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Case Study

LCA of Soybean Meal

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Abstract

Background, Aim and Scope. Soybean meal is an important protein input to the European livestock production, with Argentina being an important supplier. The area cultivated with soybeans is still increasing globally, and so are the number of LCAs where the production of soybean meal forms part of the product chain. In recent years there has been increasing focus on how soybean production affects the environment. The purpose of the study was to estimate the environmental consequences of soybean meal consumption using a consequential LCA approach. The functional unit is 'one kg of soybean meal produced in Argentina and delivered to Rotterdam Harbor'.

Materials and Methods. Soybean meal has the co-product soybean oil. In this study, the consequential LCA method was applied, and co-product allocation was thereby avoided through system expansion. In this context, system expansion implies that the inputs and outputs are entirely ascribed to soybean meal, and the product system is subsequently expanded to include the avoided production of palm oil. Presently, the marginal vegetable oil on the world market is palm oil but, to be prepared for fluctuations in market demands, an alternative product system with rapeseed oil as the marginal vegetable oil has been established. EDIP97 (updated version 2.3) was used for LCIA and the following impact categories were included: Global warming, eutrophication, acidification, ozone depletion and photochemical smog.

Results. Two soybean loops were established to demonstrate how an increased demand for soybean meal affects the palm oil and rapeseed oil production, respectively. The characterized results from LCA on soybean meal (with palm oil as marginal oil) were 721 g CO_2 eq. for global warming potential, 0.3 mg CFC11 eq. for ozone depletion potential, 3.1 g SO_2 eq. for acidification potential, –2 g NO_3 eq. for eutrophication potential and 0.4 g ethene eq. for photochemical smog potential per kg soybean meal. The average area per kg soybean meal consumed was 3.6 m^2year. Attributional results, calculated by economic and mass allocation, are also presented. Normalised results show that the most dominating impact categories were: global warming, eutrophication and acidification. The 'hot spot' in relation to global warming, was 'soybean cultivation', dominated by N_2O emissions from degradation of crop residues (e.g., straw) and during biological nitrogen fixation. In relation to eutrophication and acidification, the transport of soybeans by truck is important, and sensitivity analyses showed that the acidification potential is very sensitive to the increased transport distance by truck.

Discussion. The potential environmental impacts (except photochemical smog) were lower when using rapeseed oil as the marginal vegetable oil, because the avoided production of rapeseed contributes more negatively compared with the avoided production of palm oil. Identification of the marginal vegetable oil (palm oil or rapeseed oil) turned out to be important for the result, and this shows how crucial it is in consequential LCA to identify the right marginal product system (e.g., marginal vegetable oil).

Conclusions. Consequential LCAs were successfully performed on soybean meal and LCA data on soybean meal are now available for consequential (or attributional) LCAs on livestock products. The study clearly shows that consequential LCAs are quite easy to handle, even though it has been necessary to include production of palm oil, rapeseed and spring barley, as these production systems are affected by the soybean oil co-product.

Recommendations and Perspectives. We would appreciate it if the International Journal of Life Cycle Assessment had articles on the developments on, for example, marginal protein, marginal vegetable oil, marginal electricity (related to relevant markets), marginal heat, marginal cereals and, likewise, on metals and other basic commodities. This will not only facilitate the work with consequential LCAs, but will also increase the quality of LCAs.

Keywords: Agriculture; consequential LCA; soybean meal; system expansion

Introduction

Soybean meal is an important input to livestock and fish production globally and comes from the cake of soybeans after crushing the beans and extracting the soybean oil. In 2004, the consumption of soybean meal in the EU25 was 34 million tonnes (Oil World 2005). The amount of soybeans and cake of soybeans traded globally increased from 48 million tonnes in 1985 to 106 million tonnes in 2004. Soybeans exported from USA were the fourth most important agricultural commodity in dollar value traded globally in 2004, with soybeans from Brazil ranking as no. 7 and cake of soybeans from Argentina as no. 10 (FAOSTAT 2006a).

The 6,979 million US dollar worth of soybeans *imported* to China in 2004 topped the FAO's list of agricultural commodities traded globally and four European countries (Spain, Italy, the Netherlands and Denmark) with large pig productions imported 46% of the soybean meal from Argentina, Spain, Italy, the Netherlands and Denmark. The global area cultivated with soybeans has expanded from 38 million hectares in 1975 to 91 million hectares in 2005 (FAOSTAT 2006b), with the major land increases taking place in Argentina and Brazil. In Argentina, the area with soybean increased from 6 million hectares in 1996 to 14.2 million in 2004, of which the transgenic varieties accounted for more than 90%, under no-tillage systems (Pengue 2006), where ploughing is not used. The environmental impacts from soybean production have been addressed in several reports, e.g., Dros (2004), Pengue (2005), Benbrook (2005) and Casson (2003). The combination of no-tillage systems and transgenic Roundup Ready (RR) soybeans has made large-scale soybean cultivation a powerful competitor to other types of land use and has caused both a concentration of land tenure, the conversion of traditional farming systems with pastures and hay fields, cereals and other crops, and deforestation. More than 40% of the increased soybean area in Argentina has come from virgin lands, including forests and savannahs, thus causing losses in biodiversity (Pengue 2006). Likewise, in Brazil, the possibility to obtain cheap credit for a fast-return export crop production has allowed soybean producers to expand in a complex interaction with the increasing cattle production leading to deforestation (Dros 2004). The use of glyphosate in Argentina has increased to more than 45 million kg in 2004, up from 20 million in 2000 and less than 1 million in the beginning of the 90s (Pengue 2006). While glyphosate as an active ingredient was previously considered harmless to humans and warm-blooded animals (Anonymous 1996), new research indicates that some of the formulations used with this type of pesticide may cause health problems for farm workers and negative environmental effects on biodiversity and aquatic life, as discussed by Ho & Cummings (2005) and Ho & Ching (2003).

Soybean production is often part of the system when performing Life Cycle Assessments of different agricultural products. Analyzing the environmental consequences of changes in food consumption (Gerbens-Leenes & Nonhebel 2002) or livestock production systems often involves changes in the demand for soybean meal (Cederberg & Mattson 2000, Eriksson et al. 2004, de Boer 2003, Cederberg & Flysjö 2004, Basset-Mens & van der Werf 2005, van der Werf et al. 2005, Dalgaard & Halberg 2005). This is particularly the case when the LCA is based on the consequential approach where the analysts are looking for the marginal product being used or saved when expanding the delimitations of the investigated system in order to avoid allocation (Nielsen et al. 2004).

Mass or economic allocation has been used to distribute the environmental burden between the soybean meal and the soybean oil in most of the LCAs on livestock products where soybean meal is included. In this article, however, we are seeking to avoid an allocation. Instead, we aim at following the principles of system expansion according to ISO 14044 (2006). This means that the system boundaries of soybean production must be enlarged in order to include the production system of the vegetable oil substituted by the soybean oil.

1 Goal and Scope Definition

More specifically, the objectives are

- to establish a reliable representation of soybean meal production for use in LCAs of European livestock production chains
- to identify the environmental hot spots in the product chain of soybean meal

In order to ensure the usability of the LCA presented for researchers preferring to use allocation to handle co-products, sufficient numbers and figures will be displayed to allow for this.

The purpose of this study is to estimate the environmental consequences of soybean meal consumption, and to provide data on the LCA of soybean meal. This is partly because there is a lack of these data for LCAs on livestock products, and because soy protein could potentially have a significant environmental impact as a consequence of the increasing production of meat products worldwide.

Soybean meal is co-produced with soy oil, and a demand for soybean meal obviously necessitates a production of soybean oil. The production of oil might affect other agricultural product systems, but to what extent, and how can it be quantified? In this article; these issues will be analyzed further.

The functional unit is 'one kg of soybean meal produced in Argentina and delivered to Rotterdam Harbor in the Netherlands'. The Netherlands is the country within Europe that imports the largest amount of oil meals (Oil World 2005).

The impact categories considered include: global warming, ozone depletion, acidification, eutrophication and photochemical smog. Impact categories concerning toxic aspects are not included due to methodological limitations. Land use, impacts on biodiversity and other impacts are not integrated in the present LCA, due to methodological limitations (as discussed by Milà i Canals et al. (2007)), although results on land use (unit: m^2year) are presented.

2 Methods

2.1 LCA approach

Identification and delimitation of the analyzed product system is increasingly seen as being important for the outcome and quality of the LCA (Weidema 2003, Ekvall & Weidema 2004, Schmidt 2004). Two fundamentally different approaches can be used in this respect: the new (consequential) approach and the traditional (attributional) approach. Most existing LCAs are based on the attributional approach, but the tendency is for studies to increasingly use the new (consequential) approach (Thrane 2006, Schmidt & Weidema 2007, Ekvall & Andræ 2006, Cederberg & Stadig 2003, Kim & Dale 2002, Dalgaard & Halberg 2005, Weidema 1999). In the present study, it has been chosen to apply the consequential approach, which has two main characteristics:

- It seeks to model the technology (or processes) actually affected by a change in demand (the marginal technology).
- Co-product allocation is 'systematically' avoided through system expansion.

These characteristics are opposite to attributional LCA, where average technologies (not marginal) are used, and where co-product allocation is often handled by mass or value allocation (Weidema 2003).

In consequential LCA we basically use a 'market oriented' approach to identify the affected technology (or process), also called marginal. We continuously ask: what is affected by a change in demand? For example, when impacts related to electricity input for a certain unit process are considered – the question is: what are the environmental consequences related to a change (typically small) in the demand of electricity in this market? Among the Nordic countries, this is mainly coal or gas-based technologies according to Weidema (2003). Hence, in this case the marginal technology is gas or coal (or a mix). In traditional (attributional) LCA, electricity consumption is often modeled as an average of all electricity sources within the region, but this would then include electricity from, for example, windmills, which produce as a function of the wind speed – not the demand. The same applies to other renewable energy sources such as hydropower, which should be left out of the product system, according to the consequential LCA. Thus, in consequential LCA, only affected technologies (or processes) should be included, and socio-economical considerations should be applied to identify these (Weidema 2003).

In this article, the term 'marginal technology (or process)' refers to the technology or process, which is actually affected by a change in demand. The changes that are considered in this article are small, which means that they do not affect the determining parameters for the overall market situation, i.e., the direction of the trend in market volume and the constraints on and production costs of the products and technologies involved (Weidema et al. 2004).

Concerning the handling of co-product allocation, attributional LCAs have often based allocation on the relative value of the products and co-products, be it mass or other parameters. In consequential LCA, however, this is entirely avoided through system expansion (if technical subdivision of the processes is impossible). System expansion means the inputs and outputs are entirely ascribed to the product of interest (often the main product). Subsequently, the product system is expanded to include the products avoided, i.e., products that are avoided due to the co-products. Accordingly, when performing consequential LCA on soybean meal, the inputs and outputs relate entirely to the soybean meal, but the avoided production of vegetable oil, caused by the co-product soybean oil, is included in the calculations. Because vegetable oil (e.g., palm oil, rapeseed oil) is nearly always co-produced with protein (e.g., palm kernel meal, rapeseed meal), this will introduce another need for system expansion, which again could include a co-production of protein, etc. This never-ending story is described by Weidema (1999) as the so-called soybean-rapeseed-loop. While Weidema at the time assumed rapeseed to be the marginal oil replaced by soybean oil, in this article we will demonstrate and compare the use of this loop principle for LCAs of soybean meal using both palm oil and rapeseed oil as the marginal products to be replaced. Palm oil is chosen because Schmidt & Weidema (2007) presently identified this as the marginal oil. For further details regarding the consequential LCA methodology, see Ekvall & Weidema (2004) and Weidema (2003).

2.2 Method applied for LCIA

Among the different methods available for Life Cycle Impact Assessment (LCIA), we have used the EDIP97 (Wenzel et al. 1997, updated version 2.3). The method has been implemented in the PC-tool SimaPro 6.0 (Pré 2004). The EDIP-methodology has recently been launched in a revised EDIP2003 version (Hauschild & Potting 2005) but, as this new revised version has not yet been implemented in any PC-tool, it was decided to stick to the well-documented and familiar EDIP97 methodology.

EDIP97 also includes human toxicity, eco-toxicity, waste and resource use, but we have chosen not to include these impact categories due to methodological limitations regarding pesticide emissions from agriculture.

2.3 System delimitation

The soybean plant (*Glycine max.)* is a legume, which grows to a height of 120–180 cm (Tengnäs & Nilsson 2003). Soybeans contain approximately 35% protein and 18% oil (Møller et al. 2003, an update from Møller et al. 2000) and are the highest-yielding source of vegetable protein globally (Dros 2004, p. 7). The protein is primarily used for livestock feed after crushing and extraction of the oil, which is mainly used for consumption.

Argentina has become the largest global exporter of soybean cake and is projected to have the highest increase in export until 2014 (FAPRI 2006). Therefore, in this study, soybean meal produced in Argentina is used as the marginal soybean meal. An increase in the demand for soybean meal implies an increase in the production of soybean oil, which would then compete with other vegetable oils on the world market. Following the methodology of consequential LCA, this 'avoided production' of vegetable oil must be included in the LCA of soybean meal (protein).

As mentioned earlier, rapeseed oil was until recently regarded as the marginal oil that was affected when the demand for general vegetable oils changed (Weidema 2003). Recent studies, however, show that palm oil has increased its competitiveness compared to other major oils on the market - rape, soy and sunflower oils (Schmidt & Weidema 2007).

The fatty acid composition of rapeseed, soy, sun and palm oil is not the same. Thus, they are not completely substitutable. However, according to Schmidt & Weidema (2007), the oils are substitutable within the most important applications: frying oil/fat, margarine, shortening and possibly salad oils. One of the co-products from palm oil milling is palm kernels, which are processed into palm kernel oil and palm kernel meal. The applications of palm kernel oil, which is a lauric oil, differ from the most important applications mentioned above. The only other lauric oil on the market is coconut oil. The use of this oil is constrained due to a 5–7 year maturing period before harvesting can begin making it less responsive to fluctuations in market demand (Schmidt &

Weidema 2007). Therefore, changes in the production of palm kernel oil are not considered likely to affect the production of coconut oil. Schmidt & Weidema (2007) argue that palm oil and the co-product palm kernel oil jointly can be considered as the marginal oil on the global market. In the following, 'palm oil' designates a mix of oil from mesocarp of fresh fruit bunches and oil from palm kernels.

As market situations often change from one year to another, we have decided to make two LCAs. One with palm oil as the marginal oil (here called: Soybean meal (PO)), and one with rapeseed oil as the marginal oil (here called: Soybean meal (RSO)).

Avoided production of palm oil and rapeseed oil implies avoided production of palm kernel meal or rapeseed meal, respectively. This avoided production of meal will be compensated for by the production of marginal meal. Thus, a demand for soybean meal does not only result in production of the demanded amount, but also in the production of an extra amount of soybean meal to compensate for the 'missing meal' (palm kernel meal or rapeseed meal) that are missing because of the avoided oil production. The extra amount of soybean meal produced will again cause an avoided production of meal, and this loop will continue. The mass of extra soybean meal produced is very dependent on the protein and energy contents of the ingredients involved, and is therefore not the same in the LCA of soybean meal (PO) as in the LCA of soybean meal (RSO). To demonstrate this difference and to facilitate the LCAs of soybean meal, two loops (based on the concept developed by Weidema (1999)) will be established for the two LCAs of soybean meal: A soybean/palm loop for the soybean meal (PO), and a soybean/rapeseed loop for the soybean meal (RSO). Data on dry matter, oil, protein and energy contents of relevant items in the loops are based on data from **Table 1**. The yields of soybean meal and soybean oil from soybeans and the yields of rapeseed cake and rapeseed oil from rapeseeds are calculated on the basis of these data, taking into consideration that some of the oil from soybeans and rapeseeds form part of soybean meal and rapeseed cake, respectively. The yields of oil and kernels from fresh fruit bunches, and the yields of palm kernel oil and meal from the kernels are based on Malaysian data for 2004 given in MPOB (2005). In the calculations, soybean oil substitutes marginal oil at the ratio of 1 to 1 (by weight). The amount of marginal meal substituted by palm kernel meal or rapeseed cake is estimated according to the protein and energy contents (energy in feed is calculated in Scandinavian Feed Units (SFU), where 1 SFU approximately equals the amount of energy in 1 kg barley). For example, one kg of rapeseed cake (= 0.31 kg protein and 1.1 SFU) substitutes 0.95 kg marginal meal, which is a mix of 0.66 kg soybean meal (= 0.28 kg protein and 0.8 SFU) and 0.29 kg spring barley (=0.03 kg protein and 0.3 SFU). Thus, the amount of protein and energy in the rapeseed cake is equal to the total amount of protein and energy in soybean meal and spring barley. In the calculations, spring barley is assumed to be the marginal feed grain, as proposed by Weidema (2003).

3 Inventory

In the following section, we present the data used to establish the crop production and crop processing in the LCAs. As explained, due to the need for systems expansion, the soybean product system includes the cultivation and processing of oil palms, rapeseed and spring barley. For ease of comparison, the crop data are all presented in **Table 2**, while explanations and references are given in separate sections.

3.1 Agricultural production

Soybeans. Yields of 2,630 kg ha^{-1}, which was the average yield in Argentina 2001/2002, were used, cf. Table 2 (SAGPyA, 2006). At this time approx. 25% of the soybean area was cultivated in a system with two crops (typically wheat and soybeans) per year (Begenisic 2003), giving an average land use of 0.88 ha year (=0.75 + (0.25/2)) for the 2,630 kg beans. Fertilizer, diesel and pesticide use was taken from Begenisic (2003), according to whom approximately 70% of the soybeans at that time were cultivated in a no tillage cropping system (diesel consumption: 35 liters ha^{-1}) using transgenic varieties (RR) and 30% were cultivated in a conventional cropping system (diesel consumption: 60 liters ha^{-1}). The nutrient balance approach (Halberg et al. 1995; Kristensen et al. 2005) was used for estimating nitrate and phosphate leaching. No N-fertilizer was given, leaving the beans to depend on biological nitrogen fixation (corresponding to 132 kg N ha^{-1}, estimated from Peoples et al. (1995)), and available soil N for its N supply. N removed from the field was calculated on the basis of yields (see Table 2) and protein content (see Table 1) of the soybeans, and equaled 152 kg N ha^{-1}. Because more N was removed than applied to the soybean fields, it was assumed that nitrate leaching related to soybeans was insignificant (see Table 2). This is in accordance with Austin et al. (2006), who also concluded that less N is applied than removed from the soybean fields in the Pampas in Argentina. Phosphate adsorbs to soil particles and it was assumed that only 2.9% of the P surplus was leached as phosphate (Dalgaard et al. 2006). N_2O emissions were calculated according to IPCC (2000).

Table 1: Characteristics of items in the soybean/palm loop and soybean/rape loop (Møller et al. (2003), an update from Møller et al. (2000))

	Soybeans	Soybean meal	Palm kernel meal	Rapeseed	Rapeseed cake	Spring barley
Dry matter (DM), %	87	87.5	92	92	89	85
Protein, % of DM	40.8	49.1	16.2	21.6	34.8	10.8
Oil, % of DM	20.8	3.2	10.9	48.0	11.2	3.1
Energy, SFU [a] per kg DM	1.44	1.37	0.86	1.86	1.19	1.12

[a] SFU: Scandinavian Feed Units

Table 2: Inventories for cultivation of 1 hectare of soybean, oil palms, rapeseed and spring barley

	Soybean	Oil palms (fresh fruit bunches) [a]	Rapeseed	Spring barley
Location	**Argentina**	**Malaysia**	**Denmark**	**Denmark**
Yields, tons/ha	**2.63**	**18.80**	**2.83**	**4.90**
Resource use				
Fertilizer (N), kg	0	90	167	123
Fertilizer (P), kg	16	12	24	21
Fertilizer (K), kg	0	134	77	62
Diesel, L	42	64	125	114
Lubricant oil, L	4	0	13	11
Electricity (natural gas), kWh	0	7	23	29
Emissions to water				
Nitrate, kg NO_3	0	83	326	202
Phosphate, kg PO_4	0	0.7	0.6	0.7
Emissions to air				
Ammonia, kg	0	0	12.2	10.5
Nitrous oxide, kg	4.7	6.5	6.7	4.8
Nitrogen dioxide, kg	0	1.7	0	0
Sulfur dioxide, kg	0	0.8	0	0

[a] Data based on Yusoff & Hansen (2007)

Average pesticide application over the RR and conventional systems was estimated from Begenisic (2003) and Benbrook (2005). In the no-tillage system, farmers use 5–6 liters of glyphosate solution per ha and an average 0.35 liters of 80% 2,4-D while, in the conventional cropping system, 2 liters of glyphosate is supplemented with 1 liter of imazethapyr. Benbrook (2005) reports an increased used of imazethapyr in Argentina, even though the proportion of RR soybeans has increased, which indicates that this herbicide may be used in combination with glyphosate, possibly to avoid problems with glyphosate-resistant weeds. Imazethapyr is slightly hazardous in WHO (World Health Organization) terminology (Agrocare 2002). The substance has been withdrawn from the European market (Anonymous 2002), but is used in Brazil and Argentina. A number of insecticides are used in soybean cultivation, mostly pyrethroids (0.1 liter per ha of cypermethrin or deltamethrin) and chlorpyrifos (0.8 liter per ha), which are all highly toxic to aquatic environments. The first Sorghum halepensis biotype resistant to glyphosate in the north of Argentina was reported in 2005 (Anonymous 2006a). Because of lack of a reliable fate model to represent the pesticide application techniques used and linking this with the geographical distribution of biodiversity and water bodies, the pesticides were not included in the LCA as such. As discussed below, there is a risk of significant and large-scale impacts on biodiversity because of glyphosate's broad-spectrum effect on non-target plants and amphibians.

Fresh fruit bunches from oil palms. Yields of 18,800 kg ha^{-1} fresh fruit bunches are used, calculated as an average of the yields in 2003 and 2004 as reported by the Malaysian Palm Oil Board (MPOB 2005). Remaining data are based on Yusoff & Hansen (2005). Due to lack of data, MgO fertilizer is not included in the calculations. Production of organic fertilizer is not incorporated in the calculations, because it is assumed that these organic fertilizers are residues that are not produced as a consequence of palm oil cultivation. In accordance with phosphate leaching from soybeans, rapeseed and spring barley, 2.9% of the P surplus is assumed to be leached as phosphate. Literature on nitrous oxide (N_2O) emissions from palm oil cultivation was not available, thus it was assumed that the N_2O emissions were equal to the emissions from soybean cultivation (4.7 kg N_2O ha^{-1}) plus N_2O emissions from the 90 kg N fertilizer that was applied yearly. N_2O emissions from fertilizer were calculated in accordance with IPCC (2000), and the total emission was therefore calculated at 6.5 kg N_2O ha^{-1}. Available information on pesticide use for oil palm cultivation is limited, but according to Wakker (2005), around 25 different pesticides are used and the most commonly used weed killer in oil palm plantations is paraquat dichloride ('paraquat'). Paraquat is banned or restricted in Denmark, Austria, Finland, Sweden, Hungary and Slovenia because of its high toxicity (Anonymous 2006b). Malaysia, the biggest producer of palm oil, has implemented a 2-year phase-out period, but is now reconsidering the phase-out. Glyphosate is also used in oil palm plantations (DTE 2005).

Rapeseed and spring barley. Yields of 2,830 and 4,900 kg ha^{-1}, respectively, were used. All agricultural data are from a National Agricultural Model (Dalgaard et al. 2006), which is representative for the Danish agricultural sector. The model consists of 31 farm types that are representative of the entire agricultural sector in Denmark. For each farm type, resource use and emissions are established using representative farm accountancy data. The Economic model ESMERALDA (Jensen et al. 2001) was used to identify the marginal rapeseed and spring barley producers amongst the 31 farm types, so that marginal Danish data and not average data were used. In the National Agricultural Model, nitrate leaching was assumed to be equal to the farm-gate N balance minus ammonia losses and denitrification (Kristensen et al. 2005) and net change in soil N status. The farm-gate N balance was established according to the methods developed by Halberg et al. (1995) and Kristensen et al. (2005). N_2O emissions were calculated according to IPCC (2000), and the diesel use was modeled according to Dalgaard et al. (2001). The balance approach was also used for calculation of phosphate leaching, but assuming that only 2.9% of the P surplus was leached (Dalgaard et al. 2006). Pesticide use was estimated from inventories established yearly by the Danish Environmental Protection Agency (Anonymous 2005) based on total national sales and the distribution of crops. The most abundant herbicide in rapeseed was clomazone (used on 43% of the rapeseed area in 2004, giving on average 0.14 liter per ha) followed by propyzamide (1 liter per ha on 36% of the land, high aquatic toxicity) and clopyralid (0.2 liter per ha on 17% of land). Approximately 60% of the cropped rapeseed land was treated with insecticides, most often 0.2 liter per ha of cypermethrin, which is classified as moderately dangerous for humans and highly toxic to aquatic organisms. A large variety of herbicides, fungicides and insecticides were used in cereal production and the average number of standard approved dosages used per ha was 1.4 herbicide treatments, 0.61 for fungicides, 0.27 for insecticides and 0.12 for growth regulator applications (Anonymous 2005). The most frequently used herbicide applied to 36% of the barley area was tribenuron-methyl, which is classified as moderately dangerous for humans and highly toxic to aquatic organisms.

LCA data on material inputs. Within Europe a change in demand for artificial fertilizer affects the less competitive fertilizer producers, as the European market has experienced a decrease in the consumption of fertilizer due to environmental restrictions (Weidema 2003, p. 73). Data on artificial fertilizers (nitrogen, phosphorous and potassium) are from Patyk & Reinhardt (1997), as these data are assumed to represent the less competitive technology. Due to lack of data, the same data are assumed to be valid for palm oil production in Malaysia. Data on the use of agricultural machinery are based on Borken et al. (1999), but moderated to average load. These data are average, but are assumed not to differ from marginal data. For further information on the above-mentioned data, go to www.lcafood.dk (Nielsen et al. 2003). Data on electricity (electricity from fuel gas power plant in the Netherlands), pentane (used instead of hexane), transport by truck (28 t), heat (oil) and heat (gas) are all from the Ecoinvent Centre (2004).

3.2 Milling plants

The inventories for processing of soybeans, rapeseeds, fresh fruit bunches from oil palms and palm kernels are presented in **Table 3**. Fossil energy related emissions are not shown. Based on data from Oil World (2005) it is assumed that the losses from all milling processes are 2%.

Table 3: Inventories for millings plants. Functional unit: Processing of 1 ton soybeans, fresh fruit bunches, palm kernels and rapeseeds, respectively

	Soybean mill	**Palm oil mill**	**Palm kernel mill**	**Rapeseed mill**
Location	**Argentina**	**Malaysia**	**Malaysia**	**Denmark**
Products	**Soybean meal** **Soybean oil**	**Palm oil** **Palm kernels** **Pulp**	**Palm kernel oil** **Palm kernel meal**	**Rapeseed meal** **Rapeseed oil**
Transport				
Transport to mill (28 t lorry)	500 km	0 km	150 km	150 km
Transport to mill (tractor)		22 MJ Diesel		
Resources				
Hexane	0.40 kg	0	1.99 kg	0
Diesel for machinery			32 MJ	
Electricity (natural gas)	12 kWh		68 kWh	50 kWh
Heat (oil)	145 MJ	–	335 MJ	340 MJ
Heat (gas)	282 MJ	–	–	
Emissions to air				
Methane		9,570 g		
Hexane	0.20 kg	–	1.99 kg	
Carbon monoxide	Energy related	50 g	Energy related	Energy related
Nitrogen oxides	Energy related	120 g	Energy related	Energy related
NMVOC, volatile organic compounds	Energy related	239 g	Energy related	Energy related
Sulfur dioxide	Energy related	435 g	Energy related	Energy related
Particles	Energy related	276 g	Energy related	Energy related
Emissions to water				
BOD5, Biological Oxygen Demand	17 mg			
COD, Chemical Oxygen Demand	61 mg			
Nitrate	4 mg	182 g		

Soybean mill. Soybean meal consumed in the EU is primarily milled outside the EU (Oil World 2005). Consequently, it is assumed in this study that it is milled where it is produced (Argentina). The amount of hexane used for oil extraction and emitted is based on Cederberg (1998), and energy use and emissions to water are from Reusser (1994). It is assumed that soybean meal is sailed 12,082 km from Argentina (Rosario Harbor) to the Netherlands (Rotterdam Harbor). According to Oil World (2005), the Netherlands is the largest importer of soybean meal in Europe.

Palm oil mill. Processing data are based on palm oil mills owned by Unilever in 1990 (Unilever 2004). The fresh fruit bunches are transported by tractor as the oil mills are always placed near the oil palm plantation in order to have a relatively short transport time to avoid decomposition of fatty acids in the fresh fruit bunches. Energy in the palm oil mill is supplied by incineration of empty fruit bunches, mesocarp fibers and nut shells. All airborne emissions given in Table 3 are related to storage and burning of this organic matter. The emissions to air and N to water are based on Zah & Hischier (2003). Palm oil is extracted without the use of organic solvents. Possible empty fruit bunches, mesocarp fibers and shells that are not used for energy production are not included.

Palm kernel oil mill. Similar to palm oil mill, processing data for the palm kernel oil mill are based on Unilever (2004). The oil is extracted using hexane as a solvent.

Rapeseed mill. Materials and energy used for processing of rapeseeds are from Scanola, a Danish mill that processes approximately 220,000 tonnes of rapeseeds annually (Emmersen 2005). In contrast to the soybean and palm kernels mill, organic solvent is not used for the extraction.

4 Results

4.1 Soybean loops

The aim of this section is to demonstrate how an increased demand for soybean meal affects the agricultural production using the two soybean loops (PO and RSO).

Fig. 1 shows the soybean meal loop with palm oil as a marginal oil. The loop is divided into three parts that are interrelated in a loop as illustrated by the large bold arrows. To produce 1,000 g soybean meal, 1,210 g soybean is needed. These soybeans contain sufficient oil to produce 191 g pure soybean oil leaving 29 g oil in the soybean meal (not shown). The soybean oil is sold on the market and assumed to substitute palm oil, which is a mix of palm oil (from mesocarp) and palm kernel oil. When the fresh fruit bunches are milled, there is a large co-production of organic residues that are used to produce energy for the palm oil mill (see also Table 3). For each 1,000 g of soybean meal produced, there is an avoided production of 23 g palm kernel meal, which is substituted by marginal meal. The marginal meal is soybean meal but, as the protein and energy content is higher in soybean meal (see Table 1) than in palm kernel meal, this is compensated for by a mix of soybean meal and spring barley (23 g of palm kernel meal contains the same amount of protein and energy as a mix of 5 g of soybean meal and 12 g spring barley). Consequently, after the first turn in the loop, which was caused by an increased demand for 1,000 g of soybean meal, the production has increased to 1,005 g. By making this iteration for each turn, the extra amount of soybean meal produced is getting smaller. The iteration was carried out in the LCA-tool SimaPro (Pré 2004), and the result showed that an increased demand for 1,000 g of soybean meal caused a production of 1,005 g of soybean meal, –856 g of fresh fruit bunches and 12 g of spring barley.

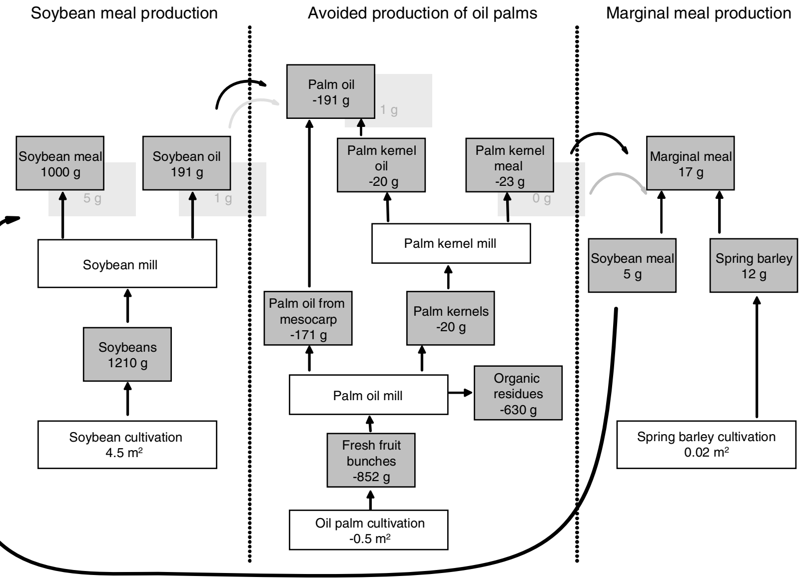

Fig. 1: Soybean/palm loop for LCA of soybean meal (PO). First turn in the loop: An increased demand for 1,000 g of soybean meal results in production of 1,005 (=1,000 + 5) g soybean meal, –852 g fresh fruit bunches and 12 g spring barley. Shadowed boxes show the beginning of second loop

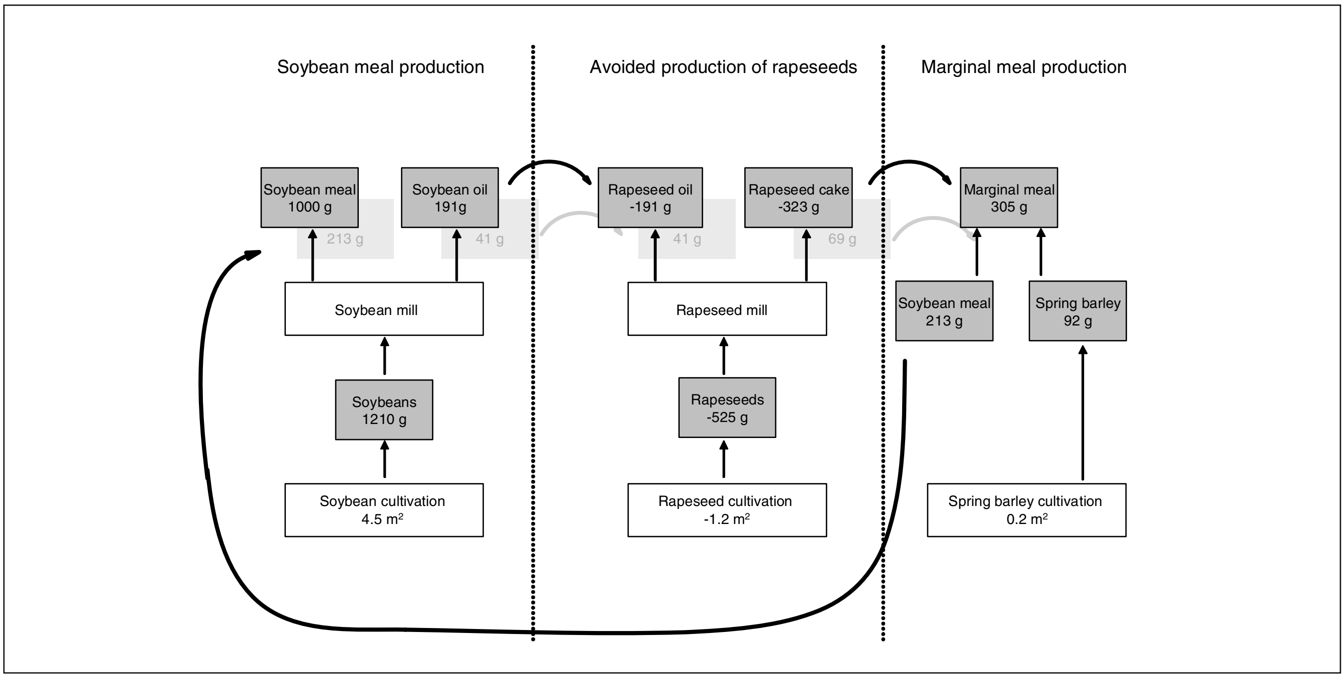

Fig. 2: Soybean/rapeseed loop for LCA of soybean meal (RSO). First turn in the loop: An increased demand for 1,000 g of soybean meal results in production of 1,213 (=1,000 + 213) g soybean meal, –525 g rapeseeds and 92 g spring barley. Shadowed boxes show the beginning of second loop

Fig. 2 shows the soybean/rapeseed loop. Here the soybean oil is assumed to substitute rapeseed oil on the market. For each 1,000 g of soybean meal produced, there is an avoided production of 323 g rapeseed cake, which is considerably more than the 23 g palm kernel meal in the soybean/palm loop (see Fig. 1). Rapeseed cake contains more protein compared with palm kernel meal, thus the soybean meal/spring barley ratio is lower in the soybean/palm loop (see Fig. 1) compared with the soybean/rapeseed loop (see Fig. 2). By iteration, the amount of soybean meal produced can be calculated as for the soybean/palm loop. The increased demand for 1,000 g of soybean meal causes a production of 1,271 g of soybean meal, –667 g rapeseed and 117 g spring barley.

Once the soybean loops are established, the effect of the increased demand for soybean meal on the palm oil, rapeseeds and spring barley needed can be quantified and used in the LCAs of soybean meal (RSO) and soybean meal (PO). Results from the LCAs are presented in the following.

4.2 Characterized results

Table 4 shows the characterized results of the two soybean meal LCAs from 'Rotterdam Harbor' together with the 'from farm gate products' used. Soybean meal (RSO) has a lower environmental impact for all effect categories (except photochemical smog) compared with soybean meal (PO), and this can be ascribed to the fact that the avoided environmental impact from rapeseeds is much larger compared with the avoided environmental impact from palm oil ('fresh fruit bunches from farm gate'). It is worth noting that exactly the same process for soybean cultivation is used for the two soybean meal productions.

In **Table 5**, the economic and mass-allocated, characterized results are presented. A comparison between soybean meal (PO) (see Table 4) and economically allocated soybean meal (69%) (see Table 5) shows that the characterized results for the impact categories 'global warming', 'ozone depletion' and 'acidification' are very similar. 'Eutrophication' from soybean

Table 4: Characterized results of soybean meal (PO), soybean meal (RSO) and crops involved in the life cycle of soybean meal. Functional unit: 1 kg of product

	Unit	Soybean meal (PO)	Soybean meal (RSO)	Soybeans	Fresh fruit bunches	Rapeseeds	Spring barley
Delimitation		**from Rotterdam**		**from farm gate**			
Global warming	g CO_2 eq.	721	344	642	177	1,550	671
Ozone depletion	mg CFC11 eq.	0.27	0.20	0.08	0.02	0.23	0.12
Acidification	g SO_2 eq.	3.1	–1.2	0.8	1.6	11.8	5.8
Eutrophication	g NO_3 eq.	–2	–81	1	8	139	53
Photochemical smog	g ethane eq.	0.4	0.4	0.1	0.0	0.3	0.2

Table 5: Characterized results of soybean meal. Calculated by the use of economic and mass allocation. Functional unit: 1 kg of soybean meal (PO) delivered to Rotterdam Harbor

	Unit	Economic allocation [a]		Mass allocation	
		Soybean meal (69%)	Soybean oil (31%)	Soybean meal (84%)	Soybean oil (16%)
Global warming	g CO_2 eq.	726	1,819	901	901
Ozone depletion	mg CFC11 eq.	0.20	0.49	0.24	0.24
Acidification	g SO_2 eq.	3.3	8.3	4.1	4.1
Eutrophication	g NO_3 eq.	3.1	7.8	3.8	3.8
Photochemical smog	g ethane eq.	0.3	0.8	0.4	0.4

[a] Prices from Argentina year 2002: Cake of soya beans 158 US$, oil of soya beans 396 US$ (FAOSTAT 2006)

meal (69%) (see Table 5) is positive, in contrast to soybean meal (PO) (see Table 4), but still much lower than 'eutrophication' from 'rapeseeds' and 'spring barley' in Table 4.

Normalization of the characterized results in Table 4 showed that the most dominating impact categories were: Global warming, eutrophication, and acidification. In the following, environmental hot spots within these categories will be presented.

4.3 Environmental hot spots

In **Fig. 3, 4** and **5**, environmental hot spots of the product chains of soybean meal (PO) and soybean meal (RSO) are shown. 'Energy' includes emissions (e.g., fossil CO_2) related to cultivation of soybeans, rape seeds, oil palms and spring barley, but also energy used on the milling plants. 'Fertilizer' includes processing (including energy) of artificial fertilizer used for the cultivation of soybeans, rape seeds, oils palms and spring barley. All three figures are dominated by large negative emissions from 'Avoided agricultural cultivation' which are saved emissions caused by 'avoided production of oil palms' (see Fig. 1) and 'avoided production of rapeseeds' (see Fig. 2), respectively. The avoided production of rapeseeds is largest, because the emissions per kg rapeseed are higher than the emissions from fresh fruit bunches (see Table 4). For all the figures, the positive contributions are smaller for soybean meal (PO) than for soybean meal (RSO). This is also clearly demonstrated in soybean loops, where an increased demand for soybean meal (PO) only results in production of 1,005 g soybean meal (and 12 g spring barley), whereas an increased demand for soybean meal (RSO) results in the production of 1,271 g soybean meal (and 117 g spring barley).

The contributions to **global warming potential** from different parts in the product chains of soybean meal (PO) and soybean meal (RSO) are shown in Fig. 3. The major contributor to global warming is the cultivation of soybean, where 8% of the greenhouse gases emitted during the soybean cultivation is fossil CO_2, and the rest N_2O. The N_2O comes from degradation of crop residues (e.g., straw) and biological nitrogen fixation. Contributions from 'freighter oceanic' and 'truck' are almost equal (the latter also includes avoided transportation of rapeseeds/palm kernels). For soybean meal (RSO), there is a considerable amount of avoided emission from fertilizer production. The demand for soybean meal (RSO) results in a shift from rapeseed cultivation (N fertilizer use = 167 kg N ha^{-1}) to soybean cultivation (N fertilizer use = 0 kg N ha^{-1}), thus saving fertilizer. The production of N fertilizer emits considerable more greenhouse gases, CO_2 and N_2O in particular, than P and K fertilizers. The contributions from 'truck' (transport of soybeans in Argentina (500 km)) and 'freighter oceanic' (shipping of soybean meal from Rosario in Argentina to Rotterdam in the Netherlands (12,082 km)) are very similar, despite the large difference in distance. This indicates that shipping is much more environmentally friendly than transport by truck.

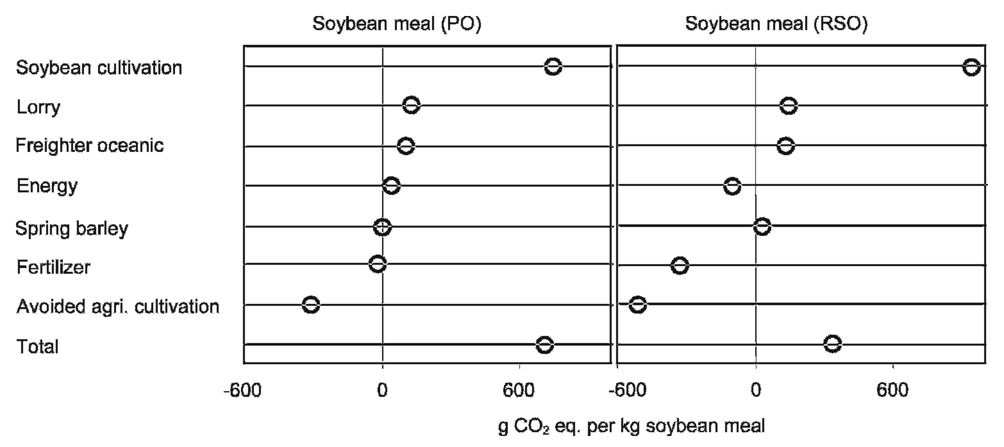

Fig. 3: Contribution to global warming potential from different parts of the product chain of soybean meal

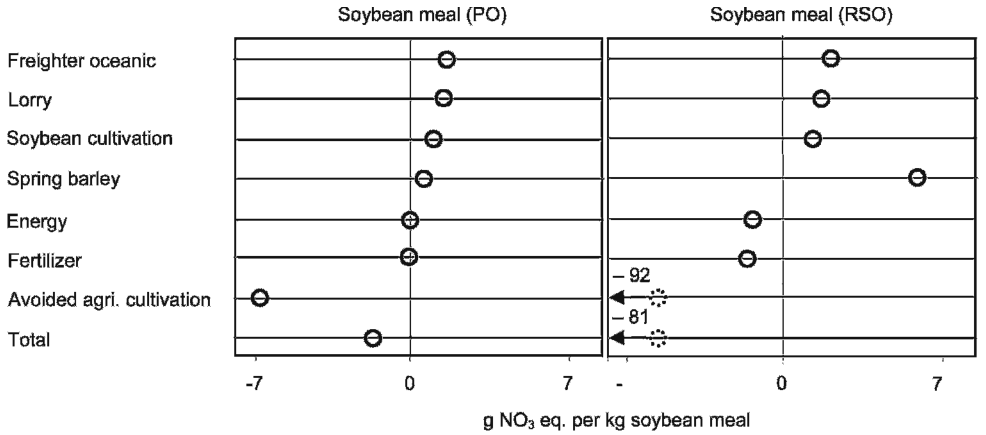

Fig. 4: Contribution to eurtrophication potential from different parts of the product chain of soybean meal

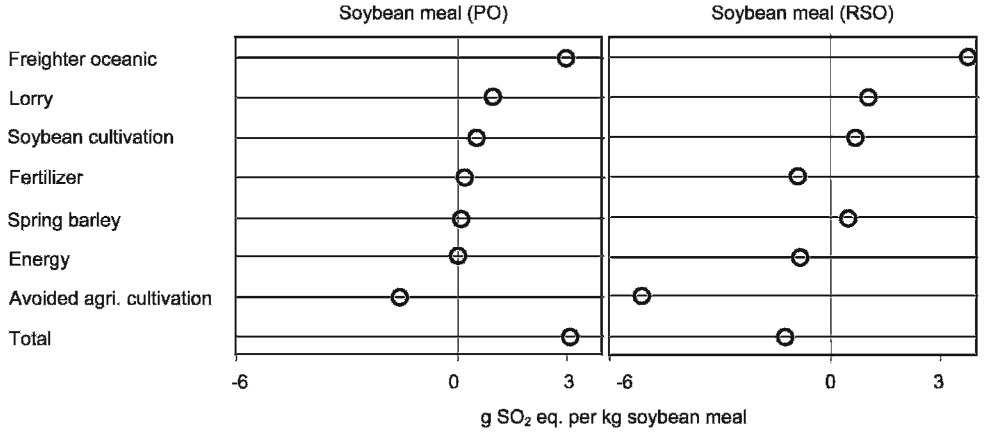

Fig. 5: Contribution to acidification potential from different parts of the product chain of soybean meal

Even though transport from Rotterdam Harbor to feedstuff companies and to farm gate was not part of the LCA in this study, we performed sensitivity analyses of this part of the product chain to see how much it could change the results. If the soybean meal (PO) was transported 650 km, this resulted in an increase of 20% in global warming potential.

Concerning **eutrophication potential** from soybean meal (RSO), it is clear that agricultural production avoided dominates the picture (see Fig. 4). This is because rapeseed contributes 139 g NO_3-eq. kg^{-1} produced compared with only 1 g NO_3-eq. kg^{-1} for soybeans (see Table 4). The environmental hot spot for eutrophication is 'spring barley' for soybean meal (RSO). The contribution from 'soybean cultivation' is smaller than the contribution from 'freighter oceanic' and 'truck'. Site-dependent impact assessment is not used in this study, so that, in the interpretation of the results, it must be taken into consideration that nutrifying substances emitted at sea damage vulnerable ecosystems (e.g., lakes, bogs) much less than on-land emissions.

The environmental hot spot regarding **acidification potential** (see Fig. 5) is 'freighter oceanic', but it must again be taken into consideration that acidifying substances emitted at sea are more harmless than if they were emitted on land. The second largest contributor is 'truck'. As for global warming, the production of N fertilizer avoided for rapeseed cultivation contributes negatively. When assuming 650 km of transport of soybean meal (PO) from Rotterdam Harbor, the acidification potential was increased by 32%.

4.4 Land use

As part of the inventory, data on land use for the different agricultural production systems were collected. The land used for the production of 1 kg of soybean meal (PO) and soybean meal (RSO) is 3.6 and 3.0 m^{2}year respectively (**Table 6**). The use of land in Argentina is higher than the total land use. The interpretation of this is of course that the use of 'one kg soybean meal (RSO)' costs 5.1 m^{2}year in Argentina, but saves 2.1 m^{2}year in Europe. Thus, the pressure on the pristine ecosystems in Argentina becomes quite obvious: Growing demands for soybean meal thus aggravate the pressures on land in other countries. At the end of the day, that eventually leads to a loss of biodiversity. Unfortunately, we have at present no method that reasonably translates the pressures on land into loss of biodiversity, although some efforts have been done to do so (Weidema & Lindeijer 2001, Lindeijer 2000, Mattson et al. 2000). These methodologies

Table 6: Land use per kg product (Unit: m²year). Data on soybean meals include both the soybean cultivation and the avoided productions of fresh fruit bunches and rape seeds

	Soybean meal (PO)	Soybean meal (RSO)	Soybeans	Fresh fruit bunches	Rapeseeds
Total	3.6	3.0	3.3	0.5	3.5
Of this in Argentina or Malaysia	4.0	5.1	3.3	0.5	0

can be criticized for not addressing a suitable way of linking known pressures on agricultural land in terms of occupation (m^2year) with actual transformation between land use types. We argue that the most relevant aspect of land use impact is the transformation of pristine ecosystems into agricultural land. But we are only able to establish a link between the functional unit (1 kg soybean meal (RSO)) and the area occupied in Argentina (5.1 m^2year) and Europe (–2.1 m^2year). In addition to this, new research results linking landscape transformations and biodiversity using landscape ecology methodologies are being applied in Argentina to help to solve these limitations (Matteucci et al. 2004).

It should be noted that pesticide use was not included in the LCA results, but should be considered separately. The extensive use of broad-spectrum herbicides with glyphosate, fungicides and insecticides in the non-tillage RR soybean system may impact the health of farm workers and can have severe effects on biodiversity and aquatic environments, such as rivers and lakes, in the large areas where soybeans are virtually the only crop (see references in Ho & Ching 2003, Ho & Cummings 2005, Benbrook 2005). In the case where rapeseed is replaced by increased soybean production, this would increase the use of pesticides, also with potentially toxic effects on waterborne organisms but in a totally different location. The palm oil plantations also use glyphosate-containing herbicides. However, both the rapeseed and especially the palm oil cropping systems use significantly lower amounts of pesticides compared with the soybeans.

5 Discussion

5.1 Methodology: the use of consequential LCA

The rapeseed production had a large influence on the LCA of soybean meal (RSO) (see 'avoided agricultural cultivation' in Fig. 3, 4 and 5), and it even resulted in a negative eutrophication potential for soybean meal (RSO). This might appear irrational, but, according to the assumptions in these systems, when an extra amount of soybean meal is demanded, the vegetable oil production will shift from rapeseed oil to soybean oil. Seen in relation to eutrophication the rapeseed production is more harmful compared with the soybean production, because the nutrient surplus from the soybean production is low. Therefore, as long as an increased demand for soybean meal implies production of more soybean, at the same time it also induces a shift to an oil production causing less eutrophication. In the present LCA, it is assumed that an 'additional' production of 1 kg soybean oil results in a similar reduction in the production of rapeseed or palm oil (one-to-one substitution by kg oil). This is obviously a simplification because we assume (among other things) that prices remain unaffected and, thus, the model does not include price elasticity. However, this assumption is not only made in relation to system expansion, but in all the steps of a typical LCA inventory, as explained in Weidema (2003, p. 37).

Another obvious challenge of consequential LCA is the identification of affected processes, i.e., marginal processes/technologies. The present study shows significantly different results between the two soybean meal systems (PO vs. RSO), reflecting the use of palm oil or rapeseed oil as the marginal oil type. It cannot be established with certainty which of the oil types (palm or rapeseed oil) is the marginal oil – or whether it is a mix – or whether other types are included in this mix. The identification of the actual marginal is a great challenge, and an obvious source of uncertainty. However, it is not a better solution to assume that all plant oils are affected proportionally to their present market volume, which in reality would be the assumption behind an attributional LCA using average data.

In the present LCA of soybean meal, the changes in CO_2 emission caused by land-use changes (e.g., transformation of forest to cropland) were not included, due to conceptual and methodological limitations. Conceptually, it is debatable whether changes in above ground and soil carbon content due to changed land use should be included in an LCA of a product, especially when the functional unit is not related to carbon sequestration. If the impacts from 'land-use changes' related to crop cultivation are included in an LCA of agricultural products, this must be performed consequently. If, for example, the LCA data on soybean meal is used in an LCA of milk, the inclusion of the CO_2 emissions from land-use changes in Argentina should be combined with similar calculations of possible changed CO_2 sequestration in the dairy system (for example, more or less grassland versus maize in the crop rotation, which would influence soil organic matter). This is not presently done in LCAs involving agriculture for food nor bio-energy products (e.g., Cederberg & Flysjö 2004, Basset-Mens & van der Werf 2005, Heller et al. 2003, Kim & Dale 2005).

Methodological problems include the knowledge of land use before conversion, estimates of changes in above ground as well as below ground carbon content, both immediately and after initiation of cultivation and choice of depreciation time.

For example, the history of the area used is unknown, previously it might have been covered with crops, savannah, forest or something else. As there is a large difference in the amount of carbon stocked in these types of land (e.g., Fearnside 2000), it will influence the result strongly. Also the choice of depreciation time influences the result. Whether the emissions related to the land-use change should be ascribed completely to the crops cultivated during the first year or divided over the next 20–100 years of cultivation is debatable, and to determine the depreciation time demands better knowledge of the driving forces behind land-use changes. Despite the methodological limitations, we performed a sensitivity analysis, where it was assumed that the above-ground biomass of the forest before clear-cutting was 94 tons C ha^{-1} (area weighted mean for all tropical forests (Houghton 2005)), and the depreciation time was set at 20 year. Below-ground biomass and avoided deforestation related to palm oil production in Malaysia were not included in the calculation. According to the sensitivity analysis, the global warming potential inclusion of changes in CO_2 emissions caused by land-use changes increased the global warming potential dramatically from 721 g to 5.7 kg CO_2 eq. per kg soybean meal (PO).

In consequential LCAs, the use of marginal data is to be preferred, because the consequential LCA seeks to reflect the environmental consequences of an increasing demand for a certain product. But when are data marginal and when are they average? Argentina is the marginal soybean meal producer as argued in the 'system delimitation' section and, therefore, we have used averaged data on soybean meal yields in Argentina. Preferably, we should have used yield data from the marginal soybean producers within Argentina. Marginal data on yields of soybeans and fresh fruit bunches were not available and, as we did not find a reason to believe that the marginal yields would be very distinct from the average yields, we used average data.

N_2O emissions from cultivation of soybeans, rapeseeds, spring barley and oil palms appeared to have a large impact on the global warming potential per kg soybean meal. This is in good agreement with other studies, showing that N_2O plays a major role in the greenhouse gas emissions from agricultural production (Olesen et al. 2006; Dalgaard et al. 2006). N_2O emissions from soybeans, rapeseeds and spring barley were calculated according to the IPCC guidelines. However, we had difficulties in finding literature or methods for estimating N_2O emissions from oil palms, and we therefore used the same data as for soybeans, but adding N_2O emitted from the N fertilizer applied to the oil palms. This was unsatisfactory as the N_2O turned out to be important for the final result of the LCA of soybean meal (PO).

5.2 Comparison with previous studies

A majority of the previous LCA studies on livestock products, where soybean meal was included, does not directly present LCA data on soybean meal. However, Eriksson et al. (2004), who based the soybean inventory on data from Cederberg & Darelius (2001), have published LCA data on soybean meal. Ecoinvent Centre (2004) also provide data for the LCA database on 'soybean scrap', based on soybeans produced in Switzerland. Economic allocations were performed in both the above-mentioned studies. The environmental impacts of producing one kg of soybean meal, according to Eriksson et al. (2004) and Ecoinvent Centre (2004), are as follows: Global warming: 730 and 507 g CO_2 eq.; acidification 8 and 13 g SO_2 eq.; eutrophication: 541 and 198 g NO_3 eq. (LCIA method applied for Ecoinvent data: EDIP97 (Wenzel et al. 1997, updated version 2.3)). The results on global warming are in good agreement with ours (soybean meal (PO) in Table 4 and soybean meal (69%) in Table 5), whereas our results on acidification and eutrophication are considerably lower. These differences are not only due to the use of consequential versus attributional LCA, but to a larger extent due to the estimated emissions. For example, the soybean cultivation in Ecoinvent contributes negatively to GWP, because biotic fixation of CO_2 from the atmosphere is considered as a negative contribution to global warming potential. In our calculation, we consider the biotic fixated CO_2 as neutral, because it will be released to the atmosphere after digestion by livestock. The similarity of the results on global warming potential must be ascribed to accidental occurrence. The environmental hot spots in Ecoinvent Centre (2004) are, as in our study, transport by freighter oceanic and truck. But, in our results, site-dependent aspects are not taken into consideration.

Cederberg & Flysjö (2004) estimated that nitrate leached from soybean cultivation in Cerrado in Brazil equaled 36 kg N ha^{-1}, whereas we estimated no nitrate leaching. In the study of Cederberg & Flysjö (2004), the input of N (fertilizer and BNF) to the soybean cultivation was assumed to be 230 kg N ha^{-1}. We find this is a very high estimate because the average N application (fertilizer) to soybean fields in the Pampas was only 2 kg N ha^{-1} in 2002 (FAO 2004). According to Austin et al. (2006), nitrate was not leached from the soybean fields in the Pampa region. In contrast, a substantial net loss of nitrogen at the regional scale was taking place, and the current agricultural practices in the Pampa region are essentially 'mining', the nutrient capital of the region (Austin et al. 2006). Unfortunately, this export of nutrients out of the region probably leading to nutrient deficiencies in the soil, is not captured in our LCA of soybean meal. The discrepancy between the results of Cederberg & Flysjö (2004) and our results might be due to differences in cultivation practices in Brazil and Argentina. For example, the fertilizer use efficiency in Argentina is four times higher than in Brazil (Austin et al. 2006), and the fertilizer use is generally considerably lower.

5.3 Relative impact of the Danish soybean consumption: Scaling up from FU to national level

The results demonstrate that the soybean meal consumption in Europe has an impact on the global environment (e.g., global warming) and on the local environment outside Europe (e.g., acidification, land use). But what is the magnitude of these environmental impacts from soybean meal production compared with the environmental impacts of the livestock production itself? As an example, we compared greenhouse gas emissions: According to Gyldenkærne & Mikkelsen (2004), 10.5 million tonnes CO_2 eq. were emitted from the entire Danish agricultural sector in 2002. In the same year, 1.5 million tonnes of soybean meal were imported to Denmark (Statistikbanken 2006). If the transport from Rotterdam Harbor to a Danish feed company is set at 650 km, the greenhouse gas emission is 869 g CO_2 eq. per kg soybean meal (PO) (=721 * 1.20). This results in a 'soybean meal related greenhouse gas emission' of 1.3 million tonnes CO_2 eq., which is approximately equivalent to 12% of the greenhouse gas emitted directly from the Danish agricultural sector. So, in addition to the 10.5 million tonnes emitted from the agricultural sector, an extra amount of 1.3 million tonnes is emitted as a consequence of the soybean meal import to Denmark. Unfortunately, it was not possible to estimate the environmental impact from pesticide use and loss of biodiversity caused by pressure on pristine ecosystem.

6 Conclusions

Consequential LCA was successfully performed on soybean meal. An increased demand for soybean meal implies an increased production of soybean oil as both commodities originate from the soybean. This soybean oil will substitute the marginal vegetable oil on the market and, therefore, an increased demand for soybean meal results in an avoidance of the production of the crop producing the marginal oil. This avoided crop production (and other affected crops) was included in the calculations. A recent study by Schmidt and Weidema (2007) has identified palm oil as the marginal oil. However, a shift to rapeseed oil might be possible, as the two vegetable oils are comparable in many aspects. To be prepared for such a shift and to analyze to what extent the choice of marginal oil affects the result of the LCA, two LCAs on soybean meal were performed: One with palm oil as the marginal oil (soybean meal (PO)) and one with rapeseed oil as the marginal oil (soybean meal (RSO)).

The functional unit was 'one kg soybean meal produced in Argentina and delivered to Rotterdam Harbor'. The characterized results from the LCA on soybean meal (PO) were 721 g CO_2 eq. for global warming potential, 0.3 mg CFC11 eq. for ozone depletion potential, 3.1 g SO_2 eq. for acidification potential, –2 g NO_3 eq. for eutrophication potential and 0.4 g ethene eq. for photochemical smog potential. The potential environmental impacts (except photochemical smog) were lower for soybean meal (RSO), because the avoided environmental impact was larger from rapeseed compared with oil palms.

Normalized results showed that the most dominating impact categories were: global warming, eutrophication and acidification. The 'hot spot' in relation to global warming was 'soybean cultivation', dominated by N_2O emissions from degradation of crop residues (e.g., straw) and during the biological nitrogen fixation. Eutrophication is not a major problem in the soybean cultivation. In relation to acidification, the transport of soybeans by truck was important, and sensitivity analyses showed that the acidification potential was very sensitive to increased transport distance by truck.

7 Recommendations and Perspectives

This study clearly shows that consequential LCAs are quite easy to handle and that LCA data on soybean meal are now available for consequential (or attributional) LCAs on livestock products. But there are, of course, some limitations to this analysis. First of all, it is important to know which of the related product systems, e.g., the vegetable oil system, are marginal. We would appreciate it if International the Journal of Life Cycle Assessment had articles on the developments on, for example, marginal protein, marginal vegetable oil, marginal electricity (related to relevant markets), marginal heat, marginal cereals and, likewise, on metals and other basic commodities.

It is also recommended that more effort be put into describing the impacts of land use. With a growing global population and increasing demands on meat instead of vegetable products, the pressures on arable land and eventually reclamation of natural habitats for farming puts tremendous pressures on the natural habitats in many places around the world. It is thus pivotal that we become able to manage loss of biodiversity as a fundamental impact category in LCA studies.

Soybean expansion in Latin America represents a powerful threat to biodiversity in Brazil (Cerrados), Argentina (Chaco, Yungas and Monte Ecoregions), Paraguay and Bolivia. In addition to herbicide use and genetic pollution, the massive requirement for infrastructure projects (highways, ports and railways) are also threats to the high biodiversity that presently exists in Latin America (Alteri and Pengue 2006).

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