was executed in order to compare the climate impacts from three different protein feeds aimed for cattle. The life cycle assessment of the arable land use options has a cradle-to-grave perspective. This means that the use and disposal phases of the products were considered in the study. However, the life cycle assessment of protein feeds performed in this study has a cradle-to-feed-factory-gate perspective, i.e. the assessment stopped when the feeds had been produced and transported to a feed factory. The feed factory later uses the protein feeds to make compound feeds for cattle. The use and disposal phases of protein feeds were considered too complex to investigate further and were also assumed to cause similar amount of emissions in all three protein feed scenarios. Hence, the emissions from the use and disposal of the protein feeds were not considered in this study.

The climate impact from bioethanol, DDGS and carbon dioxide produced at Lantmännen Agroetanol were investigated in this study. The production of RME, rapeseed meal and glycerine were considered to occur at a large-scale plant in Östergötland, Sweden, but no site specific data was used. Instead, general data of Swedish production was used in the assessment. In the soybean meal scenario, a general case for the Brazilian state Mato Grosso was assumed and no specific production site was investigated.

As mentioned above, the method explained in ISO 14040:2006 together with ISO 14044:2006 was followed in the life cycle assessments. The LCA method described in the Renewable Energy Directive 2009/28/EG (RED) was not followed since this method is developed in order to evaluate the greenhouse gas performance of biofuels compared to fossil fuels in the unit g CO_2 eq/MJ (European Parliament and the Council, 2009). The two life cycle assessments performed in this study includes more products than only biofuels and have other functional units (see chapter 3.1.1) which means that RED can not be applied. However, how the result is affected if parts of REDs system boundaries are considered was investigated in the sensitivity analysis.

3.1.1 Functional units

The functional units in this study are "*one hectare of arable land during one year*" for the three land use scenarios and "*100 kg digestible crude protein*" for the three protein feed scenarios. The functional unit is a quantitative unit reflecting the function of a product, which enables comparisons of different products with the same functions (ISO 14040:2006(en), 2006; ISO 14044:2006(en), 2006). Arable land has a function to provide conditions for something to grow, e.g. grass, wheat or rapeseed. Protein feeds have a function to provide animals, in this case cattle, with protein in their daily feed intake, e.g. feeds such as DDGS, rapeseed meal or soybean meal.

The functional unit "*one hectare of arable land during one year*" was chosen even though the use of land is not seen as a service with a productive function in many studies (González-García, et al., 2016). To be able to compare wheat and rapeseed cultivations with land in fallow, a land based functional unit must be used (since the use of arable land is the only function the three scenarios have in common). Furthermore, by using this functional unit, the question how arable land best should be used from a climate change perspective can be answered.

Since the main purpose of protein feeds is to provide protein to the animal (Lywood, et al., 2009), the three different protein sources were chosen to be compared by digestible crude protein content. Thus, the functional unit “*100 kg digestible crude protein*" was chosen. Calculations of emissions from complete feed rations, one containing DDGS, one containing rapeseed meal and one containing soybean meal, were chosen not to be made since the feed rations contains many different ingredients and since the rations often contains more than one protein source, which will make the comparison complex.

3.1.2 Land use reference

Energy crops cultivated on cropland must have an alternative land use as a reference in the calculations, since the choice of reference affects the amount of greenhouse gas emissions from the land. When the calculations are based on the same reference it will make the comparisons more consistent (Börjesson, et al., 2010).

In the life cycle assessment of 1 hectare arable land during one year, the choice of reference was selected to be the fallow scenario; unfertilized and un-grazed grassland lying uncultivated for a long period of time until a steady state in carbon stocks was reached. The three options, keeping the land in fallow, transforming it into wheat cultivation or transforming it into rapeseed cultivation, were then investigated.

Another land use reference was used in the life cycle assessment of protein feeds. In the LCA of 100 kg digestible crude protein, the same land use reference could not be used in the three different scenarios since the cultivations occur in different countries (Sweden and Brazil). With Swedish statistics about the usage of arable land one can estimate how big part of the wheat and rapeseed cultivations that occur on former grassland and on former cropland (Börjesson, et al., 2010). With this statistics in mind, ¾ of the wheat and rapeseed cultivation in the life cycle of 100 kg digestible crude protein were considered to occur on former cropland (not leading to direct land use change) and ¼ was assumed to occur on former grassland (Börjesson, et al., 2010). For the soybean cultivation, it was estimated that 3.2 % of the cultivation occur on former rainforest land (Ecoinvent centre, 2007). This estimation has been made by knowing the rate of deforestation and the increase in land used for soybean cultivation.

3.1.3 System boundaries

The life cycle assessment of arable land use options included the cultivation on the land and the production and use of pesticides, fertilisers and fossil fuels required for the cultivations. The scenario of 1 hectare wheat included the production of bioethanol, carbon dioxide and DDGS and the scenario of 1 hectare rapeseed included the production of RME, glycerine and rapeseed meal. The use and disposal of the products were also included. However, the distribution of products to the end user was not included. In figure 7, the system boundaries in the wheat and rapeseed scenarios can be seen.

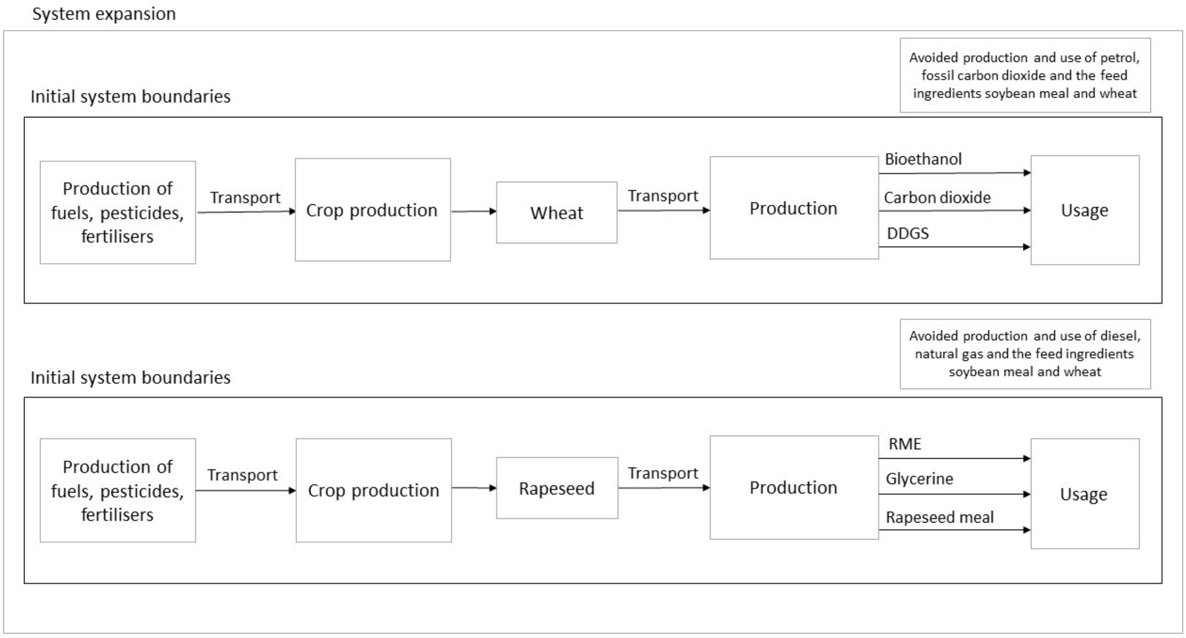

Figure 7: System boundaries of the life cycle assessment on 1 hectare arable land used for cultivation of wheat or rapeseed. The products produced by the wheat and rapeseed lead to avoided production and use of alternative products.

In figure 8, the system boundaries of 1 hectare arable land used as fallow can be seen. The fallow was not assumed to produce any products since the grass residues were considered to be left on the land after mowing. The wheat and rapeseed cultivations were considered to take place at the same Swedish field as the fallow takes place.

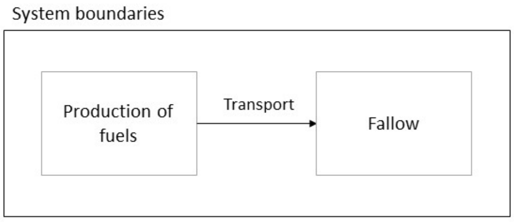

Figure 8: System boundaries of the life cycle on 1 hectare arable land used as fallow. No products are produced from the grass residues.

The life cycle assessment of protein feeds was conducted from the cultivation of wheat, rapeseed and soybean to the production of DDGS, rapeseed meal and soybean meal. The production and use of pesticides, fertilisers and fossil fuels were included in the life cycle assessment. The life cycle ended at the gate of the compound feed factory, receiving the protein feeds. The production of soybean meal were considered to occur in Brazil and then transported to Sweden. The compound feed factory, where all the produced protein feeds are transported, was assumed to be located in Lidköping, Sweden. In figure 9, the system boundaries in the three protein feed scenarios can be seen.

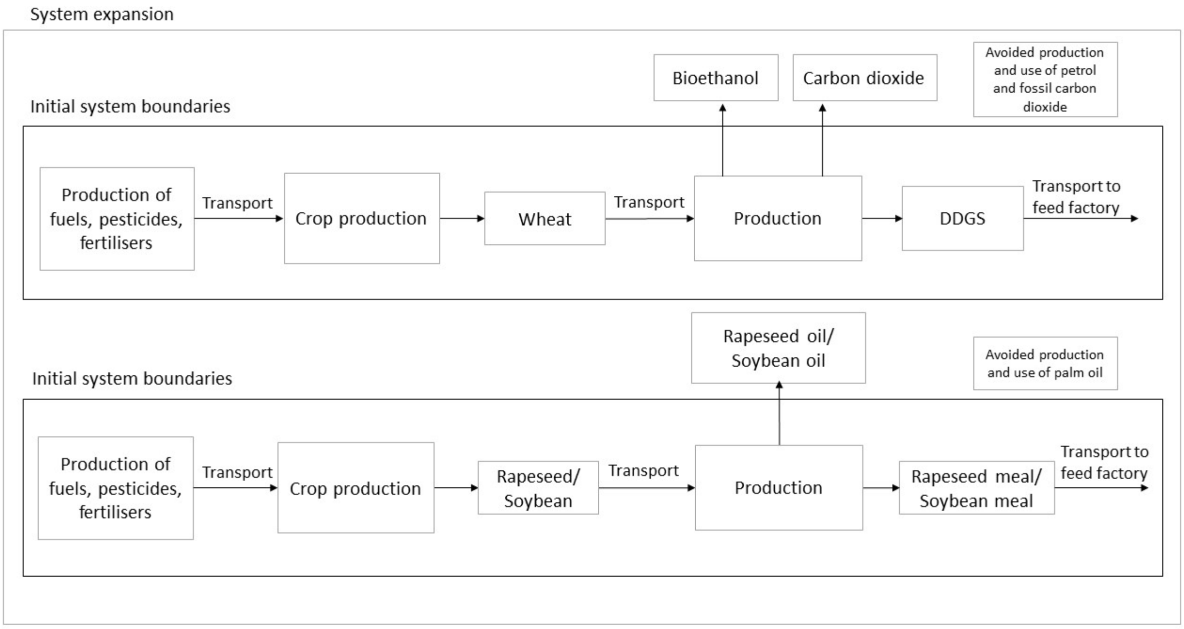

Figure 9: System boundaries of the life cycle assessment on protein feeds DDGS, rapeseed meal and soybean meal. The co-products replace the production and use of alternative products.

All transports in the cultivation and from the cultivation to the production factory were included in both life cycle assessments. The transports of inputs (e.g. chemicals and fertilisers) were also included. For the life cycle of protein feeds, the transport from the production factory to the feed factory was included because of large differences in distance between soybean meal and the other protein feeds. The manufacturing of machinery and buildings required at the investigated production sites were not considered in the life cycle assessments, since the emissions caused by the machinery and buildings are very small and can be neglected when producing ethanol and RME (Bernesson, et al., 2004; Bernesson, et al., 2006). However, the manufacturing of the infrastructure required for other processes, such as vehicles required for the transportations, infrastructure to produce inputs to the cultivation and infrastructure to produce fossil fuels, were considered since this data was included in the Ecoinvent 3 database.

In both life cycle assessments, straw and other crop residues from the wheat and rapeseed cultivations were considered as waste and were considered to be left on the field, since straw is not frequently used to produce energy (Corré, et al., 2016).

3.1.4 Accounting for co-products

System expansion, which is described and recommended by the ISO-standard for LCA, was used on co-products to avoid allocation. In the LCA of arable land use options, system expansion was used on all products produced to be able to compare the wheat and rapeseed scenarios with the fallow scenario. The co-products in both LCAs were considered to replace products on the market with the same function (see figure 7 and figure 9). Since emissions from the use phase of the co-products and from the use phase of the substituted products may differ, the use phase of the co-product and the use phase of the avoided products were included in the life cycle assessments (Weidema, 2001). See information about substitution ratios in chapter 4.

The marginal protein feed was considered to be soybean meal (Schmidt & Weidema, 2008), hence the production of DDGS and the production of rapeseed meal were considered to replace the production and use of soybean meal. To make a fair comparison, rapeseed meal and DDGS were not only considered to replace soybean meal to some extent but also wheat. This is because the assumption that one protein meal fully substitutes the other cannot be made, since different meals have different protein and energy content and different digestibility (Lywood, et al., 2009). Hence, an energy rich ingredient in the feed, e.g. wheat or barley, can be added in the comparison to make the protein and energy contents of the feeds more comparable (Lywood, et al., 2009). In this study, wheat was chosen as the energy rich ingredient. How much soybean meal and how much wheat 1 kg of DDGS and 1 kg of rapeseed meal can substitute were retrieved from the studies by Lywood et al. (2009) and Corré et al. (2016).

Palm oil was considered to be the marginal oil (Schmidt & Weidema, 2008), hence the co-production and use of soybean oil and rapeseed oil were considered to replace the production and use of palm oil. The production and use of biogenic carbon dioxide that is captured and sold were considered to replace the production and use of fossil carbon dioxide and the produced bioethanol and RME were considered to replace the production (extraction and refining) and use of petrol and diesel.

The co-product glycerine was considered to be digested into biogas and replace the production and use of natural gas, which has been made in the study by Corré et al. (2016). The glycerine was not considered to replace synthetic glycerine, since the market for glycerine used in high-value applications is saturated due to the increased biodiesel production (Corré, et al., 2016).

3.1.5 Data collection

See the inventory tables in Appendix for detailed information about the data collection. Data was collected from agricultural statistics, previous studies, from Lantmännen Agroetanol and from the LCI-database Ecoinvent 3. Ecoinvent provides process and emission data for thousands of products in different industrial sectors, e.g. transport, agriculture, biofuels, energy supply and waste treatment (Ecoinvent, n.d.). The aim when searching for data was to find current data under Swedish conditions (except in the soybean meal scenario, when Brazilian conditions occur) to maximize the comparability of the different scenarios.

Data on greenhouse gas emissions from the production and use of e.g. energy and fertilisers as well as data on vehicles for transportation were taken from the Ecoinvent 3 database. In the case of production of nitrogen fertiliser, new updated data based on best available technology (BAT) were used and taken from literature. Other emissions that could not be found in Ecoinvent, e.g. emissions from production of certain pesticides and emissions from direct land use change, were retrieved from literature.

Information about inputs and outputs to the production of bioethanol, DDGS and carbon dioxide was retrieved from Lantmännen Agroetanol, where they have compiled this information for their factory. Inputs and outputs to the production of RME, rapeseed meal, glycerine and soybean meal were retrieved from literature and were not site specific. Some transportation distances of inputs were retrieved from Lantmännen Agroetanol, and these distances were estimations made by employees. Some transport distances were calculated with the help of google maps and others were taken from previous studies.

3.1.6 Impact assessment

With the help of the collected data, the environmental impact from the different life cycles were calculated in the ISO-compliant programme SimaPro with the database Ecoinvent 3. SimaPro is an LCA software package and it contains updated science-based databases and methods (SimaPro, n.d.). The investigated environmental impact category in this study was climate change and the method IPCC 2013 GWP 100a was used to calculate the climate impact. This method was developed by IPCC, and contains climate change factors for each greenhouse gas with a time frame of 100 years (see table 3).

Table 3: Global Warming Potential (GWP) with a time frame of 100 years for each greenhouse gas emission to the air in kg CO2 eq/kg emission (IPCC, 2013).

Emissions	Global Warming Potential (GWP)
Carbon dioxide, CO_2	1
Methane, CH_4	28
Nitrous oxide, N_2O	265

3.1.7 Sensitivity analysis

The sensitivity analysis in chapter 6 investigates different input variables, parameters and system boundaries that are uncertain or has a large impact on the result. It tests the robustness of the results and gives an increased understanding of the relationships between input and output variables in the different processes of the life cycle assessments. The sensitivity analysis was performed by changing one factor at a time to see how the result was affected. Which parameters that should be tested in the sensitivity analysis were selected by looking at which parameters previous studies have tested, RED's system boundaries and which parameters that influence the result significantly. In table 4, the different sensitivity analysis performed can be seen for both life cycle assessments.

Table 4: The different sensitivity analysis performed in this study.

Sensitivity analysis	Changed parameters
Life cycle assessment of 1 hectare arable land during one year	
6.1.1 Excluding the use phase	The use phase of the co-products are excluded and the plants CO_2-uptake are considered
6.1.2 Excluding direct land use change in the cultivation	Emissions caused by direct land use change are excluded
6.1.3 Excluding glycerine	The co-product glycerine is not accounted for in the rapeseed scenario
6.1.4 Alternative production of nitrogen fertiliser	Older technology which causes higher amounts of greenhouse gas emissions are used when producing nitrogen fertiliser
6.1.5 Grain cultivation as a land use reference	The land use reference is changed from unfertilized and un-grazed grassland to grain cultivation
6.1.6 Change of yield per hectare and year	The yields of wheat and rapeseed are decreased by 50 %
6.1.7 Producing biogas from grass residues	The grass residues in the fallow scenario are digested into biogas and are replacing the production and use of natural gas
Life cycle assessment of 100 kg digestible crude protein	
6.2.1 Excluding the use phase of co-products	The use phase of the co-products are excluded and the plants CO_2-uptake are considered
6.2.2 Alternative system expansion with avoided production of rapeseed oil	The co-products rapeseed oil and soybean oil substitute the production and use of rapeseed oil instead of palm oil
6.2.3 Alternative system expansion with production of RME and SME	The co-products rapeseed oil and soybean oil are used to produce biodiesel and glycerine and substitute diesel and natural gas instead of palm oil
6.2.4 Excluding direct land use change in the cultivation of wheat and rapeseed	The wheat and rapeseed cultivations are not considered to contribute to direct land use change
6.2.5 Alternative production of nitrogen fertiliser	Older technology which causes higher amounts of greenhouse gas emissions are used when producing nitrogen fertiliser
6.2.6 Allocation based on lower heating value	An allocation method based on lower heating value is used instead of system expansion
6.2.7 Comparing the protein feeds based on AAT20 value	The functional unit is changed from 100 kg digestible crude protein to 100 kg AAT20

3.2 Source criticism

Articles published in scientific journal and reports published by scientists from the Swedish University of Agricultural Sciences (SLU) have been used in a large extent in this study. The information retrieved from these sources has been reviewed and is therefore considered to be reliable. The LCI-database Ecoinvent 3 has also been used extensively, and this database is considered to be reliable since it is based on scientific research. However, the data in Ecoinvent 3 may be a few years old, since it takes time to update such a comprehensive database. Since new technology can have big impacts on greenhouse gas emissions, it is preferable if the data is as new as possible when performing life cycle assessments. Some literature used to retrieve data, e.g. the study by Bernesson (2004), are older than preferred but were used since no more updated data for Swedish conditions were found.

Data was also retrieved from employees at Lantmännen Agroetanol. The data about amounts of inputs and outputs to the factory has been reviewed by a third party and can therefore be reliable. Some transport distances of inputs to the factory were estimated by employees and might therefore not be totally correct.

3.3 Method criticism

This report is following the life cycle assessment method explained in ISO 14040:2006 together with ISO 14044:2006. As mentioned before, this method advocates system expansion before allocation when possible since system expansion more accurately reflect the climate impact from the produced products, which is the perspective applied in this study. However, a drawback with the system expansion-perspective is that a change in the production or usage phases of the replaced products may have significant effects on the result. It is also difficult to predict how the market is affected when producing products and what these products will substitute, since it depends on demand responses and if the market is saturated etc.

The emissions from production of bioethanol, DDGS and carbon dioxide are based on Agroetanol's processes. This means that site-specific data has been used in some cases. The scenarios involving rapeseed or soybean are based on data from literature and are not site-specific, which implies some uncertainties in the comparison between the different scenarios.

The emissions caused by indirect land use change is not quantified in this report, even though they can have a large impact on the result (Börjesson, et al., 2010; Flysjö, et al., 2008). This should be kept in mind when the result is interpreted.

The use phase of the protein feeds is not included in the life cycle assessment of protein feeds, even though different feeds can lead to different emissions from the cow during the digestion (Liljeholm, et al., 2009). However, to consider the digestion part of the different feeds was considered to be too complex for this study. Furthermore, life cycle assessments of animal feed usually have a cradle-to-factory-gate perspective (Flysjö, et al., 2008; Lehuger, et al., 2009; Samuel-Fitwi, et al., 2013).

In the life cycle assessment of arable land use options, the use phase of the produced protein feeds are included. The assumption is made that the produced feeds have the same environmental impact during the use phase as the avoided protein feeds would have had if they were used. This way of thinking is a simplification of reality.

4. Inventory analysis

The following chapter presents the life cycle inventory of input/output data for the studied systems. It starts with a presentation of data collection for the three arable land use options followed by a presentation of data collection for the three protein feeds.

4.1 Arable land use options

Below, the data inventory of the three different arable land use options is presented. In Appendix table 1-3, the data inventory of 1 hectare wheat, 1 hectare rapeseed and 1 hectare fallow is presented and can be seen in detail.

4.1.1 Cultivation of wheat and rapeseed

The wheat and rapeseed were assumed to be cultivated in Östergötland, Sweden, with one harvest per year. Data for winter wheat and winter rapeseed was used in the life cycle assessment. The yields per hectare of winter wheat and winter rapeseed were calculated as a mean value for the years 2011-2015 (Jordbruksverket, n.d.). Data for production of nitrogen fertiliser were based on BAT from the year 2011. The production of nitrogen fertiliser has become increasingly energy efficient over the last years and modern plants have been equipped with catalytic cleaning of nitrous oxide (Ahlgren, et al., 2011).

4.1.2 Production, use and disposal of bioethanol, DDGS and carbon dioxide

The bioethanol, DDGS and carbon dioxide production was assumed to take place at Lantmännen Agroetanol's factory in Norrköping, and data from Agroetanol's production was used in the life cycle assessment. Data for the production at Lantmännen Agroetanol is confidential and is therefore not presented in the report.

Since bioethanol and carbon dioxide are made from biomass, the use phase of these products were not considered to contribute to any climate change. This is since the carbon dioxide released during the use of the products were considered to have been absorbed during the cultivation of the raw material, which means that the emissions can be seen as carbon neutral. This way of thinking is common when performing life cycle assessments (Wiloso, et al., 2016). DDGS are also made of biomass, but when the feed is digested inside the cow, the carbon in the feed is not only turned into carbon dioxide, but will also be emitted in other forms, e.g. as methane (Liljeholm, et al., 2009). This means that the use and disposal phases of DDGS cannot be seen as carbon neutral. However, the use of DDGS will substitute the use of other feed ingredients, and these feeds were assumed to contribute to the same greenhouse gas emissions during the use and disposal phases. Hence, the emissions from the use and disposal phases of the feeds offset each other in the life cycle assessment and were therefore not included in the calculations.

The assumption was made that 1 kWh bioethanol substitute 1 kWh petrol, and an energy content of 9.06 kWh/l was used for petrol (Biogasportalen, 2015) and an energy content of 5.90 kWh/l was used for bioethanol (Gröna bilister, 2012) when the amount of petrol being substituted by bioethanol was calculated. Information about greenhouse gas emissions from petroleum production was retrieved from Ecoinvent. Emissions caused by combusting petrol were taken from Börjesson et al. (2010) and were assumed to be 0.072 kg CO_2/MJ petrol.

In this study, 1 tonne of DDGS was assumed to substitute 0.615 tonne soybean meal and 0.406 tonne wheat (Lywood, et al., 2009). The production of the substituted soybean meal was assumed to occur in Brazil and the production of the substituted wheat was assumed to occur in Germany. Data for the production of the substituted soybean meal and wheat was retrieved from Ecoinvent.

Avoided emissions from extraction and purification of fossil carbon dioxide (seen as a waste flow from a factory using fossil fuels) were assumed to be the same as the emissions caused by extraction and purification of biogenic carbon dioxide produced at Lantmännen Agroetanol. Hence, the emissions from these two extraction and purification processes were assumed to offset each other and were therefore not included in the calculations. During the use phase, 1 kg of carbon dioxide from Agroetanol was assumed to substitute 1 kg of fossil carbon dioxide.

4.1.3 Production, use and disposal of RME, rapeseed meal and glycerine

The RME, rapeseed meal and glycerine production was assumed to take place at a Swedish large-scale plant that services 50 000 ha of winter rapeseed cultivated in Östergötland, Sweden. Production data was retrieved from Bernesson et al. (2004).

In the use phase, the same approach was used as in the use phase of bioethanol, DDGS and carbon dioxide (see chapter 4.1.2). The RME and glycerine digested into biogas were considered to be carbon neutral during the use phase, and the use and disposal phases of the rapeseed meal were considered to be offset by the use and disposal phases of the replaced feed ingredients and were therefore not included in the calculations.

1 kWh of RME was assumed to substitute 1 kWh of diesel. The energy content in RME was considered to be 33.3 MJ/l (Malgeryd, n.d.) and the energy content in diesel was considered to be 35.1 MJ/l (Malgeryd, n.d.). Emissions caused by combusting diesel were taken from Börjesson et al. (2010) and were assumed to be 0.074 kg CO_2/MJ diesel.

In this study, 1 kg of rapeseed meal was assumed to substitute 0.596 kg of soybean meal and 0.152 kg of wheat (Corré, et al., 2016). The substituted soybean meal was assumed to have been produced in Brazil and the wheat in Germany. The emissions from the production of the substituted soybean meal and wheat were retrieved from Ecoinvent.

The glycerine was considered to be digested into biogas. From 1 kg glycerine, 0.56 m^3 methane can be produced in theory (Pokój, et al., 2014). This means that 1 kg glycerine can substitute 0.56 m^3 natural gas, with the assumption that natural gas consist of 100 % methane. When it comes to the production of biogas and natural gas, the greenhouse gas emissions will be reduced with 67 kg CO_2 eq/tonne RME produced when biogas production from glycerine replaces natural gas production (Corré, et al., 2016). When natural gas is burned, 1.88 kg CO_2 is emitted per m^3 natural gas (U.S. Energy Information Administration, 2016). The biogas was assumed to be carbon neutral during the use phase.

4.1.4 Fallow

In this study, fallow of type long-term grassland where perennial grasses are grown was investigated. The fallow was assumed to have been uncultivated for a long period of time until a steady state in carbon stocks was reached. Since the grasses are perennial, the sowing of the grass was not considered in the life cycle assessment. The fallow was assumed to be mowed once a year, since Swedish regulations say that arable land in fallow must be mowed (Jordbruksverket, 2016). The grass residues were considered to be left on the land. During the mowing, diesel were used for the machines and data about diesel consumption was retrieved from Flysjö et al. (2008). In the study made by Flysjö et al (2008), the grass is mowed twice a year. Since the grass in this study is mowed once a year, half of the amount of diesel used in the study by Flysjö et al. was considered to be required. The lubricating oil required for the machines per ha was calculated by assuming 0.0024 kg lubricating oil is required per MJ diesel used by the machines (Flysjö, et al., 2008).

The grass residues left on the field will decompose. The carbon in the residues will then either be released back to the air in the form of carbon dioxide, in the case of aerobic decomposition, or in the form of methane, in the case of anaerobic decomposition (Wiloso, et al., 2016). It is impossible to say how much of the carbon that will be released as carbon dioxide and how much that will be released as methane, since this depends on how the piles of grass residues is formed which influences the amount of available oxygen during decomposition (Wiloso, et al., 2016). Therefore, the assumption was made that the carbon in grass residues is released as carbon dioxide, which means that the carbon dioxide absorbed by the grass will be released back to the air during the investigated year. Hence, the grass residues were assumed to be carbon neutral.

4.1.5 Nitrous oxide emissions from soil

Direct and indirect nitrous oxide emissions from the wheat and rapeseed cultivations were retrieved from the study by Ahlgren et al. (2011), where the model developed by IPCC had been used to estimate nitrous oxide emissions. The direct and indirect emissions can be seen in table 1 and table 2 in Appendix.

Quantification of nitrous oxide emissions in the fallow scenario has been based on the European Union GREENGRASS project from 2002-2004 (Flechard, et al., 2007). In this project, as mentioned earlier, 10 grassland sites in eight European countries were monitored in case of soil/atmosphere exchange fluxes of nitrous oxide. These studied sites investigated different management practices, such as nitrogen fertilisation and grazing intensity. Fluxes were measured using static (non-steady-state) chamber methods and the N_2O concentrations were determined using e.g. gas chromatography (GC). The result was presented as mean annual N_2O fluxes where data from all sites and the three measurement years were pooled into fertilized/unfertilized and grazed/un-grazed systems (see table 5).

This study investigates an unfertilized and un-grazed fallow. Therefore the annual N_2O emissions were assumed to be 0.32 kg per hectare.

Table 5: Mean annual N_2O emissions at the GREENGRASS sites for different types of grassland (Flechard, et al., 2007).

Type of grassland	**Mean annual N_2O emissions [kg N_2O-N/hectare and year]**
Fertilised and grazed	1.77
Fertilised and un-grazed	0.95
Unfertilised and grazed	0.48
Unfertilised and un-grazed	0.32

4.1.6 Direct land use change

Carbon stock changes caused by direct land use change were calculated with the assumption that the wheat and rapeseed cultivations are taking place on previous fallow of the type unfertilised grassland (since grassland is the land use reference). In table 6, the differences in carbon stock changes compared to unfertilised grassland can be seen. The carbon stock in the grassland is assumed to be in equilibrium (Börjesson, et al., 2010). As seen in the table, wheat and rapeseed cultivations decrease the carbon stock with 350 kg C/ha and year compared to fallow of the type grassland. After 30 to 50 years, an equilibrium is reached in the wheat and rapeseed cultivations and carbon stock changes will no longer occur (Börjesson, et al., 2010). When this comparison was made, the straw left on the field was regarded. Some of the carbon in the straw will help to build up the carbon stocks in the soil (Börjesson, 1999). The carbon stock changes presented in table 6 are partly based on Swedish field studies but also contain assumptions (Börjesson, 1999; Börjesson, et al., 2010).

Table 6: Yearly carbon stock changes for the three land use options (Börjesson, et al., 2010).

Arable land use option	Biomass yield[1] GJ/ha and year (excluding crop residues)	Kg C/ha and year (unfertilised grassland as a reference)[2]	Kg CO_2/GJ harvested biomass (excluding crop residues) (unfertilized grassland as a reference)
Wheat	124.4	-350	-11
Rapeseed	96.9	-350	-16
Fallow	0	0	0

[1] Biomass yield based on statistics from Jordbruksverket. Conversion factor tonne DM/hectare and year to GJ/hectare and year are based on Börjesson et al. (2010).

[2] Carbon stock changes occurring every year until an equilibrium is reached after around 30 to 50 years.

4.2 Protein feed scenarios

Below, the data inventory of the three different protein feeds DDGS, rapeseed meal and soybean meal is presented. When the life cycle assessment of protein feeds was performed in this study, the quantities of the different feeds required to obtain 100 kg digestible crude protein were calculated with the digestible crude protein contents presented in table 1. In Appendix table 4-6, the data inventory of 100 kg digestible crude protein from DDGS, rapeseed meal and soybean meal can be seen in detail.

4.2.1 Production of DDGS

Inventory data for DDGS is seen in Appendix, table 4. Data for the cultivation of wheat, production and transport is the same data as in the land use option of wheat but expressed per 100 kg digestible crude protein. Quantities of inputs and outputs from the production at Lantmännen Agroetanol are confidential and are therefore not presented in the report.

The co-products bioethanol and carbon dioxide were not considered to contribute to climate change during the use phase, since they are made from biomass (see further explanation in chapter 4.1.2). The emissions from extraction and purification of biogenic carbon dioxide from Agroetanol were not included in the calculations since these emissions were assumed to be offset by the emissions from the avoided extraction and purification of fossil carbon dioxide.

1 kWh of the produced bioethanol was considered to substitute 1 kWh of petrol, using an energy content of bioethanol and petrol of 5.90 kWh/l (Gröna bilister, 2012) and 9.06 kWh/l (Biogasportalen, 2015) respectively. 1 kg of carbon dioxide produced at Agroetanol was assumed to substitute 1 kg of fossil carbon dioxide.

4.2.2 Production of rapeseed meal

Data collected for the production of rapeseed meal is seen in Appendix, table 5. Data for the cultivation of rapeseed and transport is the same data as in the land use option of rapeseed but expressed per 100 kg digestible crude protein. Data of the production processes of rapeseed meal are almost the same as for the land use option of rapeseed, but in this case the transesterification step was excluded since RME is not produced.

The co-product rapeseed oil and the substituted palm oil were considered to have the same climate impact during the use phase. Hence, the emissions from the use of the oils were assumed to offset each other and were therefore not quantified in this report. The assumption was made that 1 kg rapeseed oil substitutes 1 kg palm oil. The climate impact from the production of palm oil was retrieved from Ecoinvent.

4.2.3 Production of soybean meal

Data for soybean cultivation and soybean meal production are seen in Appendix, table 6. The data of soybean cultivation was collected from 55 farms located in Mato Grosso. An average of the farms quantities of inputs and an average of the years 2007-2010 were used in this study.

The soybean oil that is co-produced with the soybean meal and the substituted palm oil were considered to have the same climate impact during the use phase. The greenhouse gas emissions from the use of the oils therefore offset each other and were not included in the calculations. The assumption was made that 1 kg of soybean oil substitutes 1 kg of palm oil, and the climate impact from producing palm oil was retrieved from Ecoinvent.

4.2.4 Nitrous oxide emissions from soil

Nitrous oxide emissions from the wheat and rapeseed cultivations were retrieved from Ahlgren et al. (2011) (see Appendix, table 4 and table 5). Nitrous oxide emissions from the soybean cultivation were retrieved from Ecoinvent (Ecoinvent centre, 2007). The emissions can be seen in Appendix, table 6.

4.2.5 Direct land use change

In the life cycle assessment of protein feeds, the assumption was made that ¼ of the wheat and rapeseed cultivations occurs on former grassland and ¾ of the wheat and rapeseed cultivations occur on former cropland, which does not cause land use change (see chapter 3.1.1). In the soybean meal scenario, the assumption was made that 3.2 % of the cultivation is taking place on former rainforest land (see chapter 3.1.1), and the deforestation leads to emissions of 0.281 kg CO_2/kg soybeans (Ecoinvent centre, 2007). See table 4-6 in Appendix for quantification of emissions caused by direct land use change for the three different protein feeds.

4.3 Transportation

Transport distances of inputs and outputs by road or sea can be seen in Appendix (table 1-3 for the arable land use options and table 4-6 for the protein feeds). The transport distances of pesticides, fertilisers, lubricating oil and light fuel oil to the farm for all scenarios were assumed to be 200 km. The transport distances of hexane, methanol and potassium hydroxide (KOH) catalyst to the rapeseed meal and RME factory were also assumed to be 200 km. Wheat, rapeseed and soybean meal were considered to be transported 50 km from the farm to the production sites. Transport distances of chemicals, yeast and enzymes to the bioethanol, DDGS and carbon dioxide production site were retrieved from employees at Lantmännen Agroetanol, but these distances are confidential and are not shown in the report. Some of these distances have also been retrieved with the help of Google maps. Transport distances from the soybean meal production site to Sweden were retrieved from literature and google maps and are in total 13 134 km by lorry and ship. All the protein feeds were considered to be transported to a feed factory in Lidköping, 270 km from the DDGS and rapeseed meal production site. The transportation of diesel and seeds were neglected, and so was the transport of rapeseed oil to the RME factory (since the rapeseed oil and RME production were considered to occur in the same factory).

All transports by lorry were considered to be made with a light lorry, 16-32 metric tonne, EUR04. The transports by sea were either considered to occur by transoceanic ship or transoceanic tanker, depending on if the goods were solids or liquids. The emissions from the transports were retrieved from Ecoinvent.

4.4 Chemicals

Emissions from production of chemicals were retrieved from Ecoinvent. For chemicals that were not available in Ecoinvent, data on greenhouse gas emissions were retrieved from Bernesson (2004). Emissions from production of yeast and enzymes were retrieved from the study by Bernesson (2004) and Bundgaard et al. (2014) respectively.

4.5 Energy

The emissions from the production of electricity were retrieved from Ecoinvent. A Swedish electricity mix was used for the processes occurring in Sweden and a Brazilian electricity mix was used for the processes occurring in Brazil. During the cultivation when electricity was required for drying the seeds, medium voltage electricity was assumed. High voltage electricity was used in the Swedish and Brazilian production sites producing the different biofuels and feeds.

The emissions for producing the light fuel oil were retrieved from Ecoinvent and the emissions from burning the oil were retrieved from Bernesson (2004). The climate impact from the production of diesel was taken from Ecoinvent and the emissions from combustion of diesel in the cultivation were retrieved from Bernesson (2004).

Emissions from the steam used at the ethanol, DDGS and carbon dioxide production site were retrieved from the study by Bernesson and Strid (2011). In the study, the steam was assumed to be produced from wood chips. The steam used by Lantmännen Agroetanol is by 90 % produced from wood waste and other biomass. The heat used in the soybean meal production was assumed to be produced from hardwood chips from forest, and the emissions were retrieved from Ecoinvent.

5. Impact assessment

This chapter presents the results of the life cycle assessments. First the total climate impacts from the arable land use options are presented, followed by a more in-depth presentation of the result of each scenario. The same presentation of the result for the protein feed scenarios will be made.

5.1 Arable land use options

The total climate impacts from the three arable land use options can be seen in table 7. The best investigated land use option from a climate change perspective is to cultivate wheat on the arable land and this option has a total climate impact of -5094 kg CO_2 eq/hectare and year. The second best land use option is to cultivate rapeseed on the arable land and this option has a total climate impact of -2148 kg CO_2 eq/hectare and year. The worst option is to have the arable land in fallow with a climate impact of 105 kg CO_2 eq/hectare and year, since it does not contribute with any products and therefore no greenhouse gas emissions from alternative products can be avoided. The negative numbers in the wheat and rapeseed scenarios mean that the scenarios do not contribute to climate change but instead avoid greenhouse gas emissions from being released.

Table 7: Total climate impact from the three land use options.

Arable land use option	**Total climate impact [kg CO_2 eq/ha and year]**
Wheat	-5094
Rapeseed	-2148
Fallow	105

5.1.1 Wheat

The climate impact from the different processes included in the arable land use option wheat can be seen in figure 10. The red bars represent the released greenhouse gas emissions to the air and the green bars represent the avoided greenhouse gas emissions when applying system expansion.

In figure 10, the wheat cultivation includes the emissions from the cultivation. Production includes the emission from the production of bioethanol, DDGS and carbon dioxide. Transport includes the emissions caused by transport of inputs used in the cultivation and in the production. The negative emissions in the figure arise since the bioethanol and DDGS lead to avoided production of petrol, soybean meal and wheat grain and avoided usage of petrol and fossil carbon dioxide. Extraction and purification of fossil carbon dioxide were assumed to be equal with the extraction and purification of biogenic carbon dioxide and are therefore not shown in the figure. Usage of soybean meal and wheat grain have no net contribution of greenhouse gas emissions since they were assumed to have the same impact during the use and disposal phases as DDGS. Hence, the emissions from the usage and disposal of DDGS and the avoided soybean meal and wheat compensate for each other, and are therefore not shown in figure 10. Together, these processes result in a total climate impact of -5094 kg CO_2 eq/ha and year.

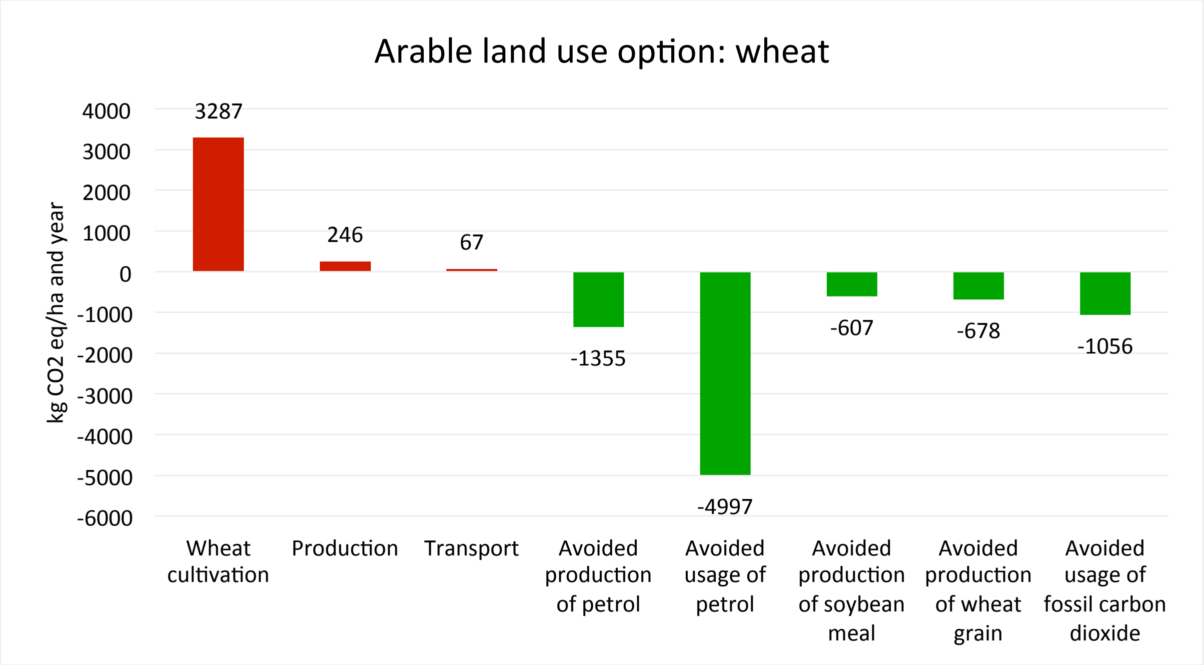

Figure 10: The climate impact from the different processes included in the arable land use option: wheat. Avoided usage of fossil carbon dioxide can also be seen as a carbon capture and replacement process (with accordance to RED).

Wheat cultivation is the predominant cause of greenhouse gas emissions and contributes to 91 % of the total released greenhouse gas emissions from wheat cultivation, production and transport (3600 kg CO_2 eq/hectare and year in total). See figure 11 for the distribution of greenhouse gas emissions in the wheat cultivation. Production of bioethanol, DDGS and carbon dioxide as well as transportation of inputs to the cultivation and production have therefore in comparison with the wheat cultivation an insignificant climate impact. The largest contributor to the climate impact in the production site is the production of steam (42 % of total CO_2 eq), followed by production of chemicals (26 % of total CO_2 eq) and electricity used at the production site (19 % of total CO_2 eq). The transportation of wheat from farm to production site by lorry contributes to 83 % of total transport emissions.

The avoided production of petrol, soybean meal and wheat grain together with avoided usage of petrol and carbon dioxide contribute with avoided greenhouse gas emissions of -8693 kg CO_2 eq/hectare and year in total.

Since the wheat cultivation is the major cause of released greenhouse gas emissions, it is interesting to see the distribution of greenhouse gas emissions between the processes included in the cultivation of wheat, which can be seen in figure 11. In figure 11, the wheat seed, fertilisers, pesticides and lubricating oil processes include the production of the products. The diesel and light fuel oil include the production and use of the fuels. Nitrous oxide emissions are direct and indirect nitrous oxide emissions from the field and carbon stock changes are the emissions caused by land use change from fallow to wheat cultivation.

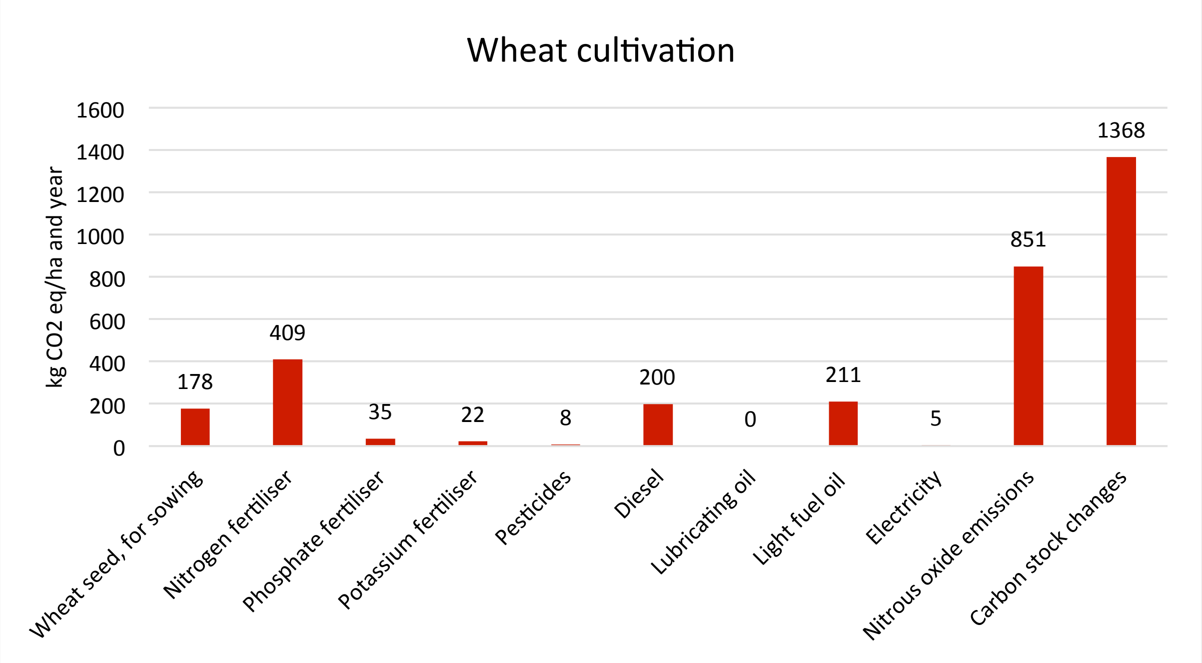

Figure 11: The climate impact from the different processes included in the wheat cultivation.

Carbon stock changes in the soil contribute the most to climate change during the wheat cultivation. This high impact is because fallow of the type long-term grassland is used as a land use reference. When grasslands are converted to crop cultivation, carbon is released from the soil, which has a large climate impact. This is also called direct land use change. The second largest contributor to the climate change from the cultivation of wheat is nitrous oxide emissions from the soil. This is because intensive agriculture with a high input of nitrogen fertiliser in the combination with other favouring conditions (mentioned in chapter 2.4.3) contribute to the formation of nitrous oxide. These emissions, as mentioned before, are of great importance since N_2O contributes 265 times more to climate change than CO_2. The third largest contributor to climate change is the production of nitrogen fertiliser. This is because the production of nitrogen fertiliser requires significant amounts of energy and currently accounts for approximately 1.2 % of global primary energy demand on an annual basis (IFA, 2014) and since the production leads to N_2O emissions (Andersson, et al., 2010). However, the factories have become increasingly energy efficient during the past few years (Ahlgren, et al., 2011).

5.1.2 Rapeseed

The climate impact from the different processes included in the arable land use option rapeseed can be seen in figure 12. In figure 12, rapeseed cultivation includes the emissions from the cultivation. Production includes the emission from the production of RME, rapeseed meal and glycerine. Transport includes the emissions caused by transport of inputs used in the cultivation and in the production. The negative emissions in the figure arise since the RME, rapeseed meal and glycerine lead to avoided production of diesel, soybean meal, wheat grain and natural gas. The avoided production of natural gas is a net greenhouse gas emission reduction, which results from replacing natural gas with biogas, since the glycerine is digested into biogas (Corré, et al., 2016). The avoided usage of alternative products includes greenhouse gas emissions from the usage of diesel and natural gas. Usage of soybean meal and wheat grain have no net contribution of greenhouse gas emissions since they were assumed to be the same as the emissions from the use of rapeseed meal. Together, these processes result in a total climate impact of -2148 kg CO_2 eq/ha and year.

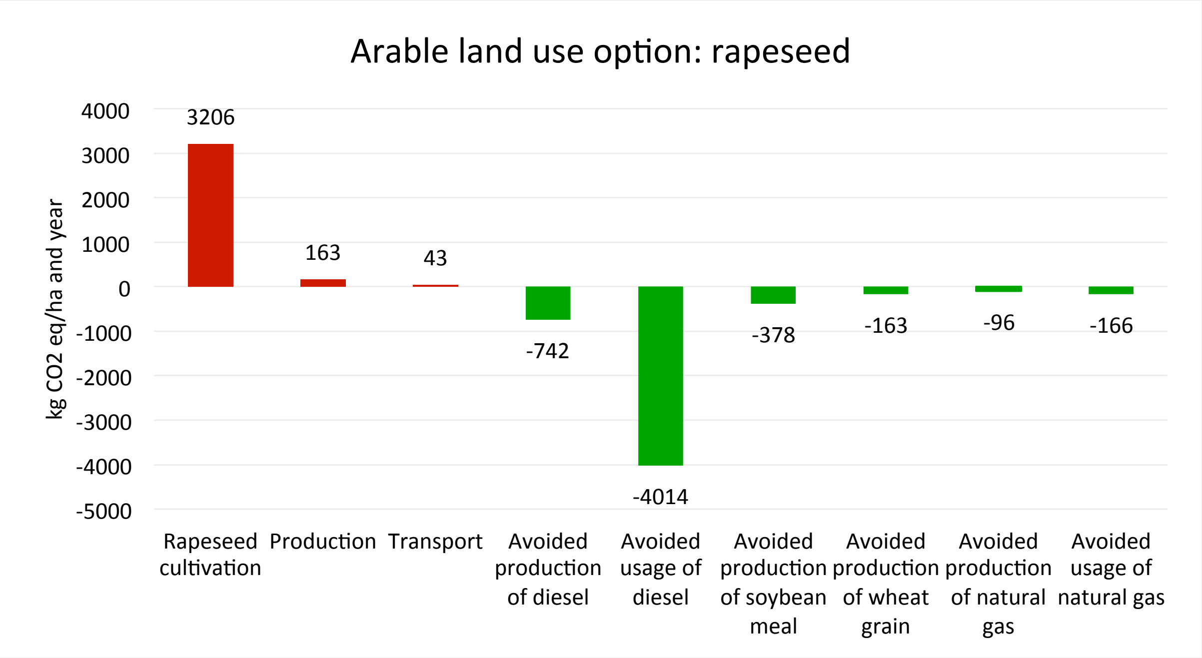

Figure 12: The climate impact from the different processes included in the arable land use option: rapeseed.

The cultivation is the predominant cause of greenhouse gas emissions and contributes to 94 % of the total released greenhouse gas emissions from rapeseed cultivation, production and transport (3412 kg CO_2 eq/hectare and year in total). See figure 13 for the distribution of greenhouse gas emissions in the rapeseed cultivation. The largest contributor to the climate change in the production is the production of methanol, which contributes to 64 % of the total greenhouse gas emissions from the production. The production of potassium hydroxide (catalyst in the transesterification process) contributes to 22 % of the total greenhouse gas emissions followed by the production of electricity, which contributes to 14 % of the total greenhouse gas emissions from the production. The transportation of rapeseed from farm to production site by lorry contributes to 67 % of total transport emissions.

The avoided production of diesel, soybean meal, wheat grain and natural gas together with avoided usage of diesel and natural gas contribute with avoided greenhouse gas emissions of -5559 kg CO_2 eq/hectare and year in total.

The distribution of greenhouse gas emissions between the processes in the cultivation of rapeseed can be seen in figure 13. In the figure, the rapeseed, fertilisers, pesticides and lubricating oil processes include the production of the products. The diesel and light fuel oil include the production and use of the fuels. Nitrous oxide emissions are direct and indirect nitrous oxide emissions from the field and carbon stock changes is the emissions caused by land use change from fallow to rapeseed cultivation.

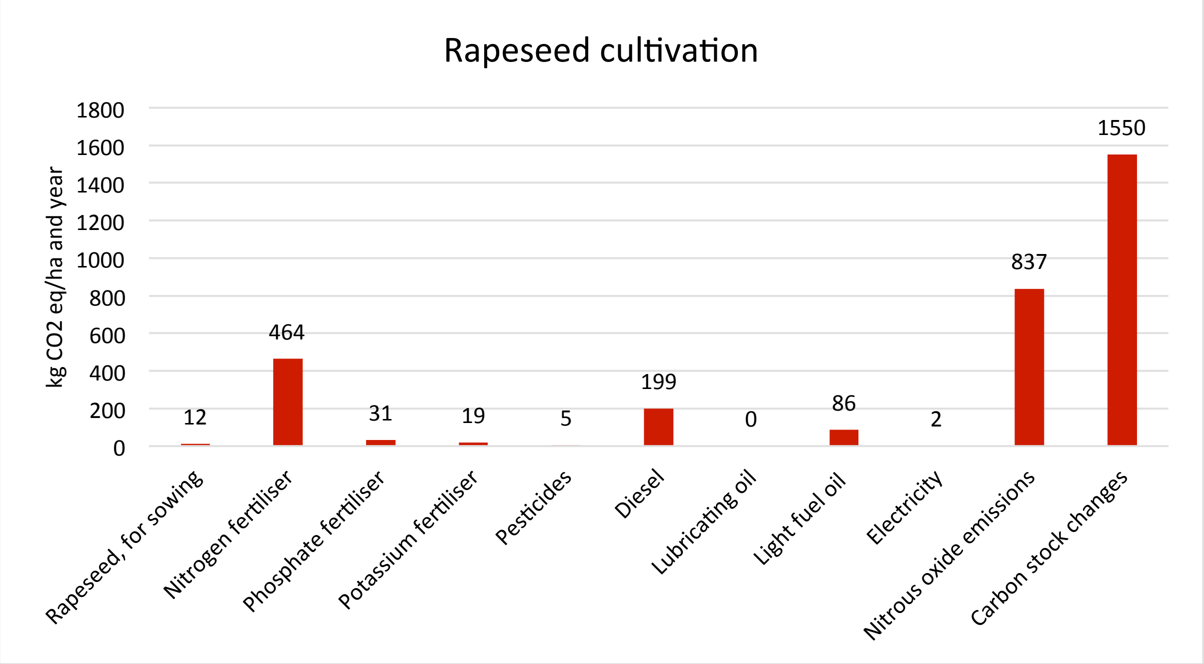

Figure 13: The climate impact from the different processes included in the rapeseed cultivation.

The result presented in figure 13 is almost identical with the distribution of greenhouse gas emissions from the wheat cultivation. Carbon stock changes, followed by nitrous oxide emissions and nitrogen fertiliser are the three largest contributors to the climate impact from the rapeseed cultivation.

5.1.3 Fallow

The climate impact from the different processes included in the arable land use option fallow can be seen in figure 14. In figure 14, diesel includes production and use of diesel for mowing, lubricating oil includes the production of the oil used in machines, transport includes the transportation of lubrication oil to the fallow and nitrous oxide emissions are the direct and indirect emissions from the field. Together, these processes result in a total climate impact of 105 kg CO_2 eq/ha and year.

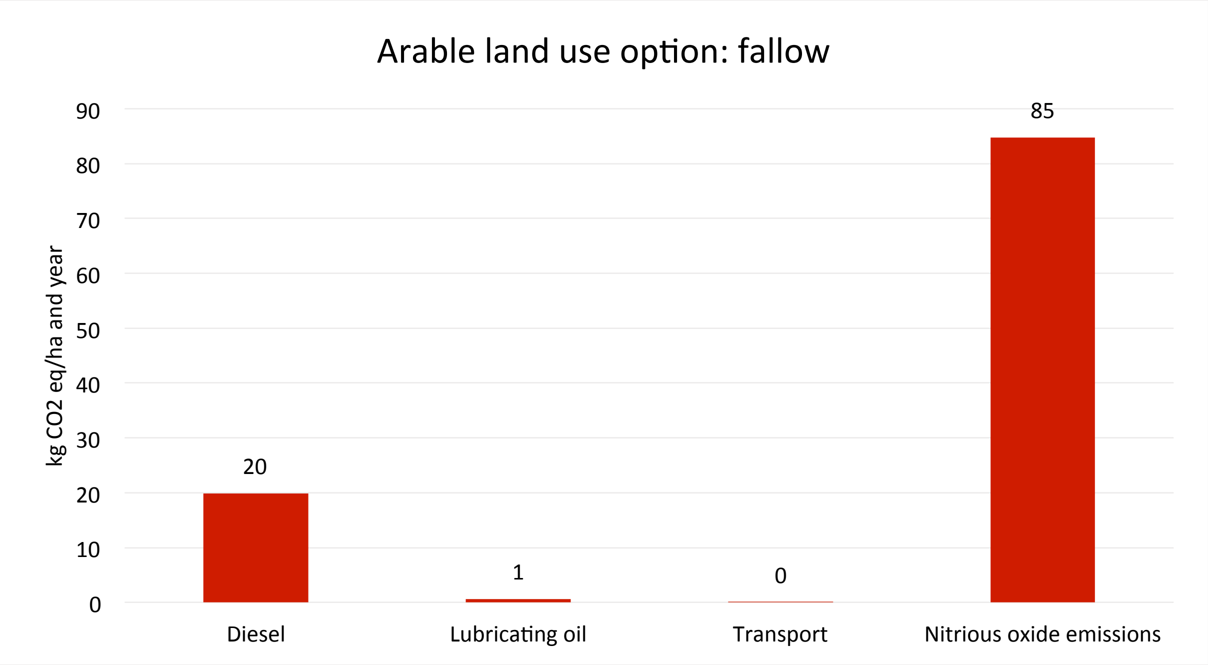

Figure 14: The climate impact from the different processes included in the arable land use option: fallow.

The fallow scenario does not contribute with any products and system expansion is therefore not needed. Nitrous oxide emissions are the largest contributor to climate change with an impact of 85 kg CO_2 eq/ha and year followed by the diesel consumption when mowing the grass once a year.

5.2 Protein feed scenarios

The total climate impact from the three protein feed scenarios can be seen in table 8. DDGS and rapeseed meal are the best protein feeds from a climate change perspective with total climate impacts of -669 kg CO_2 eq/100 kg digestible crude protein and -639 kg CO_2 eq/100 kg digestible crude protein respectively. The worst protein feed from a climate change perspective is soybean meal with a total climate impact of 139 kg CO_2 eq/100 kg digestible crude protein. Both DDGS and rapeseed meal are significantly better from a climate change perspective compared to soybean meal. DDGS is almost 5 % better than rapeseed meal from a climate change perspective according to the result. However, since DDGS and rapeseed meal have so similar results and since the study contains uncertainties and several assumptions, a distinct conclusion which of the two protein feeds is best from a climate change perspective cannot be made. The negative numbers in the DDGS and rapeseed meal scenarios mean that the feeds do not contribute to climate change but instead avoid greenhouse gas emissions from being released.

Table 8: Total climate impact from the three protein feed scenarios.

Protein feed scenario	**Total climate impact [kg CO_2 eq/100 kg digestible crude protein]**
DDGS	-669
Rapeseed meal	-639
Soybean meal	139

5.2.1 DDGS

The climate impact from the different processes included in the protein feed scenario DDGS can be seen in figure 15. In figure 15, the wheat cultivation includes the emissions from the cultivation. Production includes the emission from the production of DDGS, bioethanol and biogenic carbon dioxide. Transport includes the emissions caused by transport of inputs used in the cultivation and in the production. The negative emissions arise since the co-product bioethanol substitutes the production and usage of petrol and the co-product biogenic carbon dioxide substitutes the usage of fossil carbon dioxide. Extraction and purification of fossil carbon dioxide were assumed to be equal with the extraction and purification of biogenic carbon dioxide and were therefore not quantified. Together, these processes result in a total climate impact of -669 kg CO_2 eq/100 kg digestible crude protein.

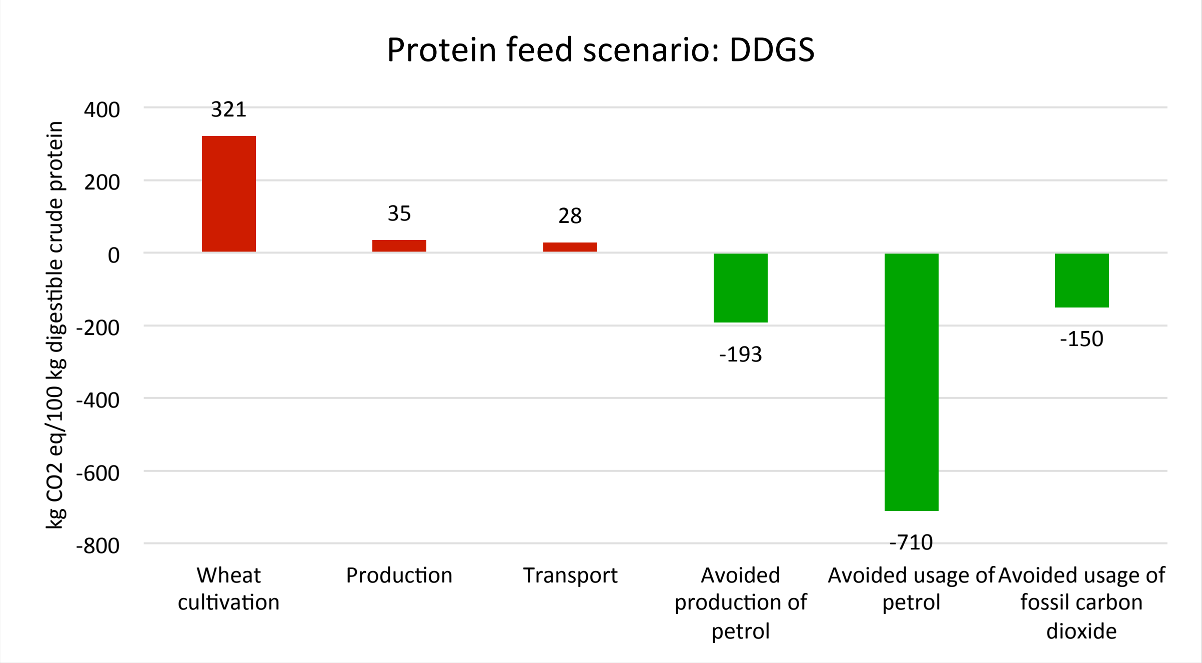

Figure 15: The climate impact from the different processes included in the protein feed scenario: DDGS. Avoided usage of fossil carbon dioxide can also be seen as a carbon capture and replacement process (with accordance to RED).

Wheat cultivation is the predominant cause of greenhouse gas emissions and contributes to 84 % of the total greenhouse gas emissions from wheat cultivation, production and transport (384 kg CO_2 eq/100 kg digestible crude protein in total). The distribution of emissions from the production is the same as for the arable land use option wheat with production of steam as the largest contributor to greenhouse gas emissions, followed by production of chemicals and electricity used at the production site. The transport of DDGS from the production site to the feed factory in Lidköping by lorry contributes to 66 % of total transport emissions.

In this scenario, ethanol and carbon dioxide are co-produced with DDGS. When applying system expansion, the production and usage of these co-products lead to avoided greenhouse gas emissions of -1053 kg CO_2 eq/100 kg digestible crude protein in total.

The distribution of greenhouse gas emissions between the processes in the cultivation of wheat can be seen in figure 16. In figure 16, the wheat seed, fertilisers, pesticides and lubricating oil processes include the production of the products. The diesel and light fuel oil include the production and use of the fuels. Nitrous oxide emissions are direct and indirect nitrous oxide emissions from the field. Carbon stock changes are the emissions caused by transforming fallow into wheat cultivation. In this scenario ¼ of the arable land required to produce 100 kg digestible crude protein was assumed to cause carbon stock changes. Therefore the emissions caused by carbon stock changes are smaller than in the arable land use option wheat.

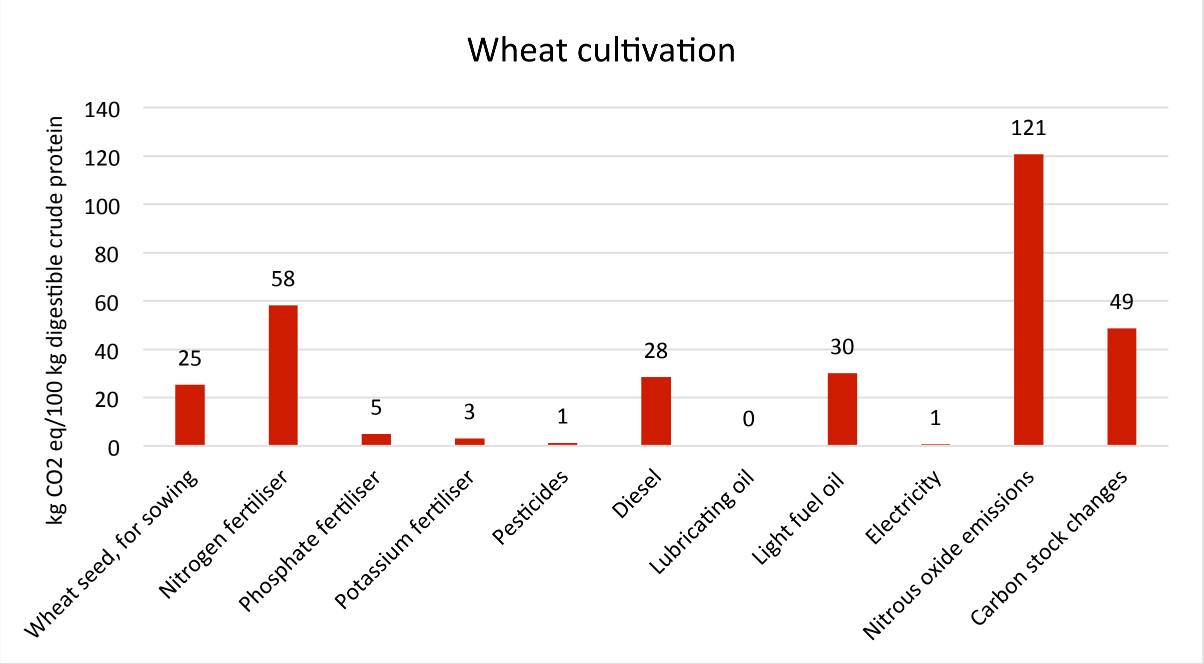

Figure 16: The climate impact from the different processes included in the wheat cultivation.

Nitrous oxide emissions are the predominant cause of greenhouse gas emissions from the cultivation of wheat and stands for 38 % of the total climate impact. The second largest contributor to climate change is the production of nitrogen fertilizer followed by carbon stock changes.

5.2.2 Rapeseed meal

The climate impact from the different processes included in the protein feed scenario rapeseed meal can be seen in figure 17. In figure 17, rape cultivation includes the emissions from the cultivation. Production includes the emission from the production of rapeseed meal and rapeseed oil. Transport includes the emissions caused by transport of inputs used in the cultivation and in the production. The negative emissions arise since the co-product rapeseed oil substitutes the production of palm oil. Together, these processes result in a total climate impact of -639 kg CO_2 eq/100 kg digestible crude protein.

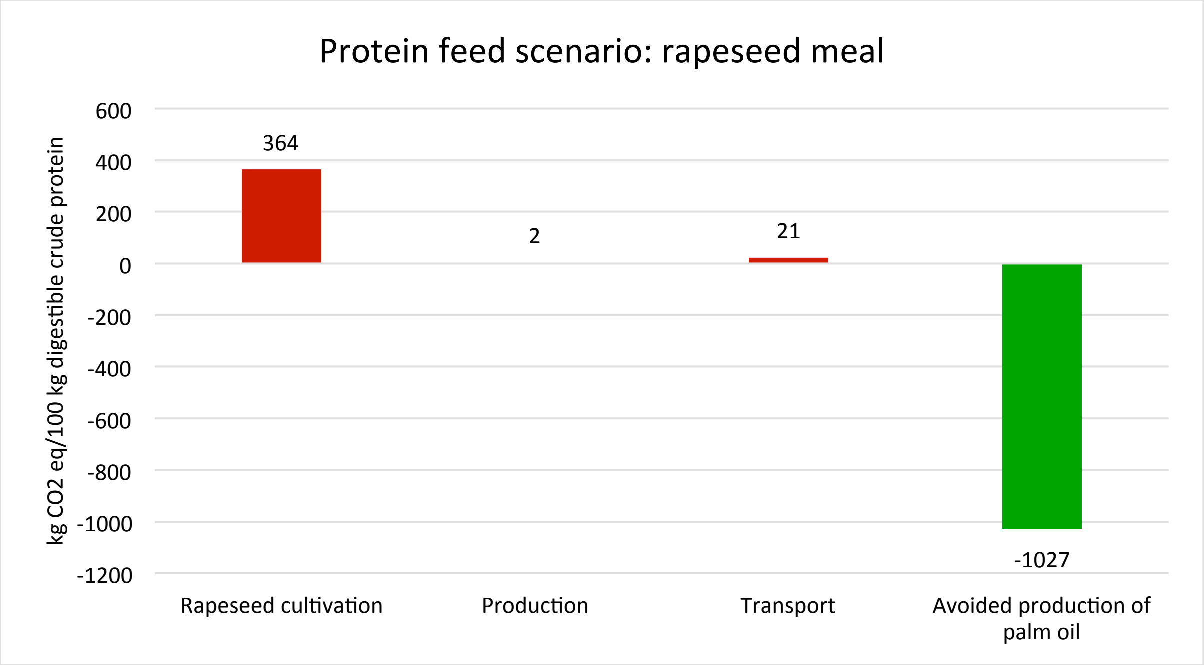

Figure 17: The climate impact from the different processes included in the protein feed scenario: rapeseed meal.

Rapeseed cultivation is the predominant cause of greenhouse gas emissions and contributes to 94 % of the total released greenhouse gas emissions from rapeseed cultivation, production and transport (387 kg CO_2 eq/100 kg digestible crude protein in total). The distribution of emissions from the production is not the same as for the arable land use option rapeseed. The production of rapeseed meal only includes the mechanical pressing of rapeseeds and the extraction phase where the rapeseed meal and rapeseed oil is separated. Greenhouse gas emissions from the production are therefore only from the addition of hexane and the production of electricity used at the production site with a total of 2 kg CO_2 eq/100 kg digestible crude protein. The transport of rapeseed meal from the production site to the feed factory in Lidköping by lorry contributes to 70 % of total transport emissions.

The avoided production of palm oil leads to avoided greenhouse gas emissions of -1027 kg CO_2 eq/100 kg digestible crude protein. The high climate impact from palm oil production is mainly because of land conversion activities connected to the cultivation of palm fruits, such as clear cutting of primary forests in Malaysia (Ecoinvent centre, 2007). It is however no avoided greenhouse gas emissions when using the palm oil in this case since the palm oil was assumed to have the same climate impact during the use phase as the rapeseed oil.

The distribution of greenhouse gas emissions between the processes in the cultivation of rapeseed can be seen in figure 18. In the figure, the rapeseed, fertilisers, pesticides and lubricating oil processes include the production of the products. The diesel and light fuel oil include the production and use of the fuels. Nitrous oxide emissions are direct and indirect nitrous oxide emissions from the field. Carbon stock changes are the emissions caused by the transformation from fallow into rapeseed cultivation. In this scenario ¼ of the arable land required to produce 100 kg digestible crude protein was assumed to cause carbon stock changes.

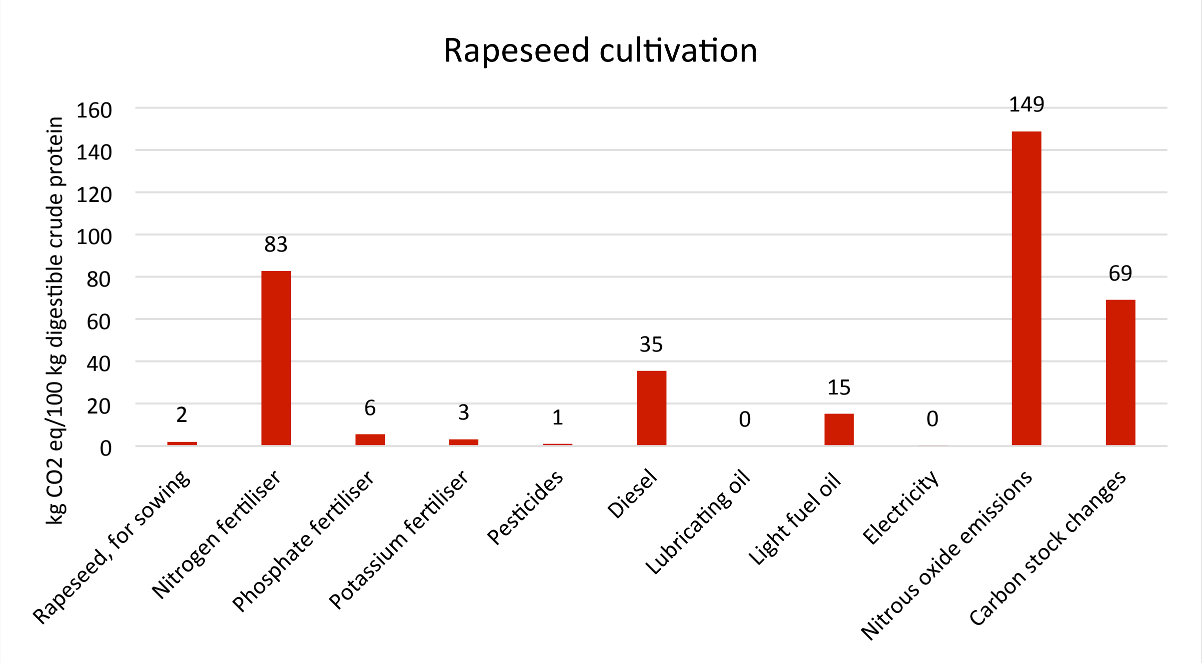

Figure 18: The climate impact from the different processes included in the rapeseed cultivation.

This result is almost identical with the distribution of greenhouse gas emissions from the wheat cultivation to produce DDGS (see figure 16). Nitrous oxide emissions, followed by nitrogen fertiliser and carbon stock changes are the three largest contributors to the climate change from the rapeseed cultivation.

5.2.3 Soybean meal

The climate impact from the different processes included in the protein feed scenario soybean meal can be seen in figure 19. In figure 19, the soybean cultivation includes the emissions from the cultivation. Production includes the emission from the production of soybean meal and soybean oil. Transport includes the emissions caused by transport of inputs used in the cultivation and in the production. The negative emissions arise since the co-product soybean oil substitutes the production of palm oil. Together, these processes result in a total climate impact of 139 kg CO_2 eq/100 kg digestible crude protein.

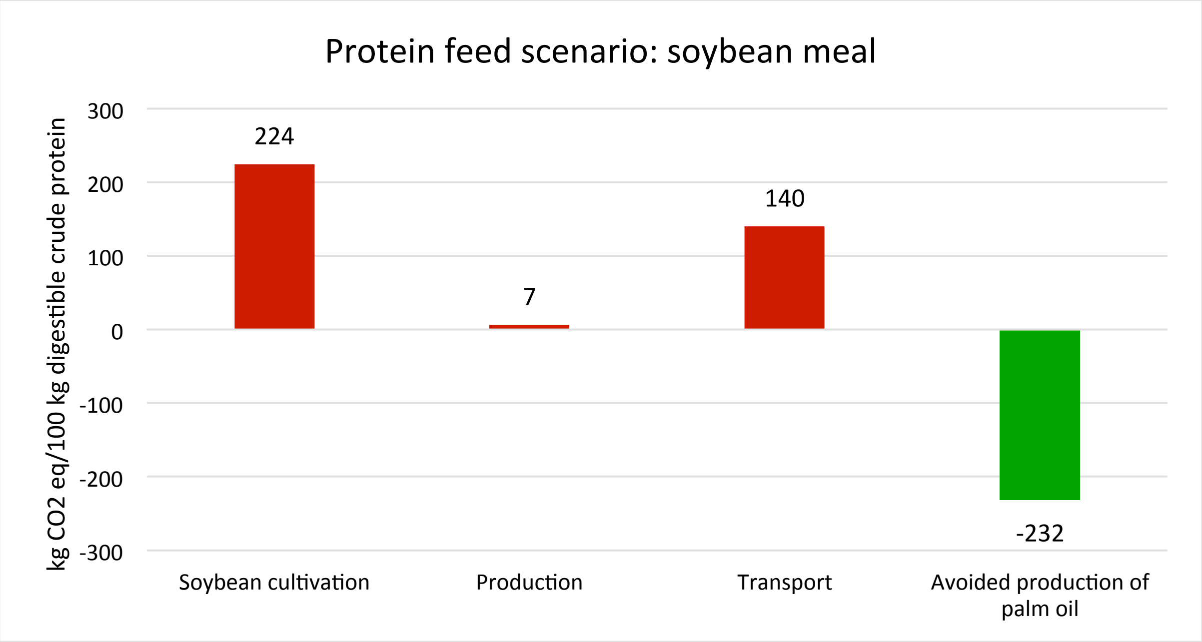

Figure 19: The climate impact from the different processes included in the protein feed scenario: soybean meal.

Soybean cultivation is the largest cause of greenhouse gas emissions and contributes to 60 % of the total released greenhouse gas emissions from soybean cultivation, production and transport (371 kg CO_2 eq/100 kg digestible crude protein in total). 99 % of the total greenhouse gas emissions from the production are from the heat and electricity used in the oil mill where the beans are crushed and the oil is extracted. The transports in this scenario contribute more to climate change than in the scenarios of DDGS and rapeseed meal. This is mainly due to the long transportation of soybean meal from the production site in Brazil to the feed factory in Sweden.

The avoided production of palm oil leads to avoided greenhouse gas emissions of -232 kg CO_2 eq/100 kg digestible crude protein. There are no avoided greenhouse gas emissions when using soybean oil instead of palm oil, since the oils were assumed to contribute the same to climate change during the use phase.

Soybean meal is the highest-yielding source of protein when comparing the protein feed scenarios. Therefore less amount of soybean meal is needed when producing the functional unit 100 kg digestible crude protein. This together with the small amounts of nitrogen fertiliser used in the soybean cultivation, lead to a lower amount of greenhouse gas emissions from the cultivation and production in the soybean meal scenario compared to the DDGS and rapeseed meal scenarios. Around 80 % of the output from the production site is soybean meal and around 20 % is soybean oil. Since a smaller amount of soybean meal than rapeseed meal is required to obtain 100 kg digestible crude protein and since the oil rate is lower for soybean than for rapeseed, a lower amount of palm oil is avoided in the soybean meal scenario compared to the rapeseed meal scenario.

The distribution of greenhouse gas emissions between the processes in the cultivation of soybean can be seen in figure 20. In the figure, the soybean seed, fertilisers, pesticides and lubricating oil processes include the production of the products. The diesel and light fuel oil includes the production and use of the fuels. Nitrous oxide emissions are direct and indirect nitrous oxide emissions from the field. Carbon stock changes are the emissions caused by land use change and it was estimated that 3.2 % of the soybean cultivation occurred on former rainforest land.

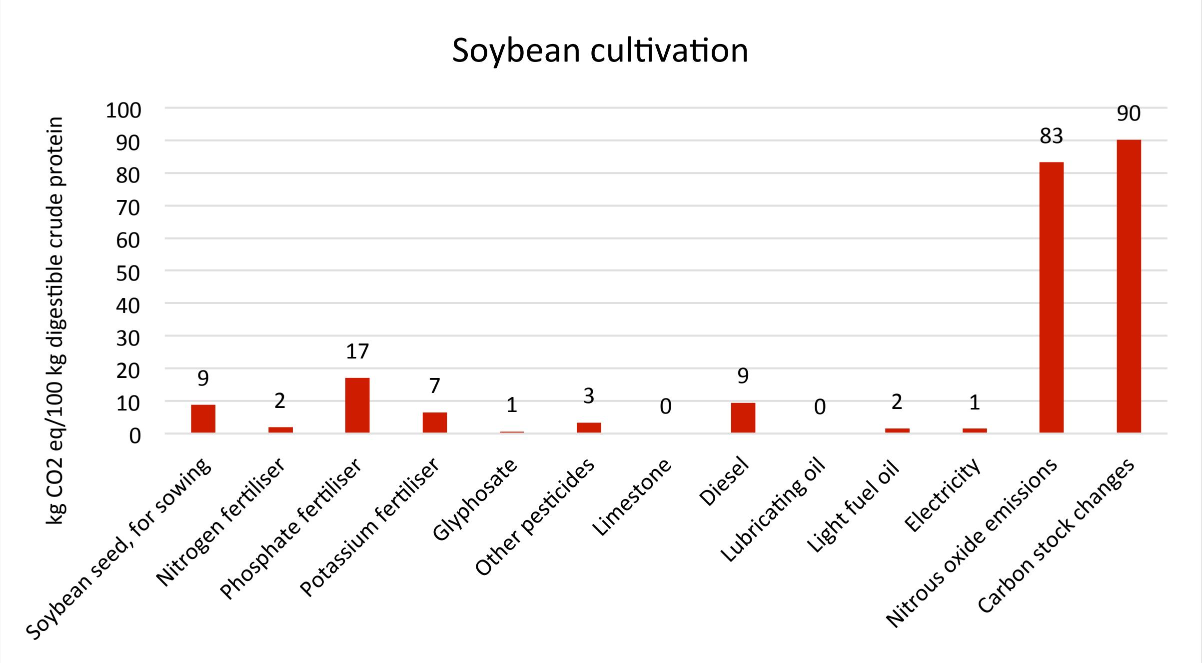

Figure 20: The climate impact from the different processes included in the soybean cultivation.

The carbon stock changes are the largest contributor to greenhouse gas emissions in the cultivation of soybean and stands for 40 % of the total climate impact. This is mainly because the deforestation that takes place in the soybean cultivation, which causes large amounts of carbon dioxide emissions to the air. The second largest contributor to climate change is caused by nitrous oxide emissions of 83 kg CO $_2$eq/100 kg digestible crude protein. The amount of used nitrogen fertiliser is small in this scenario and only contributes to 2 kg CO_2 eq/100 kg digestible crude protein. This differs from the two other protein feed scenarios where nitrogen fertiliser was a large contributor to climate change in the cultivation. The use of phosphate fertiliser is larger compared to nitrogen fertiliser in the soybean cultivation and is the third largest contributor to climate change with 17 kg CO_2 eq/100 kg digestible crude protein.

6. Sensitivity analysis

This chapter analyses different input variables, parameters and system boundaries that are critical for the result. It starts with a sensitivity analysis of the three arable land use options followed by a sensitivity analysis of the three protein feed scenarios. Lastly a summary of the sensitivity analysis is presented.

6.1 Arable land use options

In this subsection input variables, parameters and system boundaries that are critical for the result of the three arable land use options are tested.

6.1.1 Excluding the use phase

In this sensitivity analysis, the system boundaries have been changed. This is to see how the result differs if a cradle-to-gate perspective is chosen instead of a cradle-to-grave perspective. The use phase of the products is not included, but the carbon dioxide absorbed by the plants during the cultivation has been included. Since the functional unit in the life cycle assessment is 1 hectare arable land during one year, the wheat and rapeseed are considered to absorb carbon dioxide from the air and carbon from the plants will be stored in the products. The carbon in the parts of the plants that are left on the field are either going back to the soil or are released back to the air in the form of carbon dioxide during the investigated year. The part of the carbon in the crop residues that are stored in the soil are already accounted for in the emissions caused by carbon stock changes. Since the use phase of the products is not included, the carbon dioxide stored in the products will not be released back to the air. The products produced by the wheat and rapeseed will replace the production of similar products on the market, but they will not replace the use of any products. In the fallow scenario, the grass will absorb carbon dioxide, but during the year the grass will be mowed and the residues will be left on the field to decompose. The assumption is made that the carbon in the grass is released as carbon dioxide, which means that the carbon dioxide absorbed by the grass will be released back to the air during the investigated year. This is since the carbon stocks in the fallow's soil are considered to be in equilibrium.

As seen in table 9, the change of system boundaries results in wheat being the best option from a climate change perspective, followed by rapeseed. Fallow is the worst option from a climate change perspective. About half of the carbon dioxide produced at the production site in the wheat scenario is assumed to be released back to the air and not captured and stored. This result shows that the wheat and rapeseed scenarios have their big advantages during the use phase of their products and avoided products, which are not shown here.

To keep in mind when interpreting the result is that 1 hectare wheat is considered to absorb the same amount of carbon dioxide as 1 hectare rye since no information about carbon dioxide uptake during wheat cultivation could be found. Furthermore, wheat is assumed to have the same percentage crop residues as barley. These assumptions bring uncertainties to the result presented in table 9.

Table 9: Total climate impact from the three arable land use options when excluding the use phase and including CO_2-uptake in the cultivation. The total climate impact calculated in the impact assessment can also be seen in the table to be able to compare the different results.

Arable land use option	CO2-uptake by biomass in the cultivation [kg CO_2/ha and year]	C stored in produced products [kg CO_2/ha and year]	**Impact assessment:** Total climate impact [kg CO_2 eq/ha and year]	**Sensitivity analysis:** Total climate impact [kg CO_2 eq/ha and year]
Wheat	6954[1]	1990[2]	**-5094**	**-1030**
Rapeseed	9763[3]	2929[4]	**-2148**	**-896**
Fallow	2702[5]	0	**105**	**105**

[1] The assumption is made that the CO_2 uptake is the same as for rye. 1 ha of rye is assumed to absorb 6954.3 kg CO_2/year (Ecoinvent centre, 2007).

[2] The wheat seeds that are used as raw material to produce products are assumed to stand for 43 % of the crop mass, the remaining 57 % of the crop mass is left on the field (Mogensen, et al., 2015), with the assumption that wheat has the same percentages as barley. Since all the carbon dioxide produced in Lantmännen Agroetanols's factory is not captured, the assumption is also made that Lantmännen Agroetanol's factory emits the same amount of carbon dioxide as they capture and store.

[3] 1 kg of rapeseed fresh matter is assumed to absorb 2.69 kg CO_2 (Ecoinvent centre, 2007).

[4] The rapeseeds that are used as raw material to produce products are assumed to stand for 30 % of the crop mass, the remaining 70 % of the crop mass is left on the field (Mogensen, et al., 2015).

[5] This is the carbon dioxide absorbed by the grass that is mowed once a year. The carbon dioxide binding of harvested grass is assumed to be 1.65 kg CO_2/kg dry matter (Ecoinvent centre, 2007) and the amount of mowed grass is assumed to be 2702 kg dry matter/ha (Nemecek & Kägi, 2007).

6.1.2 Excluding direct land use change in the cultivation

Since it is difficult to estimate greenhouse gas emissions caused by direct land use change (Flysjö, et al., 2008; Börjesson, et al., 2010; Corré, et al., 2016), table 10 shows the result when direct land use change has been excluded. Furthermore, emissions caused by the transformation from fallow to wheat or rapeseed cultivation should not be considered if REDs way to view direct land use change is followed (Börjesson, et al., 2010). As seen in the table, excluding direct land use change has a large impact on the result, but wheat is still the best arable land use option followed by rapeseed from a climate change perspective.

Table 10: Total climate impact from the three arable land use options when excluding direct land use change.

Arable land use option	**Impact assessment:** Total climate impact [kg CO_2 eq/ha and year]	**Sensitivity analysis:** Total climate impact [kg CO_2 eq/ha and year]
Wheat	-5094	-6463
Rapeseed	-2148	-3698
Fallow	105	105

6.1.3 Excluding glycerine in the arable land use option rapeseed

According to RED, glycerine should not be accounted for in the life cycle of biofuels, hence the impact of not including glycerine in the arable land use option rapeseed has been analysed and the result can be seen in table 11. This sensitivity analysis is only affecting the result for the arable land use option rapeseed in the way that avoided production and usage of natural gas is not included. As seen in the table, the result is not affected in a significant way and wheat is still the best arable land use option followed by rapeseed from a climate change perspective.

Table 11: Total climate impact from the three arable land use options when excluding glycerine in the arable land use option rapeseed.

Arable land use option	**Impact assessment:** Total climate impact [kg CO_2 eq/ha and year]	**Sensitivity analysis:** Total climate impact [kg CO_2 eq/ha and year]
Wheat	-5094	-5094
Rapeseed	-2148	-1886
Fallow	105	105

6.1.4 Alternative production of nitrogen fertiliser

As seen in the impact assessment, the production of nitrogen fertiliser has a large impact on climate change. The production of nitrogen fertiliser was based on best available technology (the year 2011) and was produced by the company Yara in Finland, using modern plants equipped with catalytic cleaning of nitrous oxide (Ahlgren, et al., 2011). Yara is the largest supplier of mineral fertiliser to the Swedish market. However, around year 2010, price advantages led to an increasing amount of imported mineral fertilisers to Sweden produced with older technology (Andersson, et al., 2010). A sensitivity analysis that uses nitrogen fertilisers produced with older technology was therefore executed.

In this sensitivity analysis, data for production of nitrogen fertiliser have been based on average global production and are taken from the database Ecoinvent. This data is presented in the report written by Nemecek and Kägi the year 2007.

From the impact assessment, the production of nitrogen fertiliser has a climate impact of 2.9 kg CO_2 eq/kg nitrogen fertiliser (Ahlgren, et al., 2011). In the sensitivity analysis, this number is much higher with a climate impact of 10.8 kg CO_2 eq/kg nitrogen fertiliser. As seen in table 12, the result differs greatly in the arable land use options wheat and rapeseed when using older technology in the nitrogen fertiliser production. Hence, how the nitrogen fertiliser is produced is of great importance in the life cycles of wheat and rapeseed.

Table 12: Total climate impact from the three arable land use options when using an alternative production of nitrogen fertiliser.

Arable land use option	**Impact assessment:** Total climate impact [kg CO_2 eq/ha and year]	**Sensitivity analysis:** Total climate impact [kg CO_2 eq/ha and year]
Wheat	-5094	-3975
Rapeseed	-2148	-878
Fallow	105	105

6.1.5 Grain cultivation as a land use reference

Since the choice of land use reference affects the amount of emissions from the land (Börjesson, et al., 2010), it is interesting to investigate the climate impacts if an alternative land use reference is used.

The land use reference for the three arable land use options in the report is fallow of the type unfertilized and un-grazed grassland in steady state (see chapter 3.1.1). In this sensitivity analysis, an arable land with grain cultivation was selected as a land use reference. This results in no carbon stock changes in the arable land use options wheat and rapeseed (see table 13). However, in the case of fallow, the arable land is converted from grain cultivation to fallow, which leads to carbon sequestration in the soil. As seen in table 13, the amount of biomass yield is 130 GJ/ha and year for an arable land in fallow and the amount of CO_2 per GJ harvested biomass is 9.5 kg (Börjesson, et al., 2010). This leads to an amount of 1235 kg CO_2 sequestrated in the soil of the fallow.

Table 13: Carbon stock changes for the three arable land use options with grain cultivation as a land use reference (Börjesson, et al., 2010).

Arable land use option	**Biomass yield[1] GJ/ha and year (excluding crop residues)**	**Kg C/ha and year (grain cultivation as a reference)[2]**	**Kg CO_2/GJ harvested biomass (excluding crop residues) (grain cultivation as a reference)**
Wheat	124.4	0	0
Rapeseed	96.9	0	0
Fallow	130	350	9.5

As seen in table 14, wheat is still the best arable land use option followed by rapeseed when changing land use reference. All the three arable land use options get a better result in terms of climate impact compared to the result in the impact assessment.

Table 14: Total climate impact from the three arable land use options when using grain cultivation as a land use reference.

Arable land use option	**Impact assessment:** Total climate impact [kg CO_2 eq/ha and year]	**Sensitivity analysis:** Total climate impact [kg CO_2 eq/ha and year]
Wheat	-5094	-6463
Rapeseed	-2148	-3698
Fallow	105	-1130

6.1.6 Change of yield per hectare and year

The yields per hectare and year for the arable land use options wheat and rapeseed used in this report are mean values for the period 2011-2015 (Jordbruksverket, n.d.). However, the yield can change drastically from year to year and is therefore a critical parameter. For example, the wheat yields have been varied from 5560 kg/hectare and year to 7630 kg/hectare and year during the period 2011-2015 (Jordbruksverket, n.d.). Furthermore, the chosen land use reference for the arable land use options is fallow of the type long-term grassland. The parts of the arable land that usually is selected to lie in fallow often has a lower production capacity (Börjesson, et al., 2010), which can have a negative effect on the yield when converting the fallow into wheat or rapeseed cultivation. Therefore, a sensitivity analysis was made investigating the climate impact from the three arable land use options if the yields per hectare and year for wheat and rapeseed cultivations were decreased with 50 %. See table 15 for the result.

Table 15: Total climate impact from the three arable land use options when decreasing the yield per hectare and year with 50 % for the arable land use options wheat and rapeseed.

Arable land use option	**Impact assessment:** Total climate impact [kg CO_2 eq/ha and year]	**Sensitivity analysis:** Total climate impact [kg CO_2 eq/ha and year]
Wheat	-5094	-899
Rapeseed	-2148	533
Fallow	105	105

As seen in table 15, the arable land use option wheat is still the best land use option from a climate change perspective and has a positive climate impact. However, the land use option rapeseed is worse than fallow in this sensitivity analysis with a climate impact of 533 kg CO_2 eq/ha and year. From this result, it can be concluded that the yield is a very critical parameter changing the result drastically. However, it will still be better to cultivate wheat on an arable land from a climate change perspective even if the wheat yield would decrease with 50 %. The yield from the rapeseed cultivation cannot decrease more than 42 % if it should be better than the arable land use option fallow.

6.1.7 Producing biogas from grass residues

In this sensitivity analysis it was tested how the result would change if the grass residues from the fallow were used to produce biogas which will substitute natural gas.

The grass yield from an organic ley is around 3.45 tonne dry matter/hectare and year (Särnholm, 2011). In this study, the assumption was made that the yield is 50 % of this value, since the fallow in this study only is mowed once a year. Hence, the grass residues from the fallow were assumed to be 1.72 tonne dry matter/hectare and year. Projects making biogas out of ley show that around 300 m^3 methane can be produced per tonne dry matter (Särnholm, 2011). Hence, around 516 m^3 methane can be produced from the grass residues in the fallow scenario. This methane was assumed to substitute the same amount of natural gas.

The production of biogas results in 1.3 g CO_2 eq/MJ biogas emitted to the air (Särnholm, 2011). The emissions caused by the production of natural gas (onshore US production) were retrieved from Ecoinvent and are 9.27 g CO_2 eq/MJ natural gas. When natural gas is burned, 1.88 kg CO_2 is emitted per m^3 natural gas (U.S. Energy Information Administration, 2016).

In table 16, the result can be seen when the grass residues in the fallow scenario were assumed to be digested into biogas. The emissions caused by producing the biogas and the avoided emissions caused by avoided production and usage of natural gas were accounted for in the sensitivity analysis. As seen in table 16, taking advantage of the grass residues drastically improves the result for the fallow scenario. However, the wheat and rapeseed scenarios are still better from a climate change perspective.

Table 16: Total climate impact from the three arable land use options when using the grass residues to produce biogas in the fallow scenario.

Arable land use option	**Impact assessment:** Total climate impact [kg CO_2 eq/ha and year]	**Sensitivity analysis:** Total climate impact [kg CO_2 eq/ha and year]
Wheat	-5094	-5094
Rapeseed	-2148	-2148
Fallow	105	-1013

6.2 Protein feed scenarios

In this subsection input variables, parameters and system boundaries that are critical for the result in the three protein feed scenarios are analysed.

6.2.1 Excluding the use phase of co-products

In table 17, the result can be seen when the system boundaries have been changed in the life cycle of protein feeds to include the carbon dioxide uptake during the cultivation and exclude the use phase of the co-products. The plants are considered to absorb carbon dioxide from the air during cultivation. Some of this carbon will be stored in the produced products and not released back to the air, since the use phase of the products is not included. The products produced by the wheat, rapeseeds and soybeans will replace the production of similar products on the market, but they will not replace the use of any products. The parts of the cultivations that take place on former cropland (3/4 in the wheat and rapeseed cultivation and 96.8 % in the soybean cultivation) are assumed to be in equilibrium and no carbon stock changes will occur in the soil with accordance to table 13 (Börjesson, et al., 2010). This means that the carbon in the crop residues left on former cropland will be entirely released back to the air in the form of CO_2 and no carbon will be sequestrated in the soil. The crop residues can also be released in the form of methane, but the assumption here is that only carbon dioxide will be formed during the decomposition as discussed before. The parts of the cultivations that take place on former grassland and rainforest land will lead to a land use change. When the carbon stock changes per year caused by direct land use change were calculated, the carbon sequestration in the soil due to crop residues was included in this calculation. The carbon in the crop residues that are not stored in the soil is assumed to be emitted as carbon dioxide.

As seen in table 17, the result is very different compared to the result in the impact assessment. This means that the system boundaries chosen in the report have a large influence on the result. With these system boundaries, rapeseed meal will be the best option from a climate change perspective. The differences in the result compared to the impact assessment largely come from excluding the use phase. The advantages of using the co-products bioethanol and carbon dioxide instead of fossil alternatives are not shown in this result. When it comes to the oil co-products in the rapeseed meal and soybean meal scenarios, the use of the rapeseed oil and soybean oil is assumed to contribute to climate change equally much as the use of palm oil does. This means that excluding the use phase does not impact the result for rapeseed meal and soybean meal, which it does in the DDGS scenario.

However, several assumptions were made in this sensitivity analysis, e.g. that wheat absorbs the same amount of carbon dioxide as rye, which is important to keep in mind when the result is interpreted.

Table 17: Total climate impact from the three protein feed scenarios when excluding the use phase and including CO_2-uptake in the cultivation. The total climate impact calculated in the impact assessment can also be seen in the table to be able to compare the different results.

Protein feed scenario	CO2-uptake in the cultivation [kg CO_2/100 kg digestible crude protein]	CO2 stored in produced products [kg CO_2/100 kg digestible crude protein]	**Impact assessment: Total climate impact [kg CO_2 eq/100 kg digestible crude protein]**	**Sensitivity analysis: Total climate impact [kg CO_2 eq/100 kg digestible crude protein]**
DDGS	989[1]	275[2]	**-669**	**-84**
Rapeseed meal	1741[3]	522[4]	**-639**	**-1161**
Soybean meal	439[5]	176[6]	**139**	**-37**

[1] The assumption is made that the CO_2 uptake is the same as for rye. 1 ha of rye is assumed to absorb 6954.3 kg CO_2 (Ecoinvent centre, 2007).

[2] The wheat seeds that are used as raw material to produce products are assumed to stand for 43 % of the crop mass, the remaining 57 % of the crop mass is left on the field (Mogensen, et al., 2015), with the assumption that wheat has the same percentages as barley. Since all the carbon dioxide produced in Lantmännen Agroetanols's factory is not captured, the assumption is also made that Lantmännen Agroetanol's factory emits the same amount of carbon dioxide as they capture and store.

[3] 1 kg of rape fresh matter is assumed to absorb 2.69 kg CO_2 (Ecoinvent centre, 2007).

[4] The rapeseeds that are used as raw material to produce products are assumed to stand for 30 % of the crop mass, the remaining 70 % of the crop mass is left on the field (Mogensen, et al., 2015).

[5] Data is retrieved from Ecoinvent centre, 2007. 1 kg of soybeans is assumed to absorb 1.368 kg CO_2 (Ecoinvent centre, 2007).

[6] The soybeans that are used as raw material to produce products are assumed to stand for 40 % of the crop mass (Cavalett & Ortega, 2010), the remaining 60 % of the crop mass is left on the field.

6.2.2 Alternative system expansion with avoided production of rapeseed oil

As seen in the impact assessment of the protein feeds rapeseed meal and soybean meal (figure 17 and figure 19), the production of palm oil has a high climate impact, which can be avoided when producing the co-products rapeseed oil and soybean oil. Palm oil is the global marginal vegetable oil since 2000, but before that rapeseed oil was considered the marginal oil (Schmidt & Weidema, 2008). Therefore a sensitivity analysis has been executed to see the climate impact from the protein feeds if rapeseed oil still would have been considered to be the marginal oil. In table 18, the result can be seen when rapeseed oil and soybean oil are considered to substitute rapeseed oil instead of palm oil. All other steps in the life cycle of rapeseed meal and soybean meal are the same as before. Nothing has been changed in the DDGS scenario.

Table 18: Total climate impact from the three protein feed scenarios when applying an alternative system expansion with avoided production of rapeseed oil instead of palm oil in the rapeseed meal and soybean meal scenarios.

Protein feed scenario	**Impact assessment:** Total climate impact [kg CO_2 eq/100 kg digestible crude protein]	**Sensitivity analysis:** Total climate impact [kg CO_2 eq/100 kg digestible crude protein]
DDGS	-669	-669
Rapeseed meal	-639	14
Soybean meal	139	287

As seen in table 18, the result changes drastically when changing the avoided product from palm oil to rapeseed oil. The production of rapeseed oil contributes with avoided greenhouse gas emissions of the size -373 kg CO_2 eq/100 kg digestible crude protein for the protein feed scenario rapeseed meal (to be compared with -1027 kg CO_2 eq/100 kg digestible crude protein for production of palm oil in the impact assessment). The production of rapeseed oil contributes with avoided greenhouse gas emissions of -84 kg CO_2 eq/100 kg digestible crude protein for the protein feed scenario soybean meal (to be compared with -232 kg CO_2 eq/100 kg digestible crude protein for production of palm oil in the impact assessment). This results in a lower amount of avoided greenhouse gas emissions and consequently a higher climate impact from both rapeseed meal and soybean meal. DDGS is still the best protein feed scenario from a climate change perspective followed by rapeseed meal.

6.2.3 Alternative system expansion with production of RME and SME

In the life cycle assessment of rapeseed meal and soybean meal, the co-products rapeseed oil and soybean oil substitute palm oil. In this sensitivity analysis, the climate impact is investigated if the co-products are refined further and are inputs in the production of biodiesel and glycerine. This makes the comparison between the protein feeds more equal since DDGS has a biofuel as a co-product.

Figure 21 shows the climate impact from the different processes included in the protein feed scenarios rapeseed meal and soybean meal. The dark blue bars represent the result from the impact assessment and the light blue bars represent the result from the sensitivity analysis. Released emissions include emissions from the cultivation, production and transportation. The avoided emissions from the impact assessment include avoided production of palm oil, since the co-products rapeseed oil and soybean oil substitute the production of palm oil. The avoided emissions from the sensitivity analysis include avoided production and usage of diesel and natural gas, since the co-products RME and glycerol in the rapeseed meal scenario and the co-products SME and glycerol in the soybean meal scenario substitute the production and usage of diesel and natural gas.

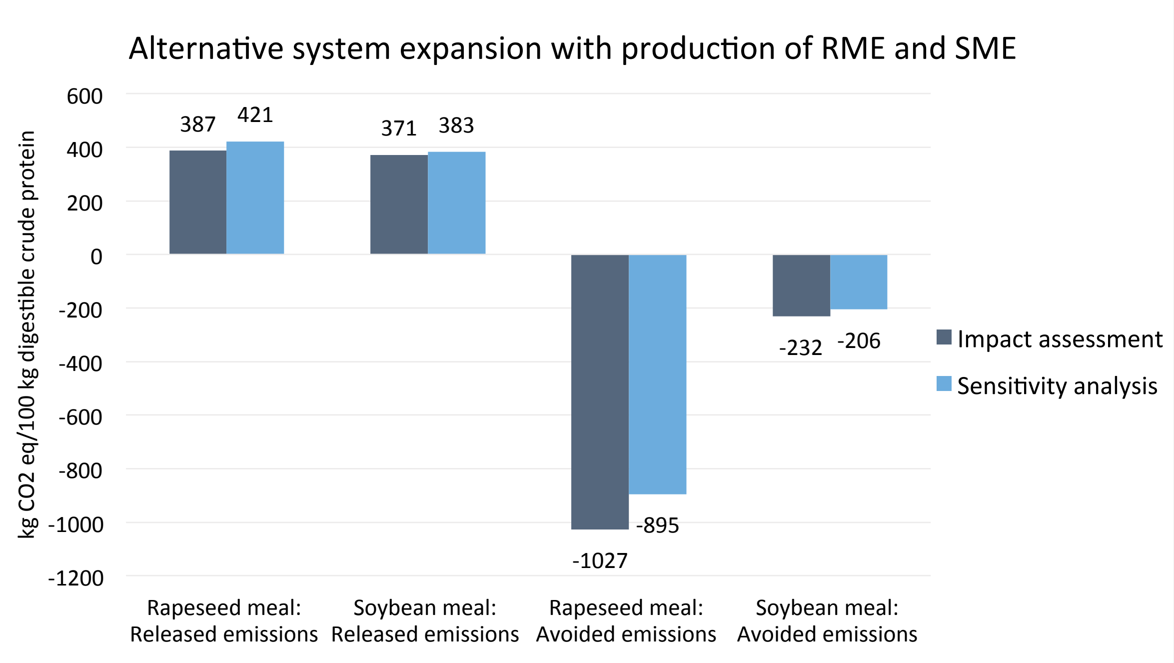

Figure 21: The climate impact when using an alternative system expansion with production of the co-products RME and glycerol in the rapeseed meal scenario and production of the co-products SME and glycerol in the soybean meal scenario.

As seen in figure 21, the climate impacts from the rapeseed meal and soybean meal scenarios are higher when producing RME and glycerine from the rapeseed oil and SME and glycerine from the soybean oil. This is because the production and usage of diesel and natural gas in the system expansion of the two protein feeds have a lower climate impact compared to production of palm oil and less greenhouse gas emissions can be subtracted from the result. The total released greenhouse gas emissions from cultivation, production and transport are also higher in the sensitivity analysis compared to the result in the impact assessment since the biodiesel production leads to more processing and refining steps.

As seen in table 19, DDGS is still the best protein feed from a climate change perspective when changing the alternative products in the system expansion, followed by rapeseed meal.

Table 19: Total climate impact from the three protein feed scenarios when applying an alternative system expansion with production of RME and SME.

Protein feed scenario	**Impact assessment:** Total climate impact [kg CO_2 eq/100 kg digestible crude protein]	**Sensitivity analysis:** Total climate impact [kg CO_2 eq/100 kg digestible crude protein]
DDGS	-669	-669
Rapeseed meal	-639	-474
Soybean meal	139	177

6.2.4 Excluding direct land use change in the cultivation of wheat and rapeseed

Since it is difficult to estimate in which extent Swedish wheat and rapeseed cultivations contribute to direct land use change (Flysjö, et al., 2008), and since the emissions caused by direct land use change used in the DDGS and rapeseed meal scenario most likely is overestimated (Börjesson, et al., 2010), this sensitivity analysis aims to investigate how the result would differ if greenhouse gas emissions caused by direct land use change in the DDGS and rapeseed meal scenarios are assumed to be zero. Emissions caused by direct land use change in the soybean meal scenario are assumed to be the same as before. This is since there has been several studies during the recent year estimating the carbon stock changes caused by deforestation in previous rainforest areas (Flysjö, et al., 2008) and there is data available in Ecoinvent about carbon loss from soil after deforestation in Brazil (Ecoinvent centre, 2007).

As seen in table 20, excluding direct land use change in the DDGS and rapeseed meal scenarios did not change the result in a significant way.

Table 20: Total climate impact from the three protein feed scenarios when excluding direct land use change in the DDGS and rapeseed meal scenarios.

Protein feed scenario	**Impact assessment:** Total climate impact [kg CO_2 eq/100 kg digestible crude protein]	**Sensitivity analysis:** Total climate impact [kg CO_2 eq/100 kg digestible crude protein]
DDGS	-669	-718
Rapeseed meal	-639	-709
Soybean meal	139	139

6.2.5 Alternative production of nitrogen fertiliser

In table 21, the climate impact from DDGS, rapeseed meal and soybean meal can be seen if older technology is used when producing nitrogen fertiliser. In the impact assessment, the production of nitrogen fertiliser has a climate impact of 2.9 kg CO_2 eq/kg nitrogen fertiliser (Ahlgren, et al., 2011). In this analysis, a climate impact of 10.8 kg CO_2 eq/kg nitrogen fertiliser was used (retrieved from Ecoinvent).

As seen in the result, the technology used when producing nitrogen fertiliser affects the total climate impacts from DDGS and rapeseed meal extensively. The total climate impact from soybean meal is not affected by the production of nitrogen fertiliser in a significant way, since soybean cultivation does not require large quantities of nitrogen fertiliser.

Table 21: Total climate impact from the three protein feed scenarios when using an alternative production of nitrogen fertiliser.

Protein feed scenario	**Impact assessment:** Total climate impact [kg CO_2 eq/100 kg digestible crude protein]	**Sensitivity analysis:** Total climate impact [kg CO_2 eq/100 kg digestible crude protein]
DDGS	-669	-510
Rapeseed meal	-639	-413
Soybean meal	139	145

6.2.6 Allocation based on lower heating value

Instead of applying system expansion, an allocation method can be used when calculating the climate impact from the protein feeds. In table 22, the percentages allocated to the feeds and their co-products can be seen. The lower heating value was chosen as allocation method since it is the method that should be used according to RED (European Union, 2015).

Table 22: Allocation percentages used in the sensitivity analysis.

Products	**Allocation based on lower heating value [%]**
DDGS/Bioethanol/Carbon dioxide	39/61/0[1]
Rapeseed meal/Rapeseed oil	36/64[2]
Soybean meal/Soybean oil	63/37[2]

[1] (Börjesson, et al., 2010)

[2] (Corré, et al., 2016)

To allocate based on lower heating value instead of using system expansion affects the result drastically, as seen in table 23. All three protein feeds had a worse result when using allocation. Rapeseed meal is the best option and soybean meal the worst option from a climate change perspective. When using an allocation method, co-products are not assumed to substitute alternative products on the market and no greenhouse gas emissions can be avoided. This is why the results presented in table 23 are worse than the results presented in the impact assessment.

Table 23: Total climate impact from the three protein feed scenarios when using allocation based on lower heating value.

Protein feed scenario	**Impact assessment:** Total climate impact [kg CO_2 eq/100 kg digestible crude protein]	**Sensitivity analysis:** Total climate impact [kg CO_2 eq/100 kg digestible crude protein]
DDGS	-669	150
Rapeseed meal	-639	139
Soybean meal	139	234

6.2.7 Comparing the protein feeds based on AAT20 value

Since there is no obvious way to compare the three protein feeds and since the view of how the feeds should be compared differs in the feed industry, the functional unit has been changed in this sensitivity analysis. Instead of using the functional unit *100 kg digestible crude protein*, the functional unit *100 kg AAT20* has been used in this sensitivity analysis. The AAT20 values for the different feeds can be seen in table 1.

Since approximately twice as much of the different feeds are required to obtain 100 kg AAT20 compared to 100 kg digestible crude protein, the total environmental impact is roughly doubled with the new functional unit (see table 24). The result shows that the choice of functional unit has a large impact on the total climate impact, but it does not affect which of the protein feeds that are the best option from a climate change perspective.

Table 24: Total climate impact from the three protein feed scenarios when comparing the protein feeds based on AAT20 content.

Protein feed scenario	**Impact assessment:** Total climate impact [kg CO_2 eq/100 kg digestible crude protein]	**Sensitivity analysis:** Total climate impact [kg CO_2 eq/100 kg digestible crude protein]
DDGS	-669	-1433
Rapeseed meal	-639	-1375
Soybean meal	139	331

6.3 Summary of sensitivity analysis

This chapter summarizes and analyses the results from the sensitivity analysis.

As seen in table 25, the results from the sensitivity analysis differs greatly in the arable land use options. For example in chapter 6.1.1, the system boundaries of the life cycle assessment were changed to exclude the use phase and include the CO_2-uptake in the cultivation. This way of performing the life cycle assessment, having a cradle-to-gate perspective instead of a cradle-to-grave perspective, makes the result worse in the wheat and rapeseed scenarios. For example, the positive effects of avoiding the usage of alternative products in the system expansion are not included, which have a big impact on the result. The cultivation of wheat and rapeseed, as seen in the impact assessment, contributes to 91 % and 94 % respectively to the released greenhouse gas emissions. The yield per hectare and year is therefore a critical parameter, as seen in chapter 6.1.6, and the result is changed drastically if the yield is decreased. When decreasing the yield per hectare and year with 50 %, the rapeseed scenario became worse than the fallow scenario.

The best result in the sensitivity analysis for the three arable land use options is when using grain cultivation as a land use reference instead of unfertilized grassland (see chapter 6.1.5). The choice of reference is therefore an important parameter, which affects the total climate impact from each arable land use option.

The green cells in table 25 show which arable land use option that is the best from a climate change perspective in the different sensitivity analysis scenarios. The red cells show which land use option that is the worst from a climate change perspective. Table 25 shows that the arable land use option wheat always is to prefer from a climate change perspective. The table also shows that having arable land in fallow is the worst option from a climate change perspective in all scenarios, except if the yield of rapeseed is very low.

Table 25: The result from the impact assessment and from the different scenarios in the sensitivity analysis. The best options from a climate change perspective are marked with a green colour and the worst options are market with a red colour.

Life cycle assessment of 1 hectare arable land during one year			
Sensitivity analysis	**Land use option wheat** [kg CO_2 eq/ha and year]	**Land use option rapeseed** [kg CO_2 eq/ha and year]	**Land use option fallow** [kg CO_2 eq/ha and year]
Impact assessment	-5094	-2148	105
6.1.1 Excluding the use phase	-1030	-896	105
6.1.2 Excluding direct land use change in the cultivation	-6463	-3698	105
6.1.3 Excluding glycerine	-5094	-1886	105
6.1.4 Alternative production of nitrogen fertiliser	-3975	-878	105
6.1.5 Grain cultivation as a land use reference	-6463	-3698	-1130
6.1.6 Change of yield per hectare and year	-899	533	105
6.1.7 Producing biogas from grass residues	-5094	-2148	-1013

As seen in table 26, the climate impact from the protein feeds differs between the different sensitivity analysis scenarios. The best result for DDGS and rapeseed meal comes from the result in chapter 6.2.6 when changing the functional unit from *100 kg digestible crude protein* to the functional unit *100 kg AAT20*. This is because the amount of protein feed required to produce 100 kg AAT20 is almost twice as much compared to the amount when producing 100 kg digestible crude protein. Since the amount of avoided emissions in these cases are higher than the released emissions to the air, the results are improved in the DDGS and rapeseed meal scenarios when the amount of required feed is increased. This is also why the result for soybean meal, when using the functional unit 100 kg AAT20, is the worst in the sensitivity analysis since the amount of avoided emissions is less in this case compared to emitted greenhouse gases to the air.

The worst result from the sensitivity analysis for the protein feeds DDGS and rapeseed meal is when allocating the emissions according to lower heating value (chapter 6.2.6), which is the allocation method RED uses. This is because the result when using allocation only distributes the greenhouse gas emissions between the products and does not consider avoided greenhouse gas emissions when the co-products substitute alternatives on the market.

The best result for soybean meal is when changing the system boundaries to exclude the usage of co-products and to include the CO_2-uptake in the cultivation. The use of rapeseed oil and soybean oil and the use of palm oil are assumed to contribute equally much to climate change and offset each other, which makes the result better for the rapeseed meal and soybean meal scenarios in this sensitivity analysis. This is because the CO_2-uptake in the cultivation is included and because rapeseed meal and soybean meal are not impacted by excluding the use phase of their co-products.

From table 26, one can see that soybean meal is the worst option from a climate change perspective in all different sensitivity analysis scenarios. DDGS and rapeseed meal have similar results in several scenarios, which makes it hard to draw a conclusion which of the feeds that is to prefer from a climate change perspective. However, DDGS has a significantly better result than rapeseed meal in three scenarios, while rapeseed meal is significantly better than DDGS in one scenario.

Table 26: The results from the impact assessment and from the different scenarios in the sensitivity analysis. The best options from a climate change perspective are marked with a green colour and the worst options are marked with a red colour. If two feeds are marked with a green colour it is because they are very close in result.

Life cycle assessment of 100 kg digestible crude protein			
Sensitivity analysis	**DDGS** [kg CO_2 eq/100 kg digestible crude protein]	**Rapeseed meal** [kg CO_2 eq/100 kg digestible crude protein]	**Soybean meal** [kg CO_2 eq/100 kg digestible crude protein]
Impact assessment	-669	-639	139
6.2.1 Excluding the use phase of co-products	-84	-1161	-37
6.2.2 Alternative system expansion with avoided production of rapeseed oil	-669	14	287
6.2.3 Alternative system expansion with production of RME and SME	-669	-474	177
6.2.4 Excluding direct land use change in the cultivation of wheat and rapeseed	-718	-709	139
6.2.5 Alternative production of nitrogen fertiliser	-510	-413	145
6.2.6 Allocation based on lower heating value	150	139	234
6.2.7 Comparing the protein feeds based on AAT20 value	-1433	-1375	331

Whether the scenarios in the sensitivity analysis are reasonable or not is hard to estimate, but some of them might be more reasonable than others. For example, the scenario when using older techniques when producing nitrogen fertiliser is less likely in the current situation. In the report written by Andersson et al. (2010), they mention that the European fertiliser industry estimates that all European production of mineral fertilisers would be done with the best available technology in the mid- 2010s.

7. Discussion

This chapter discusses the result from the life cycle assessments and compares the result with previous studies. Important aspects of the performed life cycle assessments are also discussed.

7.1 Arable land use from a climate change perspective

This study has shown that it is better to convert Swedish arable land in fallow to wheat or rapeseed cultivations from a climate change perspective. This is since the wheat and rapeseed can be processed into products and substitute other products on the market, which will lead to avoided greenhouse gas emissions. Furthermore, the study clearly shows that the best arable land use option from a climate change perspective is to cultivate wheat and produce bioethanol, DDGS and carbon dioxide. A wheat cultivation is to prefer before a rapeseed cultivation from a climate change of view since the yield of wheat is higher than rapeseed, which means that a larger amount of products can be produced in the wheat scenario which will substitute alternative products on the market.

Today, around 5.9 % of the Swedish arable land is used as fallow (Jorbruksverket, n.d.). Hence, transforming this fallow to wheat or rapeseed cultivation would be beneficial for the climate. However, it is often the parts of the arable land with the lowest production capacity that are used as fallow (Börjesson, et al., 2010). The yields of wheat and rapeseed would decrease if arable land with a lower production capacity were used for the cultivations. With lower yields, fewer products can be produced per hectare and fewer products can be avoided on the market. Hence, the wheat and rapeseed scenarios in the life cycle assessment of arable land use options would have a larger environmental impact if the wheat and rapeseed were cultivated on land with lower productivity, which land in fallow often has (Börjesson, et al., 2010). However, as seen in the sensitivity analysis (chapter 6.1.6) the yields can be decreased with over 50 % in the wheat scenario and still be better than fallow from a climate change perspective. If the rapeseed yield is decreased with more than 42 %, the fallow will become a better alternative from a climate change perspective.

As seen in the result, it is the cultivation of wheat and rapeseed that contributes the most to greenhouse gas emissions during the life cycle of 1 ha arable land. This means that measures to reduce greenhouse gas emissions from the production sites and transports will not influence the total climate impact extensively. However, Börjesson et al. (2010) believe that today's bioethanol plants are not fully optimized from an energy perspective. For example a more customized integration between a bioethanol plant and a power plant could provide energy savings through more optimal steam pressures for the respective processes as well as better heat exchange and recovery of waste heat. Improved process integration is also possible in RME-plants, for example improved heat exchange and heat recovery that leads to efficiency gains (Börjesson, et al., 2010). So there is some potential to reduce greenhouse gas emissions at the production site, even if it will not influence the result extensively. Nevertheless, from a climate change perspective, it is better to implement greenhouse gas reducing measures during the cultivation, for example using nitrogen fertiliser produced with best available technology. It is also important to use as little nitrogen fertiliser as possible (but still achieve the desired yields), since the use of nitrogen fertiliser also leads to N_2O emissions from the field. There are several tools to optimize the nitrogen fertiliser use. For example, an N-sensor measuring the amount of light emitted from the plant can be used. The measured amount of light is then translated to the biomass and nitrogen content in the plant. By doing this measurement, the nitrogen fertiliser can be redistributed by taking into account field variations and a higher efficiency of nitrogen can be achieved (Berglund, et al., 2009). The largest climate impact during the cultivation is carbon stock changes due to the transformation from fallow to wheat or rapeseed cultivation, since land that has been storing carbon for a long time now is ploughed which will result in greenhouse gas emissions to the air. Hence, when cultivating crops, it is important to investigate how the land has been used before. As seen in the result, from a climate change perspective it is preferred if the wheat and rapeseed cultivations are taking place on former cropland and not on former fallow. However, transforming the fallow to cropland is still better than keeping the arable land in fallow from a climate change perspective even though it contributes to carbon stock changes in the soil.

In the fallow scenario, the climate impact can be reduced by taking advantage of the mowed grass, e.g. use it as animal feed or digest it into biogas. By doing this, alternative products will be substituted and greenhouse gas emissions can be withdrawn from the result. In chapter 6.1.7, one can see that the climate impact from fallow will be reduced drastically if the grass residues are digested into biogas, avoiding the production and use of natural gas. Hence, from a climate change perspective it is recommended to use the grass residues to produce products.

The production sites have their biggest potential to contribute to a reduced climate change by taking advantage of all raw material entering the production sites, reduce the amount of wheat and rapeseed going to waste and making sure as much products as possible are produced from the wheat and rapeseed inputs. This is since the cultivation of wheat and rapeseed have such a large negative impact and since the products produced from the wheat and rapeseed have such a large positive impact since they can substitute alternative products, which makes it important to take advantage of and produce products from all raw material coming from the cultivations.

7.2 Protein feeds from a climate change perspective

The result from this study clearly shows that DDGS produced at Lantmännen Agroetanol's factory and rapeseed meal produced in Sweden are to prefer before Brazilian soybean meal from a climate change perspective, since soybean meal has a higher climate impact than DDGS and rapeseed meal. This can be explained by the smaller share of co-products produced in the soybean meal scenario compared to the DDGS and rapeseed meal scenarios. Since the production and use of co-products leads to avoided greenhouse gas emissions (since they substitute alternatives), the amount of co-products being produced is an important factor. In the DDGS scenario, around 60 % of the produced products are co-products by weight. In the rapeseed meal scenario and soybean meal scenario, the percentages are around 50 and 20 respectively. Hence, the more co-products produced that can substitute worse alternatives on the market, the better. The sensitivity analysis also shows that the choice of which products that are substituted on the market have a large impact on the result. In chapter 6.2.2 and 6.2.3, rapeseed oil and soybean oil were not assumed to substitute palm oil (but instead other products) which makes the corresponding meals worse from a climate change perspective. The soybean meal also has a large climate impact due to transports, mainly the transportation of the soybean meal from Brazil to Sweden. In the soybean meal scenario it would be better if the meal could be used in Brazil to avoid the transportation to Sweden.

For all three scenarios, the cultivation contributed the most to greenhouse gas emissions. DDGS and rapeseed meal have a higher climate impact during cultivation than soybean meal. This is since soybean cultivations require very small amounts of nitrogen fertiliser, since a large part of the crops nitrogen requirement is achieved by biological fixation (Raucci, et al., 2015). The large amount of nitrogen fertiliser required by the wheat and rapeseed contributes to both greenhouse gas emissions during production of the fertiliser and the N_2O emissions from the field. To use nitrogen fertiliser as efficient as possible and to use fertiliser produced with best available technology are therefore very important measures in the life cycles of DDGS and rapeseed meal. In the soybean meal cultivation, the carbon stock changes contributed to most greenhouse gas emissions. To make the soybean meal more climate friendly, it is important to make sure the soybean cultivation does not take place on previous rainforest land.

Since DDGS and rapeseed meal are very close to each other in the result, and since this study contains assumptions and uncertainties, it is hard to draw a conclusion which of the feeds that is to prefer from a climate perspective. However, the impact assessment shows that DDGS is around 5 % better than rapeseed meal. In the sensitivity analysis, DDGS were significantly better than rapeseed meal in three scenarios while rapeseed meal was significantly better than DDGS in only one scenario. This result indicates that DDGS is a bit better than rapeseed meal from a climate change perspective.

7.3 Comparison with previous studies

Since no other studies have been found comparing different arable land use options, the result in this report cannot be fully compared to other studies. However, Börjesson et al. (2010) concluded when comparing bioethanol and RME that RME is better from a climate perspective when calculating greenhouse gas emissions per hectare. This differs from the result presented in this report. The study by Börjesson et al. (2010) cannot be fully compared with this study, since different functional units have been used. Börjesson et al. (2010) are looking at biofuels as the main product while this study is looking at biofuels as co-products. This means that the biofuels will substitute the use of fossil fuels in this study, while it will not in the study by Börjesson et al. (2010). Since the yield is higher for wheat than for rapeseed per hectare, more fossil fuels can be substituted in the wheat scenario than in the rapeseed scenario.

Like previous studies (Corré, et al., 2016; Lehuger, et al., 2009; Flysjö, et al., 2008), this study also conclude that it is the cultivation of wheat, rapeseed and soybeans that has the largest impact during the life cycle of arable land and protein feeds, partly because of the use of synthetic nitrogen fertiliser.

In contrast to the study by Lehuger et al. (2009) this study shows that rapeseed meal is better than soybean meal from a climate change perspective. However, Lehuger et al. (2009) have not included direct land use change in their study and they used mass-based allocation instead of system expansion. As seen in the sensitivity analysis, to use an allocation method instead of system expansion can drastically change the result. During the cultivation of soybean, emissions caused by direct land use change were the largest contributor to climate change. Hence, to not include these emissions would change the result in a significant way. Furthermore, Lehuger et al. (2009) used another functional unit in their study, which also has a large impact on the result as seen in the sensitivity analysis.

The presented results in this report go along with the result presented by Flysjö et al. (2008). Flysjö et al. (2008) calculated the total climate impact from 1 kg of the three different feeds. When using these climate impacts for the different feeds and multiplying them with the number of kg required for this reports functional unit, DDGS became the best option from a climate change perspective followed by rapeseed meal. Soybean meal became the worst option, which means that the result by Flysjö et al. (2008) is in accordance with this study’s result.

7.4 Impact categories

This study only investigates the impact category climate change, which means that other important environmental aspects, e.g. biodiversity, eutrophication and acidification, are not considered. For example, arable land in fallow has a positive impact on biodiversity (Toivonen, et al., 2015), but the advantages that fallow has on biodiversity is not shown in the results.

Scientific field studies show that species diversity and population density are higher on arable land in fallow compared to arable land with conventionally grown crops, such as cereals. Studies also show that the number of species increases rapidly with increasing area of the fallow and both the number of species and density increases with increasing age of the fallow. Mowing the fallow has also been shown to be beneficial for the number of species as well as the flora-diversity (Jordbruksverket, 2006). Biodiversity losses will therefore occur when arable land that has been in fallow for several years is converted to cropland.

Arable land in fallow has a positive effect on biodiversity no matter if the fallow is part of a crop rotation, and only lies in fallow for a shorter time, or if the fallow is long-term and remains as fallow for several years. Some species prefer if the arable land only has been in fallow for a short time while other species prefer long-term fallows. (Jordbruksverket, 2006)

Fallow probably has its best effect in the southern and central Sweden, especially in areas dominated by grain cultivation, where fallow strongly contributes to a more varied landscape, which is preferable for the biodiversity in the agricultural landscape (Jordbruksverket, 2006). The performed LCA of arable land in this report investigates arable land in Östergötland, thus fallow would probably be the preferred arable land use option from a biodiversity point of view when considering the argumentation above.

Eutrophication is another impact category not investigated in this report. Leaching of nitrogen is affected by a number of given factors such as location in the country and soil types. It is also affected by the choice of crop, soil management and fertilization intensity (Jordbruksverket, 2006). If the nitrogen supply is high and occurs during wrong conditions, it leads to increased risks of leakage and denitrification and the nitrogen utilization decreases (Berglund & Wallman, 2011). Arable land in fallow of the type perennial grassland has a lower risk of nitrogen leakage compared to cultivations of crops where processing takes place every year (Jordbruksverket, 2006). As well as for the biodiversity perspective, the fallow would probably be the preferred arable land use option if eutrophication was considered in the study and if the system boundaries were restricted to only include the cultivation processes. However, if the produced products from the arable land use options wheat and rapeseed as well as the avoided products when using system expansion were considered, the eutrophication potential could lead to a different result, which is unknown.

7.5 Indirect land use change

Emissions caused by indirect land use change were not quantified in this report. As explained before, indirect land use change can have a large influence on the result.

Emissions caused by indirect land use change have been estimated for biofuels made from cereals, sugars and oil crops in the directive EU2015/1513 (European Union, 2015). However, one can argue that Swedish production of biofuels does not contribute to indirect land use change, since there is a significant part of the arable land in fallow, since the intensity in the cultivation can increase and since co-products of biofuels can substitute imported soybean meal and contribute to positive land use change (Börjesson, et al., 2010). Furthermore, the study by Babcock and Iqbal (2014) shows that the agriculture sector mostly responds to increased commodity prices by intensifying the arable land rather than converting grassland and forests to arable land. This is because many countries (e.g. China) do not have the capacity to expand the arable land area and since it often is more expensive to expand the area than intensifying land use (Babcock & Iqbal, 2014). The result from the study by Babcock and Iqbal (2014) contradicts the argument that the increased cultivation of biofuels leads to land being converted into arable land somewhere else in the world, which is the perspective the European Commission has (European Comission, 2016).

Hence, how emissions caused by indirect land use change will influence the result is not clear, but since the impact can be significant it is recommended to further investigate indirect land use change in future studies.

7.6 Substitution ratios

In this study, the produced bioethanol was assumed to substitute the production and use of petrol and the produced RME was assumed to substitute the production and use of diesel. When the substitution ratios were calculated, the assumption was made that 1 kWh bioethanol can substitute 1 kWh petrol and that 1 kWh RME can substitute 1 kWh diesel. To only consider energy content when the substitution ratios were calculated is a simplification. This is since most cars are optimized on running on petrol or diesel, hence the fuel efficiency of the engine is better if petrol or diesel is used as fuels instead of biofuels (Sookrah, 2015).

When this study was performed, the assumption was made that co-products can substitute alternatives on the market. However, if large amounts of a specific co-product are produced, the market of the product might become saturated and the co-product can no longer substitute alternatives. For example, the increased production of biodiesel and the co-product glycerine has saturated the market for high–value applications of glycerine (Corré, et al., 2016). Hence, the co-product glycerine cannot be assumed to substitute synthetic glycerine, instead the assumption was made that the glycerine was digested into biogas in this study (Corré, et al., 2016). If the co-products investigated in this study are produced in such large amounts that there no longer exist a demand for the products on the market, the total climate impacts from all arable land use options and protein feeds investigated in this report would be much bigger.

7.7 Carbon neutrality

In this study, the carbon dioxide emissions from the use phase of bioethanol, biogenic carbon dioxide, RME and glycerine were assumed to be zero. This is since the carbon dioxide released in the use phase was assumed to have been absorbed during the plant growth, which is the approach the European union often uses (Wiloso, et al., 2016). In the world of LCA, it is common to assume carbon neutrality, i.e. that the use of biomass is assumed to have net greenhouse gas emissions equal to zero (Wiloso, et al., 2016). However, this way of thinking is a simplification and is not always correct. The new growing biomass must replace the harvested biomass relatively quickly for this assumption to be valid. Annual crops, e.g. wheat, rapeseed and soybean, are fast growing and the harvest biomass will quickly be replaced by new plants. Hence, the carbon neutrality is more accurate for fast growing plants than for slow growing plants (Wiloso, et al., 2016). When it comes to biofuels, the carbon balance is often disturbed because of the use of fossil fuels during cultivation and conversion processes. Furthermore, biofuels can lead to emissions caused by land use change during cultivation, which disturbs the carbon balance (Wiloso, et al., 2016). When burning biofuels, the combustion might be incomplete, which means that the carbon might be emitted as carbon monoxide instead of carbon dioxide. These aspects discussed above mean that biogenic carbon dioxide emissions not always can be assumed to be equal to zero, even though this simplification has been made in this report.

7.8 Waste streams

In this report, no consideration has been made to co-products or waste streams which occur in very small amounts. For example, the fatty substance lecithin is co-produced with soybean meal but lecithin only stands for around 0.7% of the total mass of outputs. Waste streams that occur on production sites were also considered to be small and were therefore neglected.

7.9 Generalizing the result

This study analyses the climate impact during specific conditions in some cases and general conditions in other. For example, data for production of RME, rapeseed meal and glycerine in the arable land use option rapeseed is general for a large-scale plant that can be located anywhere in Sweden. However, in the production phase of the arable land use option wheat, when producing bioethanol, DDGS and biogenic carbon dioxide, specific data for Lantmännen Agroetanol's processes has been used. Lantmännen Agroetanol offer Sweden's most sustainable biofuel (Lantmännen Agroetanol, 2016) and has a collaboration with the adjacent combined heat and power plant (Lantmännen Agroetanol, n.d.), which leads to a unique situation that is not general for other bioethanol plants. Lantmännen Agroetanol is also quite unique since they capture and sell carbon dioxide from their production, which not all ethanol producers do. This means that the result for the land use option wheat as well as the protein feed DDGS may differ from more general studies that are investigating other production systems.

This study is focusing on Swedish conditions. The life cycle assessment of arable land use options has a time frame of one year. Other studies with different geographic boundaries and time frames, for example investigating a global average, will get a different result. The land use reference is also a factor that plays a major role for the total climate impact, as seen in chapter 6.1.5, and different studies use different land use references. It is therefore hard to generalize the result from this study to other places with different conditions.

7.10 Policy implications

Today, Swedish farmers can get subsidies for land in fallow, since land in fallow can be accounted for as Ecological focus area (see chapter 2.4.1). From a climate point of view, these subsidies should be removed, since it is better to transform the fallow into wheat or rapeseed cultivation. However, the primary aim with the subsidies are to benefit the biodiversity, and not to reduce the climate impact from the agriculture (Jordbruksverket, 2016). Hence, to remove the subsidies might be beneficial from a climate change of view but could be negative for other environmental impact categories.

From a climate change perspective, Swedish policies and instruments should try to make soybean meal a less attractive protein feed compared to DDGS and rapeseed meal. The purchase price is around 2 SEK/kg for DDGS (Johansson, et al., 2012), 2.50 SEK/kg for rapeseed meal and 3.50 SEK/kg for soybean meal (Greppa näringen, 2015). However, the prices vary from year to year (Greppa näringen, 2015). When using these prices, 100 kg digestible crude protein coming from DDGS, rapeseed meal and soybean meal would cost 735 SEK, 729 SEK and 746 SEK respectively. Hence, the price differences are even out when looking per kg digestible crude protein instead of per kg. Since DDGS and rapeseed meal are much better from a climate change perspective compared to soybean meal, Swedish policies and instruments should, if it is possible, aim to make soybean meal less attractive than the other protein feeds. This can be made for example by using taxes or spreading information about the climate impact of soybean meal to farmers.

The sensitivity analysis clearly points out the factors that have a major impact on the climate, e.g. the use of nitrogen fertilisers and carbon stock changes. This knowledge is very important for the development of policies, standards and certifications of the produced products. With this knowledge, the factors that are shown to be critical can be focused on when implementing changes. In this way, more sustainable systems can be developed and less sustainable ones can be avoided.

8. Conclusions

This study has investigated and compared the climate impacts from different arable land use options and protein feeds aimed for cattle. The study shows that the best alternative of the three investigated arable land use options is to cultivate wheat and produce bioethanol, DDGS and carbon dioxide at Lantmännen Agroetanol's factory. It is better to convert Swedish arable land in fallow to wheat or rapeseed cultivations. This is because the wheat and rapeseed can be processed into products and substitute other products on the market, which will lead to avoided greenhouse gas emissions.

Furthermore, this study shows that it is much better to use DDGS produced at Lantmännen Agroetanol or rapeseed meal produced in Sweden as protein feeds for cattle instead of imported soybean meal. DDGS and rapeseed meal have similar results, which makes it hard to draw a conclusion which of the feeds is to prefer from a climate change perspective.

In the life cycles of arable land use options and protein feeds, it is the cultivations that contribute the most to climate change. In the cultivations, a large amount of greenhouse gases are emitted due to carbon stock changes, nitrous oxide emissions and production of fertilisers. The production and use of nitrogen fertiliser have been shown having a large negative impact on the climate. Hence, it is important to use nitrogen fertiliser produced with best available technology and use the nitrogen fertiliser as efficient as possible.

The sensitivity analysis shows that the methodology and the data used in the life cycle assessments have a large impact on the result. The choice of system boundaries, land use reference and marginal oil are some aspects influencing the result greatly. Life cycle assessments are complex with a large number of parameters to consider. This allows for different interpretations, since there is no strict way of performing a life cycle assessment. However, even when changing critical parameters and system boundaries, the arable land use option wheat always is to prefer and soybean meal is always the worst protein feed from a climate change perspective.

This study has only investigated the environmental impact category climate change. Hence, other important environmental aspects were not considered which should be kept in mind when interpreting the results.

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Appendix

In table 1 to 6 data used in the life cycle assessments are presented.

Table 1: Data collection for wheat as an arable land use option.

Cultivation	**Unit**	**Value**	**Reference**
Inputs			
Seeds	[kg/ha and year]	210	(Ahlgren, et al., 2011)
Fertilisers N	[kg/ha and year]	141	(Ahlgren, et al., 2011)
Fertilisers P	[kg/ha and year]	16.80	(Bernesson, 2004)
Fertilisers K	[kg/ha and year]	29.40	(Bernesson, 2004)
Herbicides	[kg/ha and year]	2.10	(Bernesson, 2004)
Fungicides[1]	[l/ha and year]	1.30	(Bernesson, 2004)
Insecticides	[kg/ha and year]	0.15	(Bernesson, 2004)
Diesel	[kg/ha and year]	52.64[2]	(Bernesson, 2004)
Lubrication and hydraulic oil	[kg/ha and year]	0.40[3]	(Bernesson, 2004)
Drying of the seed, light fuel oil (MK1)	[kg/ha and year]	65.61[3]	(Bernesson, 2004)
Drying and cleaning the seed, electricity	[MJ/ha and year]	271.08	(Bernesson, 2004) Electricity, medium voltage, is assumed.
Outputs			
Yield wheat	[kg/ha and year]	6636[4]	(Jordbruksverket, n.d.), based on a mean value for the years 2010-2015
Direct emissions of nitrous oxide (N_2O)	[kg/ha and year]	2.82	(Ahlgren, et al., 2011)
Indirect emissions of nitrous oxide (N_2O)	[kg/ha and year]	0.39	(Ahlgren, et al., 2011)
Production	**Unit**	**Value**	**Reference**
Confidential information			
Transportation	**Unit**	**Value**	**Reference**
Transportation of pesticides, fertilisers, lubrication and hydraulic oil and light fuel oil to farm by lorry	[tkm/ha and year]	51.35	Assumption that the inputs are transported 200 km.
Transportation of inputs to production site[5] is confidential information.			
Substituted product when system expansion is applied	**Unit**	**Value**	**Reference**
Petrol	[kg/ha and year]	1628.18	Energy content in petrol is 9.06 kWh/l (Biogasportalen, 2015) and energy content in bioethanol is 5.90 kWh/l (Gröna bilister, 2012). Assumption is made that 1 kWh

			bioethanol substitute 1 kWh petrol. The density of petrol is assumed to be 755 kg/m^3.
Carbon dioxide (fossil)	[kg/ha and year]	1056.10	Assumption that 1 kg carbon dioxide from Agroetanol substitutes 1 kg of fossil carbon dioxide.
Soybean meal	[kg/ha and year]	1747.86	1 tonne DDGS substitutes 0.615 tonne soybean meal (Lywood, et al., 2009). The soybean meal production occurs in Brazil.
Wheat	[kg/ha and year]	1153.87	1 tonne DDGS substitutes 0.406 tonne wheat (Lywood, et al., 2009). The wheat production occurs in Germany.

[1] One of the two fungicides used in Bernesson et al. 2004 was prohibited in the end of 2014 (Kemikalieinspektionen, 2016). Another similar fungicide that is approved today with the same function and same amount of dosage has therefore been used (ADAMA Sverige, 2016). This fungicide is assumed to have the same climate impact as the one used in Bernesson et al. 2004.

[2] Using a density of 800 kg/m^3 for diesel.

[3] Using a density of 874.6 kg/m^3 for lubricating oil and light fuel oil.

[4] 14 % water content.

[5] The production site is considered to be to be Lantmännen Agroetanol's factory in Norrköping.

Table 2: Data collection for rapeseed as an arable land use option.

Cultivation	**Unit**	**Value**	**Reference**
Inputs			
Seeds	[kg/ha and year]	6	(Ahlgren, et al., 2011)
Fertilisers N	[kg/ha and year]	160[1]	(Ahlgren, et al., 2011)
Fertilisers P	[kg/ha and year]	15	(Bernesson, 2004)
Fertilisers K	[kg/ha and year]	25	(Bernesson, 2004)
Herbicide[2]	[l/ha and year]	2	(Bernesson, 2004)
Insecticide	[l/ha and year]	0.15	(Bernesson, 2004)
Diesel	[kg/ha and year]	52.32[3]	(Bernesson, 2004)
Lubricating and hydraulic oil[4]	[kg/ha and year]	0.40	(Bernesson, 2004)
Drying of the seed, light fuel oil (MK1)	[kg/ha and year]	27.64[3]	(Bernesson, 2004)
Drying and cleaning the seed, electricity	[MJ/ha and year]	108.88	(Bernesson, 2004) Electricity, medium voltage is assumed.
Outputs			
Yield rapeseed	[kg/ha and year]	3390[5]	(Jordbruksverket, n.d.),

			based on a mean value for the years 2010-2015.
Direct emissions of nitrous oxide (N_2O)	[kg/ha and year]	2.70	(Ahlgren, et al., 2011)
Indirect emissions of nitrous oxide (N_2O)	[kg/ha and year]	0.46	(Ahlgren, et al., 2011)
Production	**Unit**	**Value**	**Reference**
Inputs			
Hexane	[kg/ha and year]	1.27	(Bernesson, 2004)
Methanol	[kg/ha and year]	164.70	(Bernesson, 2004)
KOH catalyst	[kg/ha and year]	16.20	(Bernesson, 2004)
Electricity oil extraction	[MJ_{el}/ha and year]	732.90	(Bernesson, 2004) Electricity, high voltage, is assumed
Electricity transesterification	[MJ_{el}/ha and year]	863.28	(Bernesson, 2004) Electricity, high voltage, is assumed.
Outputs			
RME	[kg/ha and year]	1438.35	(Bernesson, 2004)
Rapeseed meal	[kg/ha and year]	1826.76	(Bernesson, 2004)
Glycerine	[kg/ha and year]	157.83	(Bernesson, 2004)
Transportation	**Unit**	**Value**	**Reference**
Transportation of pesticides, fertilisers, lubricating and hydraulic oil and light fuel oil to farm by lorry	[tkm/ha and year]	46	Assumption that the inputs are transported 200 km.
Transportation of rapeseeds from farm to RME factory by lorry	[tkm/ha and year]	169.50	The assumption is made that the transportation distance is 50 km.
Transportation of hexane, methanol and KOH catalyst to RME factory buy lorry	[tkm/ha and year]	36.43	The assumption is made that the transportation distance is 200 km.
Substituted products when system expansion is applied	**Unit**	**Value**	**Reference**
Soybean meal	[kg/ha and year]	1088.75	1 kg of rapeseed meal is assumed to substitute 0.596 kg of soybean meal (Corré, et al., 2016). Brazilian soybean meal is assumed to be substituted.
Wheat	[kg/ha and year]	277.67	1 kg of rapeseed meal is assumed to substitute 0.152 kg of wheat (Corré, et al.,

			2016). The wheat is assumed to be produced in Germany.
Diesel	[kg/ha and year]	1236.32	1 kWh of RME is assumed to substitute 1 kWh of diesel. The energy content in RME is considered to be 33.3 MJ/l) and the energy content in diesel is considered to be 35.1 MJ/l (Malgeryd, n.d.), using a density of 883 kg/m^3 for RME (OKQ8, 2015) and a density of 800 kg/m^3 for diesel.
Natural gas	[m^3/ha and year]	88.38	The assumption is made that glycerine is digested to biogas which substitutes natural gas. From 1 kg glycerine, 0.56 m^3 natural gas can be substituted in theory (Pokój, et al., 2014).

[1] This value is for Västra Götaland since data for Östergötland was not available.

[2] The herbicide used in Bernesson et al. 2004 was prohibited in the beginning of 2011 (Kemikalieinspektionen, n.d.). Another similar herbicide that is approved today with the same function and same amount of dosage has therefore been used (Jordbruksverket, 2016). This herbicide is assumed to have the same climate impact as the one used in Bernesson et al. 2004.

[3] Using a density of 800 kg/m^3 for diesel.

[4] Using a density of 874.6 kg/m^3 for lubricating oil and light fuel oil.

[5] 9 % water content.

Table 3: Data collection for fallow as an arable land use option.

Fallow	**Unit**	**Value**	**Reference**
Inputs			
Diesel	[kg/ha and year]	5.20	(Flysjö, et al., 2008)
Lubricating oil	[kg/ha and year]	0.55	(Flysjö, et al., 2008)

Table 4: Data collection for DDGS as a protein feed.

Cultivation	**Unit**	**Value**	**Reference**
Inputs			
Seeds	[kg/100 kg digestible crude protein]	29.85	(Ahlgren, et al., 2011)
Fertilisers N	[kg/100 kg digestible crude protein]	20.04	(Ahlgren, et al., 2011)
Fertilisers P	[kg/100 kg digestible crude protein]	2.39	(Bernesson, 2004)

Fertilisers K	[kg/100 kg digestible crude protein]	4.18	(Bernesson, 2004)
Herbicides	[kg/100 kg digestible crude protein]	0.30	(Bernesson, 2004)
Fungicides[1]	[l/100 kg digestible crude protein]	0.18	(Bernesson, 2004)
Insecticides	[kg/100 kg digestible crude protein]	0.021	(Bernesson, 2004)
Diesel	[kg/100 kg digestible crude protein]	7.48[2]	(Bernesson, 2004)
Lubricating and hydraulic oil	[kg/100 kg digestible crude protein]	0.057[3]	(Bernesson, 2004)
Drying of the seed, light fuel oil (MK1)	[kg/100 kg digestible crude protein]	9.32[3]	(Bernesson, 2004)
Drying and cleaning the seed, electricity	[MJ/100 kg digestible crude protein]	38.54	(Bernesson, 2004) Electricity, medium voltage, is assumed
Direct emissions of nitrous oxide (N_2O)	[kg/100 kg digestible crude protein]	0.40	(Ahlgren, et al., 2011)
Indirect emissions of nitrous oxide (N_2O)	[kg/100 kg digestible crude protein]	0.055	(Ahlgren, et al., 2011)
Emissions caused by direct land use change (CO_2-eq)	[kg/100 kg digestible crude protein]	48.63	The assumption is made that ¼ of the land is on former grassland and ¾ of the land is on former arable land (which does not cause land use change) (Börjesson et al., 2010)
Outputs			
Yield wheat	[kg/100 kg digestible crude protein]	943.33	(Jordbruksverket, n.d.), based on a mean value for the years 2010-2015.
Production	**Unit**	**Value**	**Reference**
Confidential information			
Transportation	**Unit**	**Value**	**Reference**
Transportation of pesticides, fertilisers, lubrication and hydraulic oil and light fuel oil to farm	[tkm/100 kg digestible crude protein]	7.30	The assumption is made that the inputs are transported 200 km.
Transportation of DDGS from production site[5] to the feed factory by lorry	[tkm/100 kg digestible crude protein]	109.08	The assumption is made that the feed factory is located in Lidköping, the distance is retrieved from google maps and is 270 km.
Transportation of inputs to production site is confidential information.			
Substituted products when system	**Unit**	**Value**	**Reference**

expansion is applied			
Petrol	[kg/100 kg digestible crude protein]	231.45	Energy content in petrol is 9.06 kWh/l (Biogasportalen, 2015) and energy content in bioethanol is 5.90 kWh/l (Gröna bilister, 2012). Assumption is made that 1 kWh bioethanol substitute 1 kWh petrol. The density of petrol is assumed to be 755 kg/m^3.
Carbon dioxide (fossil)	[kg/100 kg digestible crude protein]	150.13	Assumption that 1 kg carbon dioxide from Agroetanol substitutes 1 kg of fossil carbon dioxide.

[1] One of the two fungicides used in Bernesson et al. 2004 was prohibited in the end of 2014 (Kemikalieinspektionen, 2016). Another similar fungicide that is approved today with the same function and same amount of dosage has therefore been used (ADAMA Sverige, 2016). This fungicide is assumed to have the same climate impact as the one used in Bernesson et al. 2004.

[2] Using a density of 800 kg/m^3 for diesel.

[3] Using a density of 874.6 kg/m^3 for lubricating oil and light fuel oil.

[4] 14 % water content.

[5] The production site is considered to be Lantmännen Agroetanol's factory in Norrköping.

Table 5: Data collection for rapeseed meal as a protein feed.

Cultivation	Unit	Value	Reference
Inputs			
Seeds	[kg/100 kg digestible crude protein]	1.07	(Ahlgren, et al., 2011)
Fertilisers N	[kg/100 kg digestible crude protein]	28.53	(Ahlgren, et al., 2011)
Fertilisers P	[kg/100 kg digestible crude protein]	2.67	(Bernesson, 2004)
Fertilisers K	[kg/100 kg digestible crude protein]	4.46	(Bernesson, 2004)
Pesticides herbicide[1]	[l/100 kg digestible crude protein]	0.36	(Bernesson, 2004)
Pesticides insecticide	[l/100 kg digestible crude protein]	0.027	(Bernesson, 2004)
Diesel	[kg/100 kg digestible crude protein]	9.328[2]	(Bernesson, 2004)
Lubricating and hydraulic oil	[kg/100 kg digestible crude protein]	0.071[3]	(Bernesson, 2004)
Drying of the seed, light fuel oil (MK1)	[kg/100 kg digestible crude protein]	4.92[3]	(Bernesson, 2004)
Drying and cleaning the seed, electricity	[MJ/100 kg digestible crude protein]	19.42	(Bernesson, 2004)

Direct emissions of nitrous oxide (N_2O)	[kg/100 kg digestible crude protein]	0.48	(Ahlgren, et al., 2011)
Indirect emissions of nitrous oxide (N_2O)	[kg/100 kg digestible crude protein]	0.082	(Ahlgren, et al., 2011)
Emissions caused by direct land use change (CO_2-eq)	[kg/100 kg digestible crude protein]	69.12	The assumption is made that ¼ of the land is on former grassland and ¾ of the land is on former arable land (which does not cause land use change) (Börjesson, et al., 2010). See table 8.
Outputs			
Yield rapeseed	[kg/100 kg digestible crude protein]	604.51	(Jordbruksverket, n.d.)
Production	**Unit**	**Value**	**Reference**
Inputs			
Hexane	[kg/100 kg digestible crude protein]	0.23	(Bernesson, 2004)
Electricity oil extraction	[MJ_{el}/100 kg digestible crude protein]	130.69	(Bernesson, 2004)
Outputs			
Rapeseed meal	[kg/100 kg digestible crude protein]	325.75	(Bernesson, 2004)
Rapeseed meal dry matter	[kg/100 kg digestible crude protein]	291.55	Assuming the water content of rapeseed meal is 10.5 % (Bernesson, 2004)
Rapeseed oil	[kg/100 kg digestible crude protein]	266.52	(Bernesson, 2004)
Transportation	**Unit**	**Value**	**Reference**
Transportation of pesticides, fertiliser, lubrication and hydraulic oil and light fuel oil to farm	[tkm/100 kg digestible crude protein]	8.21	The assumption is made that the inputs are transported 200 km.
Transportation of rapeseeds from farm to rapeseed meal factory	[tkm/100 kg digestible crude protein]	30.23	The assumption is made that the rapeseed is transported 50 km.
Transportation of hexane to production site	[tkm/100 kg digestible crude protein]	0.046	The assumption is made that the hexane is transported 200 km.
Transportation of meal from production site to the feed factory	[tkm/100 kg digestible crude protein]	87.95	The rapeseed meal factory is assumed to be located in the same area as Lantmännen Agroetanol. The feed factory is assumed to be located in Lidköping. The distance is

			retrieved from google maps and is 270 km.
Substituted products when system expansion is applied	**Unit**	**Value**	**Reference**
Palm oil	[kg/100 kg digestible crude protein]	266.52	Assumption that 1 kg rapeseed oil substitutes 1 kg palm oil.

[1] The herbicide used in Bernesson et al. 2004 was prohibited in the beginning of 2014 (Kemikalieinspektionen, n.d.). Another similar herbicide that is approved today with the same function and same amount of dosage has therefore been used (Jordbruksverket, 2016). This herbicide is assumed to have the same climate impact as the one used in Bernesson et al. 2004.

[2] Using a density of 800 kg/m^3 for diesel.

[3] Using a density of 874.6 kg/m^3 for lubricating oil and light fuel oil.

Table 6: Data collection for soybean meal as a protein feed.

Cultivation	Unit	Value	Reference
Inputs			
Seeds	[kg/100 kg digestible crude protein]	4.91	(Raucci, et al., 2015)
Fertiliser N	[kg/100 kg digestible crude protein]	0.67	(Raucci, et al., 2015)
Fertiliser P	[kg/100 kg digestible crude protein]	8.15	(Raucci, et al., 2015)
Fertiliser K	[kg/100 kg digestible crude protein]	8.75	(Raucci, et al., 2015)
Herbicides	[kg/100 kg digestible crude protein]	0.46	(Raucci, et al., 2015)
Fungicides	[kg/100 kg digestible crude protein]	0.12	(Raucci, et al., 2015)
Insecticides	[kg/100 kg digestible crude protein]	0.18	(Raucci, et al., 2015)
Limestone	[kg/100 kg digestible crude protein]	42.11	(Raucci, et al., 2015)
Diesel	[kg/100 kg digestible crude protein]	2.48[1]	(Raucci, et al., 2015)
Lubricating and hydraulic oil	[kg/100 kg of digestible crude protein]	0.019[2]	The use of lubrication and hydraulic oil is assumed to be 0.7 % of the diesel use in the cultivation (Bernesson, 2004).
Electricity	[kWh/100 kg of digestible crude protein]	2.30	(Raucci, et al., 2015)
Direct and indirect emissions of nitrous oxide (N_2O)	[kg/100 kg digestible crude protein]	0.314	(Ecoinvent centre, 2007)
Emissions caused by direct land use change	[kg/100 kg digestible crude protein]	90.09	Because of deforestation.

(CO_2-eq)			(Ecoinvent centre, 2007)
Electricity for drying of the soybeans	[MJ/100 kg digestible crude protein]	10.69	(Flysjö, et al., 2008)
Light fuel oil for drying of the soybeans	[MJ/100 kg digestible crude protein]	21.37[2]	(Flysjö, et al., 2008)
Outputs			
Soybeans (not dried)	[kg/100 kg digestible crude protein]	320.62	(Raucci, et al., 2015)
Production	**Unit**	**Value**	**Reference**
Inputs			
Soybeans	[kg/100 kg digestible crude protein]	314.20	Soybeans are dried from 15 % moister content (Corré, et al., 2016) to 13 % moister content (Flysjö, et al., 2008).
Hexane	[kg/100 kg digestible crude protein]	0.13	(Flysjö, et al., 2008)
Electricity	[MJ/100 kg digestible crude protein]	52.16	(Flysjö, et al., 2008), Electricity, high voltage, is assumed
Heat (steam from biomass)	[MJ/100 kg digestible crude protein]	305.72	(Flysjö, et al., 2008)
Outputs			
Soybean meal dry matter	[kg/100 kg digestible crude protein]	213.22	The soybean meal is 78 % of soybeans dry matter according to Corré et al. (2016). Moister content in soybeans is 13 %.
Soybean oil	[kg/100 kg digestible crude protein]	60.14	The soybean oil is 22 % of soybeans dry matter according to Corré et al. (2016). Moister content in soybeans is 13 %.
Lecithin	[kg/100 kg digestible crude protein]	1.98	(Cavalett & Ortega, 2010)
Transportation	**Unit**	**Value**	**Reference**
Transportation of pesticides, fertiliser, lubricating and hydraulic oil, light fuel oil and limestone to farm by lorry	[tkm/100 kg digestible crude protein]	12.19	The assumption is made that the inputs are transported 200 km.
Transportation of soybeans from farm to production site by lorry	[tkm/100 kg digestible crude protein]	15.71	The assumption is made that the soybeans are transported 50 km.

Transportation of hexane to production site	[tkm/100 kg digestible crude protein]	0.026	The assumption is made that the hexane is transported 200 km.
Production site – Santos by lorry	[tkm/100 kg of digestible crude protein]	383.80	The distance is 1800 km (Cederberg & Flysjö, 2004)
Santos – Rotterdam by boat	[tkm/100 kg of digestible crude protein]	2149.26	The distance is 10080 km (Cederberg & Flysjö, 2004)
Rotterdam – feed factory (Lidköping) by lorry	[km]	267.38	The distance is assumed to be 1254 km according to google maps.
Substituted products when system expansion is applied	**Unit**	**Value**	**Reference**
Palm oil	[kg/100 kg digestible crude protein]	60.14	Assumption that 1 kg of soybean oil substitutes 1 kg of palm oil (Samuel-Fitwi, et al., 2013).

[1] Using a density of 800 kg/m^3 for diesel.

[2] Using a density of 874.6 kg/m^3 for lubricating oil and light fuel oil.