The importance of system boundaries for LCA on large material flows of vegetable oils

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Abstract

The environmental effect of globalization has been discussed broadly in the last decades. In the European Environmental Agency's third assessment of Europe's Environment they conclude that the EU has stabilized its own resource use at the expense of increased resource use outside the EU. On this background I argue that there is a need for life cycle assessments of different patterns of global production and consumption. This article discusses the system delimitation of such "global" LCAs on large material flows in the case of agriculture. The discussion of system boundaries in LCA has been in focus in recent years. The issue of concern is based on the hypothesis, that the approach to system delimitation has a significant effect on the results of a comparative LCA on large material flows on the global scale. More specifically the two approaches of concern are traditional attributional approach and the consequential approach, described in Weidema (2003). Thus, this article elaborates on the following three key issues: What is the effect on the result related to the approach to system delimitation: traditional/attributional and consequential approach? What are the consequences for the setup of the investigated system – which processes and related product systems are considered as affected? And what is the added value by adopting the consequential approach in stead of the more traditional approach?

The analysis in this article is based on a case study of a comparative LCA-screening of rapeseed oil and palm oil. These two commodities represent a global and a local product system that can supply the EU with fat. Some essential elements of the product systems for the two commodities are tested for the attributional versus the consequential approach to system delimitation. These are average versus marginal energy and co-product allocation by allocation factors versus avoided co-product allocation by system expansion.

It is concluded that the results of the LCA heavily depend on the approach to system delimitation. The contribution to the included impact categories (global warming, acidification, eutrophication and land use) varies with up to a factor 200 depending on the approach to system delimitation. The investigated system tends to be significantly more comprehensive when adopting the consequential approach. In the case of the consequential LCA of palm oil four different oil crops and five oils are affected. The attributional LCA may be seen as a too simplified picture of reality, when dealing with decision support to political and regulatory decisions. On the other hand market forecasts, which are the prerequisite for system expansion, may also cause uncertainties in the result. However, this study shows that regulation of one commodity may affect several other commodities in the global market. Thus, applying regulations based on life cycle assessments may lead to undesired effects if not the consequential approach to system delimitation is taken into consideration. Hidden within the goal and scope definition, the attributional approach simply cut off too many potential important side effects when dealing with global traded large material flows of substitutable commodities. Thus, I see a great need for more focus on the approach to system delimitation in the future.

Keywords

Goal and scope, system delimitation, system boundaries, co-product allocation, system expansion, vegetable oils, rapeseed oil, palm oil, palm kernel oil, soy oil, coconut oil.

Content

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1 Introduction

In recent years the approach to system delimitation in LCA tend to have turned from the attributional/traditional approach towards the consequential approach (also called the avoided burden approach or marginal approach), see Weidema (2003). This article discusses the effect of different approaches to system delimitation in the case of vegetable oils with rapeseed and palm oils as cases. The market for vegetable oils is characterized by many substitutable oils which are produced in large quantities in many different parts of the world. I find it very relevant to discuss system delimitation for LCA on "global" large material flows because the approach may have an effect on which suppliers (region/technology) that are considered as affected.

Thus, the issue of concern is based on the hypothesis, that the approach to system delimitation has a significant effect on the results of a comparative LCA on large material flows on the global scale. The two approaches to system delimitation discussed in this article are the consequential approach and the attributional approach. This is further described in section 1.1. This article elaborates on the following key issues:

- What is the effect on the result of the approach to system delimitation in comparative LCA of large material flow global commodities?
- What are the consequences for the setup of the investigated system – which processes and related product systems are considered as affected?
- What is the added value by adopting the consequential approach in stead of the more traditional approach?

1.1 What is system delimitation in LCA?

System delimitation in LCA is a part of the goal and scope phase described in ISO 14040 (1997). Some of the important elements in the goal and scope definition is pupose, functional unit, system boundaries and co-product allocation procedures. This article focuses on the delimitation of system boundaries and co-product allocation procedures. The two main approaches to this are described in the following.

The attributional approach represents the traditional way of identifying affected processes and to handle co-product allocation in LCA. I.e. affected processes are often assumed to be represented by average data for the specific used product and co-product allocation is handled by using allocation factors. An example of an attributional LCA is a life cycle assessment of Danish electricity and heat (Eltra et al., 2000). In Eltra et al. (2000) the affected processes are assumed to be an average of the used technologies producing electric power in Denmark, which is a mix of coal, natural gas, waste incineration and wind power. For several of technologies (central and de-central coal and natural gas plants and waste incineration plants) electricity is co-produced with heat. Co-product allocation is handled by allocation by either energy or exergy content.

Weidema (2003) advocates for the consequential approach and gives several arguments against using the attributional approach. One argument against attributional approach is that it does not give a causal explanation of consequences of past and future actions. Weidema argues that only the affected processes are to be included, i.e. the marginal processes. Using the consequential approach on the above mentioned electricity example the affected technology is coal or gas since all other technologies are constrained or determined by other factors than marginal demands for electricity. Furthermore the consequential approach implies that co-product allocation is avoided by system expansion.

1.2 Why is the system delimitation important?

The European Topic Center on Waste and Material Flows has worked out a study that illustrates the importance of system boundaries (Villanueva et al., 2004). Villanueva et al. (2004) examines 73 scenarios from nine LCAs on disposal of paper. 15 key assumptions that are all related to system boundaries are identified, and it is concluded that the outcome of a LCA on disposal of paper heavily depend on these assumptions. Some of the same assumptions have been the reason for heavy critics of a cost/benefit analysis on disposal of paper worked out by The Environmental Assessment Institute in Denmark (Petersen and Andersen, 2002). The discussion of system boundaries is not only relevant for LCAs but also for the expanding use of CBA. This is of certain importance in the case of CBAs on products which life cycle is distributed over several countries.

Most existing LCAs are conducted as so called attributional LCAs, while some new LCA studies adopt the consequential approach. Also most of the existing LCI databases are based on the attributional approach, e.g. Ecoinvent (2004), EDIP (2004), ETH (1996), BUWAL250 (1996), and IDEMAT (2001). Only one database using the consequential approach is identified, i.e. LCAfood (2003). Since most LCAs – both attributional and consequential - are worked out in LCA pc-tools and to some extent are based on LCI data from databases, I argue there is a need to know the effects of the approach to system delimitation.

1.3 Characteristics of LCA of large material flow global traded products

What characterizes an environmental assessment of globalization and large material flows? And what are the differences between a more traditional LCA and a “global and large material flow” LCA? Of course a LCA on global and large material flows implies that processes all over the world are included in the product system. Often and especially in the case of vegetable oils, it also implies that the focus is on global traded commodities that can substitute each other. Furthermore, it implies that the analyzed products are regulated in many ways and on several local-global scales and the products are traded within certain market mechanisms formed by regulations and the global demand. Therefore it is important to be aware if the purpose of the study is to give decision support to the authorities on a regional/global level (review certain regulations) or at company level (review own processing and requirements to suppliers and purchasers).

I find it necessary to enlighten some of the consequences by adopting the two different approaches to system delimitation (consequential versus attributional) in LCAs of global commodities in above described markets. By consequences I mean 1) Consequences for the setup of the investigated product system – which processes and related product systems are considered as affected and 2) Consequences for the result of the LCA. I find this relevant because environmental issues and life cycle approach increasingly find its way into decision support to regulations. Examples on actors in the global market that promote the life cycle approach to politics are the UN, the EU and OECD who emphasize implementation of integrated product policy (The Commission, 2001 and UN, 1999).

2 Goal and scope definition

The purpose of the LCA cases presented in this article is to elaborate on the aspects of system delimitation in LCAs of large material flows of vegetable oils, explained in the latter. However, the presented LCA screenings have an other purpose as a part of a Ph.D. study: Life cycle assessment of vegetable oils in Denmark and Malaysia, see below. For further information, see Schmidt (2003).

2.1 Goal and functional unit

Purpose

The purpose of the comparative LCA screening of rapeseed oil and palm is to assess the environmental impact of a globalization of the European supply of vegetable oils. In this respect rapeseed oil is considered to represent the local alternative, whereas palm oil represents the global alternative. The import share and amount of supply of vegetable oil to the EU has increased significantly since the mid-nineties (FAOSTAT, 2004). The main part of the increase in imported oil can be ascribed to import of palm oil. The application of edible oils depends on the fatty acid composition. However, modifications such as fractionalization, winterization, interesterification and hardening enable substitution of many oils for several applications (Hamm and Hamilton, 2000). According to Wan (1991) palm, soy, rapeseed and sunflower seed oils tend to be the crops that meet generalized demands for oils, whatever market is left for specialty fats and oils. Palm oil and rapeseed oil are selected as cases because they belong to the three most important vegetable oils in the world market that can meet generalized demands for oils. In 2003 the world’s production of the three edible oils was: soy oil (31 mill tons), palm oil (28 mill tons) and rapeseed oil (12 mill tons) (FAOSTAT, 2004). It is chosen not to focus on soy oil since the production is determined by the demand for soy protein and not the oil (Weidema, 1999).

Attended application

The LCA provides information on potential improvements and unattended impacts in the product chains (hotspots) and information on the overall environmental performance of the two commodities enabling comparison. Thus, the LCA provides information on the environmental effect of a global production and consumption pattern. The results are aimed to provide information in regulatory decisions (which include international as well as regional, national and local regulations). Examples could be WTO decisions on free trade, EU’s import duties, agricultural subsidies, environmental protection regulation and national spatial planning and environmental regulation.

Functional unit

The functional unit is 1 kg edible crude oil. This is considered to represent an increase of either rapeseed oil from Denmark or palm oil from Malaysia in order to meet the increasing demand for fats and oils in the European market. Rapeseed oil and palm oil are considered as substitutable in most cases. Even though the two oils have a different content of fatty acids modification of the oils enable substitution. This LCA does not include an analysis of additional modification of the two oils in order to make them complete substitutable.

2.2 Scope of the study and data

The performed LCA is a so called screening. In this case it implies that the aggregate level of crop cultivators and oil mills are on average by sectors/countries and not by actual suppliers. Furthermore the inventory is based on (manipulated) existing data from previously LCAs and LCI databases. The product systems for rapeseed oil and palm oil are shown in figure 1. Figure 1 also illustrates which processes that are tested for consequential versus attributional approach – yellow boxes.

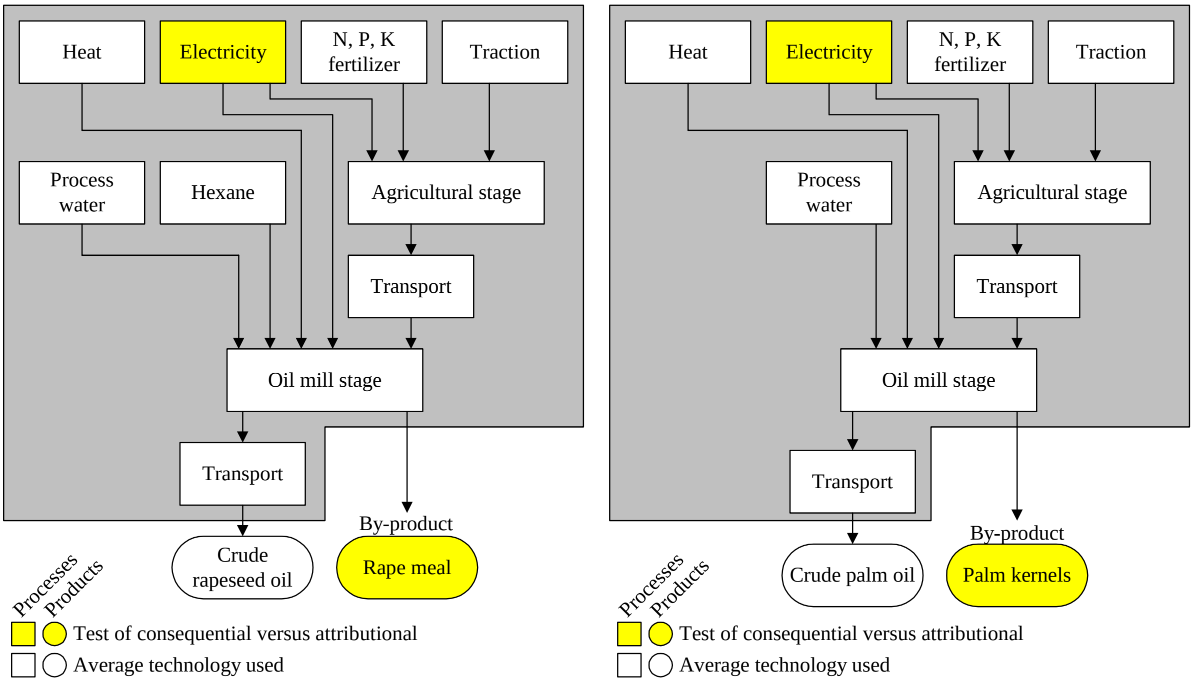

Figure 1: *Product system for crude rapeseed oil and palm oil. The yellow boxes represent processes/products that are tested for consequential versus attributional system delimitation.*

The system delimitation for rapeseed oil and palm oil (both consequential and attributional approach) is described in section 3 and 4 respectively.

2.3 Method for life cycle impact assessment (LCIA)

In the LCIA the data from the inventory phase are evaluated. All the exchanges are assigned to a number of selected impact categories, e.g. global warming, acidification and ozone depletion. The general guidelines in LCIA are described in ISO 14042. However, the ISO standards do not suggest a specific method for the LCIA. In this study the Danish method EDIP96 is used. The EDIP method is described in Wenzel et al. (1997) and Hauschild and Wenzel (1998). EDIP96 is available in the PC-tool SimaPro. The impact assessment is typically performed in three steps: Characterization, normalization and weighting. This study only includes the characterization step since the normalization and weighting steps are not necessary in order to draw conclusions on the research question in this study. Furthermore the normalization and weighting steps cause increased uncertainty.

The included impact categories are global warming, eutrophication, acidification and land use. Since EDIP does not include land use it is chosen to perform this in accordance to the method described in Weidema and Lindeijer (2001). Beside the included impact categories EDIP includes the impact categories human toxicity, ecotoxicity, ozone depletion, photochemical smog and waste. It is chosen not to include these impacts categories because the LCI data are considered most reliable in relation to the selected categories.

The use of the impact category land use has not been widespread, but in recent years more attention has been given to this aspect of the impact on the environment. Thus, it not clear how land use has been adopted in traditional LCAs (attributional system delimitation). Mattsson et al (2000) and Weidema and Lindeijer (2001) suggest that both occupied and transformed land are to be included, which also will be the case in this study. According to personal communication with Bo Weidema (2004) the main difference between attributional and consequential system delimitation concerning land use is, that the attributional approach only allocate land transformation to these crops which actually expand on expense of nature, e.g. soy and oil palms. The consequential approach implies that it is taken into account that expanding crops may influence the cultivation of other crops.

3 Product system delimitation for rapeseed oil

The included processes in the product system for crude rapeseed oil are described in table 1.

Process/product	Technology (consequential approach)	Technology (attributional approach)
Electricity	Natural gas	Average Danish electricity: Coal (47%), natural gas (25%), wind (11%), Oil (11%), biomass/waste (6%). Co-produced electricity and heat is allocated by energy content.
Co-product: Rape meal/cake	Co-product allocation avoided by system expansion. Affected products: Rapeseed oil and meal, soy oil and meal.	Co-product allocation by economic value
Agricultural stage	Danish average technology around 2000	
Oil mill stage	Danish technology (Aarhus Oil Mill)	
Heat	Heat from natural gas	
N, P, K fertilizer	Eastern European average technology in the 1990ies	
Traction	Diesel engines applied in agriculture for processes such as ploughing, harrowing, sowing and harvesting, average Danish traction	
Process water	Danish average technology for drinking water	
Hexane	Average technology for inorganic chemicals	
Transport	Average technology for diesel truck	

***Table 1:** Included processes in the product system for crude rapeseed oil. Marginal technologies are identified in Weidema (2003). Data for average electricity are from 2001 and based on IEA (2004).*

3.1 Consequential: System expansion

Rapeseed oil is co-produced with rape meal. The output from the oil mill stage in Denmark is 1.4 kg rapeseed meal per kg rapeseed oil (LCAfood, 2003). Rape meal is utilized as fodder in animal breeding. Weidema (1999) identify soy protein as the most sensitive supplier of protein for animal fodder. Therefore the dependant co-product rape meal displaces soy protein in Argentina (LCAfood, 2003). However, in LCAfood (2003) it is suggested that the avoided fodder production is 80% soy meal and 20% spring barley (by weight). For simplification reasons in this study, rape meal is assumed to replace only soy meal. According to Møller et al. (2003) the nutritional value in 1 kg rape meal is 1.06 FU (fodder units) and 1.19 FU per kg soy meal. Soy protein is co-produced with soy oil. In this process soy protein is the determining product and soy oil is the dependant product. The displaced soy protein causes that some soy oil also will be displaced. The output from soy production is 4.6 kg soy meal per kg soy oil (LCAfood, 2003). The displaced soy oil will then cause an increase in the most sensitive alternative oil production. According to Weidema (1999) rape oil is the cheapest edible oil with a fatty acid composition that makes it substitutable with soy oil in most applications.

The specific calculations are performed with linear algebra as two equations with two unknowns. The total product output from the rapeseed processing (edible oil plus meal) measured in kg oil and FU meal is named x and the total product output from the soy processing is named y. The notions $\text{oil}_{\text{rape/soy}}$ and $\text{meal}_{\text{rape/soy}}$ denote the relative output which is 1.48 FU rape meal per kg rapeseed oil and 5.47 FU soy meal per kg soy oil. The desired product output is 1 kg edible oil and 0 FU protein meal. Hence the two co-producing processes can be described as follow:

$$
\begin{array}{ccccc}
\text{oil}_{\text{rape}} \cdot x & + & \text{oil}_{\text{soy}} \cdot y & = & 1 \\
\text{meal}_{\text{rape}} \cdot x & + & \text{meal}_{\text{soy}} \cdot y & = & 0
\end{array}
$$

Applying the co-product ratio for the two processes the following equation system appears (the production of protein meal is calculated as the meal production multiplied with the nutritional value):

$$
\begin{array}{ccccc}
1 \cdot x & + & 1 \cdot y & = & 1 \\
1.48 \cdot x & + & 5.47 \cdot y & = & 0
\end{array}
$$

Using Gauss-Jordan elimination x and y can be found as $x = 1.37$ and $y = -0.37$. Hence the output from the rapeseed processing is 1.4 kg oil and 2.0 FU protein meal (equivalent to 1.9 kg rapeseed meal). Thus, the total output from the rapeseed mill is 3.3 kg oil and meal. The output from soy processing (avoided production) is -0.4 kg oil and -2.0 FU protein meal (equivalent to -1.7 kg soy meal). Thus, the output from the soy mill is 2.1 kg).

3.2 Attributional: Economic co-product allocation

Using the attributional system delimitation, co-product allocation can be performed in different ways, i.e. by energy content or by economic value. It is chosen to allocate by economic value since this method reflects the incentives for the process. According to Pileman et al. (2003) 57% of turnover from a Danish rapeseed mill can be ascribed to the rapeseed oil and 43% to the meal.

3.3 Product flow related to 1 kg rapeseed oil

Table 2 summarizes the product flow in the consequential and the attributional approach respectively. The data in table 2 together with the data given in appendix A and B form the life cycle inventory (LCI) for rapeseed oil, which is keyed into SimaPro.

Stage	Consequential: Product flow related to 1 kg crude rapeseed oil	Attributional: Product flow related to 1 kg crude rapeseed oil
Output from Agricultural stage		
Rapeseed from farm	3.3 kg	1.4 kg
Output from rape oil mill stage		
Rapeseed oil	1.4 kg	1 kg
Rape meal	1.9 kg	0 kg
Avoided products: Output from soy agricultural stage and mill stage		
Soy beans from farm	-2.1 kg	
Soy oil	-0.4 kg	-
Soy meal	- 1.7 kg	-

Table 2: *Product flow in the different stages related to 1 kg crude rapeseed oil.*

4 Product system delimitation for palm oil

The included processes in the product system for crude palm oil are described in table 3.

Process/product	Technology (consequential approach)	Technology (attributional approach)
Electricity	Natural gas	Malaysian average electricity: Coal (3%), natural gas (78%), Oil (9%), hydro (10%). Co-produced electricity and heat is allocated by energy content.
Co-product: Palm kernels	Co-product allocation avoided by system expansion. Affected products: Palm kernel oil and meal, coconut oil and meal, rapeseed oil and meal, soy oil and meal.	Co-product allocation by economic value
Agricultural stage	Average Malaysian technology in the 1990ies	
Oil mill stage	Average Malaysian technology in the 1990ies	
Heat	Heat from oil	
N, P, K fertilizer	Eastern European average technology in the 1990ies	
Traction	Average Danish traction	
Process water	Danish average technology for drinking water	
Transport	Average technology for diesel truck and oceanic freighter	

Table 3: *Included processes in the product system for crude palm oil. Marginal technology for electricity in Malaysia is assumed to be based on natural gas, since an increase in the demand for electricity from 1985 to 2001 (~400% increase) has been met almost entirely by increase in electricity from gas (IEA, 2004). Data for average electricity are from 2001 and based on IEA (2004).*

4.1 Consequential: System expansion

The output from the oil mill stage in Malaysia is 0.27 kg palm kernels per kg crude palm oil extracted (MPOB, 2004b). The palm kernels are transported and further processed into palm kernel oil and palm kernel meal. The output from the palm kernel mill is 0.45 kg palm kernel oil and 0.52 kg palm kernel meal per 1 kg palm kernels processed (MPOB, 2004b). The nutrient value of 1 kg palm kernel meal is 0.79 FU (Møller et al., 2000, p. 14). According to USDA (1999) palm kernel oil is coconut oil's principle substitute for lauric acid. Hence, the 0.12 kg produced palm kernel oil is assumed to substitute 0.12 kg coconut oil. Coconut oil is co-produced with coconut meal which is used as animal fodder. The nutrient value of 1 kg coconut meal is 1.03 FU (Møller et al., 2000, p. 14). The output from the coconut mill is 0.6 kg meal per kg oil (Zah and Hischier, 2003). The input to the coconut mill is 6 kg nuts per kg copra (Unilever, 1990). The copra is entirely processed into oil and meal.

As in the case of rapeseed meal, soybean meal is considered as the most sensitive supplier of protein for animal fodder. Therefore the dependant co-product coconut meal displaces soy protein. The system expansion for the co-produced soybean oil is described under the case of rapeseed oil. From the above the following production in the palm oil mill, the palm kernel oil mill and the coconut oil mill can be deduced.

Processes	Oil	Meal (by weight)	Meal (be nutrient value)	Total output (by weight)
Palm oil mill	1 kg	0 kg	-	1.27 kg oil and nuts
Palm kernel oil mill	0.12 kg	0.14 kg	0.11 FU	0.26 kg lauric oil and meal
Coconut oil mill	-0.12 kg	-0.072 kg	-0.074 FU	-0.21 kg lauric oil and meal

Table 4: *Output from the palm oil mill, the palm kernel oil mill and the coconut oil mill.*

From table 4 it is seen that the net production of meal per kg crude palm oil is 0.037 FU. Thus, production of 0.037 FU soy meal is avoided. The affected amount of production of soy oil/meal and rapeseed oil/meal are calculated as in the case of rapeseed oil:

$$\begin{aligned} \text{oil}_{\text{rape}} \cdot x &+ \text{oil}_{\text{soy}} \cdot y &= 0 \\ \text{meal}_{\text{rape}} \cdot x &+ \text{meal}_{\text{soy}} \cdot y &= -0.037 \end{aligned}$$

Applying the co-product ratio for the two processes the following equation system appears:

$$\begin{aligned} 1 \cdot x &+ 1 \cdot y &= 0 \\ 1.48 \cdot x &+ 5.47 \cdot y &= -0.037 \end{aligned}$$

Using Gauss-Jordan elimination x and y can be found as $x = 0.0092$ and $y = -0.0092$. Hence the output from the rapeseed processing is 0.0092 kg oil and 0.013 FU protein meal (equivalent to 0.012 kg rapeseed meal). Thus, the total output from the rapeseed mill is 0.021 kg oil and meal. The output from soy processing (avoided production) is -0.0092 kg oil and -0.050 FU protein meal (equivalent to -0.042 kg soy meal). Thus, the output from the soy mill is -0.051 kg.

4.2 Attributional: Economic co-product allocation

As in the case of rapeseed oil, it is chosen to allocate by economic value. According to MPOB (2004a) the price during 1st to 15th august 2004 for crude palm oil is 1459 RM/ton and for palm kernels it is 1004 RM/ton. Thus, 84% of the turnover from a Malaysian palm oil mill can be ascribed to the palm oil and 16% to the palm kernels.

4.3 Product flow related to 1 kg palm oil

Table 5 summarizes the product flow in the consequential and the attributional approach respectively. The data in table 5 together with the data given in appendix C and D form the life cycle inventory (LCI) for palm oil, which is keyed into SimaPro.

Stage	Consequential: Product flow related to 1 kg crude palm oil	Attributional: Product flow related to 1 kg crude palm oil
Output from oil palm agricultural stage		
Fresh fruit bunch from plantation	4.6 kg	3.9 kg
Output from palm oil mill stage		
Palm oil	1 kg	1 kg
Palm kernels	0.27 kg	0 kg
Output from palm kernel mill		
Palm kernel oil	0.12 kg	-
Palm kernel meal	0.14 kg	-
System expansion: Output from rapeseed agricultural stage and mill stage		
Rapeseed from farm	0.0212 kg	
Rapeseed oil	0.0092 kg	-
Rapeseed meal	0.012 kg	-
Avoided products: Output from coconut agricultural stage and mill stage		
Copra from plantation (6 kg nuts)	-0.192 kg	
Coconut oil	-0.12 kg	-
Coconut meal	-0.072 kg	-
Avoided products: Output from soy agricultural stage and mill stage		
Soy beans from farm	-0.0512 kg	
Soy oil	-0.0092 kg	-
Soy meal	-0.042 kg	-

Table 5: *Product flow in the different stages related to 1 kg palm oil.*

5 Life cycle impact assessment (LCIA)

In this section the impact potentials from palm oil and rapeseed oil are assessed in order to enlighten the effects of the approach to system delimitation. Figure 2 shows the result of the comparative LCA-screening in terms of characterized impact categories. The results are shown for both oils when adopting the attributional approach as well as the consequential approach.

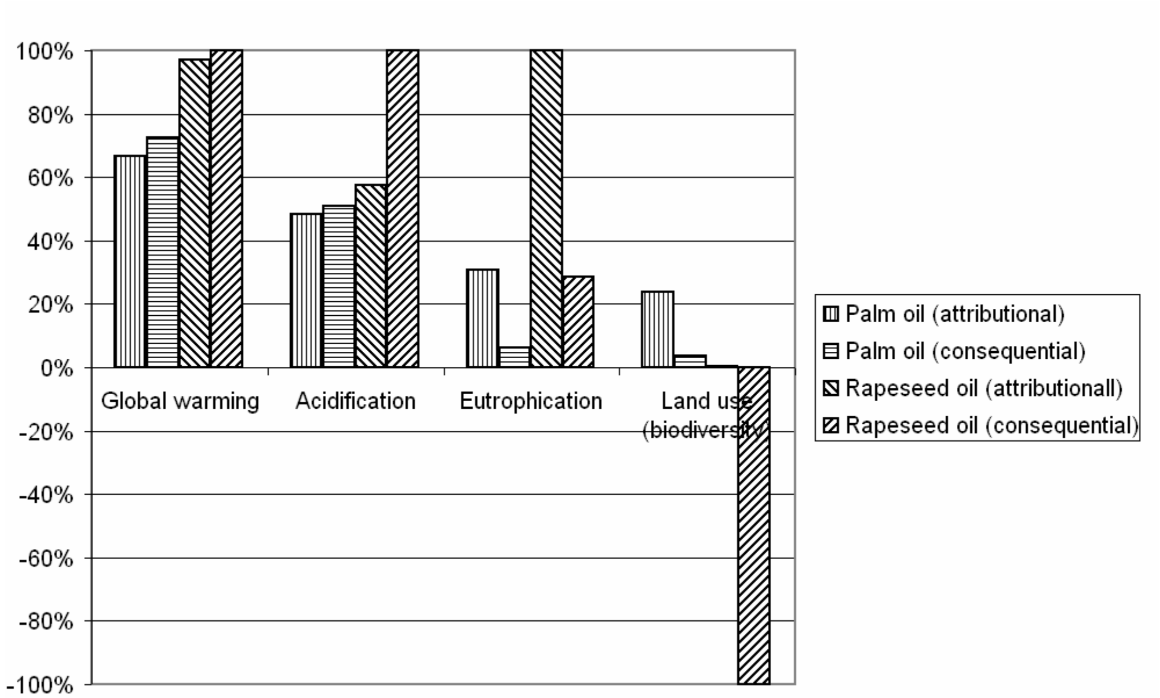

Figure 2: *1 kg palm oil compared with 1 kg rapeseed oil in terms of characterized impact categories. The results are shown for both oils when adopting the attributional approach as well as the consequential approach.*

As it appears from figure 3 the attributional and consequential LCAs gives significantly different results. For rapeseed oil the results vary with a factor from 1.03 for global warming to a factor ~200 for land use depending on the approach to system delimitation. For palm oil the results vary from a factor 1.04 for acidification to a factor 6 for land use. However, the approach to system delimitation does not change the overall result for any of the included impact categories when comparing rapeseed oil to palm oil.

In order to identify the most important factors causing the different results, the following elaborates on the contributions to each impact category in terms of substance contribution and process contribution.

5.1 Rapeseed oil

Table 6 shows the process contribution from rapeseed oil.

Stage	**Global warming ($kg\ CO_2$ eq.)**		**Acidification ($g\ SO_2$ eq.)**		**Eutrophication ($kg\ NO_3$ eq.)**		**Land use (m^2a)**	
	Consequential	**Attributional**	**Consequential**	**Attributional**	**Consequential**	**Attributional**	**Consequential**	**Attributional**
Rapeseed from farm	5340 g	2260 g	25.5 g	10.8 g	774 g	328 g	2410 Q_{bio}	1020 Q_{bio}
Rapeseed oil and meal from mill	370 g	138 g	1.0 g	1.0 g	1 g	1 g	-	-
Soy beans from farm	-2910 g	-	-1.4 g	-	-678 g	-	-215000 Q_{bio}	-
Soy oil and meal from mill	-323 g	-	-5.3 g	-	-3 g	-	-	-
Transport	23 g	23 g	0.2 g	0.2 g	0 g	0 g	-	-
Total	**2500 g**	**2421 g**	**20 g**	**12 g**	**94 g**	**329 g**	**-213590 Q_{bio}**	**1020 Q_{bio}**

Table 6: *Process contribution from 1 kg rapeseed oil.*

The agricultural stage is the most significant stage for all impact categories. It does not seem like there is any coherence between the displaced system in the consequential LCA and allocated share in the attributional LCA. In the case of acidification and eutrophication the overall results differ with a factor 1.7 and 3.5 respectively. The displaced system in the consequential system delimitation contributes to a significant share of the overall environmental performance of rapeseed oil.

Using the consequential as well as the attributional approach the most significant contribution to global warming is related to N_2O for rapeseed and soy bean (avoided emissions) in the agricultural stage, while it is CO_2 for other processes. For acidification ammonia from rapeseed agricultural stage is the most significant emission. But also NO_x and SO_2 from rapeseed and soy bean (avoided emissions) agricultural stage are significant. The most significant contributions to eutrophication are nitrate, ammonia and N_2O from rapeseed agricultural stage and nitrate and phosphate from soy agricultural stage (avoided emissions). The difference in impact on land use is determined of the impact from soy bean cultivation in Argentina. The larger scale of impact on land use in Argentina is due to transformation of natural forest, while increased production in Europe is met by using additional fertilizer. Furthermore the impact on biodiversity is larger in Argentina than Europe during the activity. The negative impact on land use, when using the consequential approach, is to be interpreted as saved transformation of natural forest. However, this does not imply that agricultural land is transformed into natural forest. The overall tendency is that the cultivated area in Argentina (arable land and permanent crops) has been expanding by 4000 km^2 per year from 1990 to 2002 (FAOSTAT, 2004). See appendix F for further description of characterization factors for land use.

5.2 Palm oil

Table 7 shows the process contribution from palm oil.

Stage	**Global warming (kg CO2 eq.)**		**Acidification (g SO2 eq.)**		**Eutrophication (kg NO3 eq.)**		**Land use (m2a)**	
	Consequential	**Attributional**	**Consequential**	**Attributional**	**Consequential**	**Attributional**	**Consequential**	**Attributional**
FFB from plantation	523 g	444 g	3.4 g	2.9 g	28.1 g	23.8 g	60000 Q_{bio}	50800 Q_{bio}
Palm oil and kernels from mill	1170 g	986 g	2.6 g	2.2 g	1.9 g	1.6 g	-	-
Palm kernel oil and meal from mill	22 g	-	0.0 g	-	0.0 g	-	-	-
Coconuts from plantation	-84 g	-	-0.4 g	-	-1.8	-	-46900 Q_{bio}	-
Coconut oil and meal from mill	-15 g	-	-0.0 g	-	0.0 g	-	-	-
Rapeseed from farm	34 g	-	0.2 g	-	5.0 g	-	16 Q_{bio}	-
Rapeseed oil from mill	2 g	-	0.0 g	-	0.0 g	-	-	-
Soy beans from farm	-71 g	-	0.0 g	-	-16.5 g	-	-5330 Q_{bio}	-
Soy oil and meal from mill	-8 g	-	-0.1 g	-	-0.1 g	-	-	-
Transport	236 g	236 g	4.7 g	4.7 g	3.4 g	3.5 g	-	-
Total	**1809 g**	**1666 g**	**10.4 g**	**9.8 g**	**20.0 g**	**28.9 g**	**7786 Q_{bio}**	**50800 Q_{bio}**

Table 7: *Process contribution from 1 kg palm oil.*

For global warming the palm oil mill tends to be the most significant process, while it is oil palm plantation that counts for the most significant contributions to eutrophication and land use. The transport stage is the most significant in the case of acidification. Even though the palm oil is transported 16,000 km it does not account for more than 13-14% of the total contribution to global warming. The affected processes identified by system expansion in the consequential system delimitation do not account as significantly as the displaced system in the rapeseed oil production.

For both the consequential and the attributional approach the most significant contribution to global warming is related to CH_4 from the palm oil mill, while CO_2 from the oil palm plantation and transport stage also are significant. For acidification SO_2 and NO_x from the transport stage and SO_2 from the palm oil mill are the most significant emissions. The most significant contributions to eutrophication are phosphate and nitrogen from the palm oil mill and avoided phosphate and nitrate from the soy bean agricultural stage. The difference in impact on land use is determined of the size of the affected and transformed oil palm and coconut palm plantations and soy bean cultivation. The low impact for the consequential approach is due to a low yield in the coconut cultivation, which implies that a relatively large area of arable land is displaced. See appendix F for further description of characterization factors for land use.

5.3 Key factors related to system delimitation that affect the result

The stages in the life cycle of rapeseed oil and palm oil that were tested for attributional versus consequential approach to system delimitation are: Electricity and co-product allocation. The following elaborates on the effect of adopting either the attributional or the consequential approach for these two issues. Furthermore it will be elaborated on the assumptions related to land use, which turned out to be the major factor considering different results achieved using the two approaches to system delimitation.

Co-product allocation

As described in sectors 5.2 and 5.3 it does not seem like there is any coherence between the displaced system in the consequential LCA and allocated share in the attributional LCA. The most significant difference between the displaced system and the share allocated to co-products is in the case of land use for rapeseed oil. The contributions to land use for the two approaches differ with up to a factor 200. Also within acidification and eutrophication significant differences are present.

Thus, it is concluded that handling co-products either by allocation or by system expansion has significant influence on the overall result. In spite of the inconsistency of existing available LCI data, future LCAs on global commodities clearly should assess the importance of adopting either the one or the other approach to system delimitation.

Energy

Energy is not assumed as an important factor causing different results depending on the approach to system delimitation. This statement is based on a test where the marginal energy in the consequential approach has been displaced with average energy as in the attributional approach, see table 8.

Impact category	**Effect on the overall environmental performance when energy in the consequential LCI is displaced with average energy**	
	Rapeseed oil	**Palm oil**
Global warming	-1%	0%
Acidification	+1%	0%
Eutrophication	0%	0%
Land use	0%	0%

Table 8: *Test: Effect on the overall environmental performance when energy in the consequential LCI is displaced with average energy. The used average energy is described in appendix E.*

The marginal electricity differs from the average electricity (in Denmark, Malaysia and Argentina) within the included impact categories with a factor 1.5 to 3. The reason why it has so little effect on the overall result is that the significant emissions that cause global warming, acidification and eutrophication are related to the agricultural cultivation (CH_4, N_2O, NH_4 and nitrate) and not the energy processes. This is considered as a general conclusion for agricultural commodities, since these emissions are relatively independent of the type of crops cultivated. Still, care should be taken in relation to electricity, especially when dealing with energy intensive products.

Land use

In this study it is assumed that an increase in production of palm oil, soy oil and coconut oil take place due to transformation of natural forest, while increased production of rapeseed oil in Europe is met by using additional fertilizer. Since the impact from land use heavily depend on whether natural nature is transformed or not, it may be questioned if above given assumptions are appropriate. In stead it could be assumed that increased production of palm oil, soy oil and coconut oil could take place due to utilizing old plantations and fields that are taken out of production (e.g. many palm oil plantations are grown on old rubber plantations, which are taken out of production because of the emerged technology for synthetic production of rubber). In the case of rapeseed it could be assumed that increased production was met by including set aside areas in the agricultural production. These changes could turn the picture in favour to palm oil. As indicated above it may be hard to identify the actual marginal affected land (nature type) and to collect data on agricultural regulations in the affected regions. Thus, it is concluded that great uncertainties related to system delimitation and impact on land use are present. And I argue that more attention should be given to this issue.

6 Conclusion

The purpose of this article is to investigate the consequences of adopting either the consequential or the attributional approach to system delimitation in a LCA of vegetable oils. This embraces both the consequences for the result of the LCA and the consequences for the setup of the investigated system – which processes and related product systems are considered as affected. Finally the added value by adopting the consequential approach in stead of the more traditional approach is of certain interest.

It is concluded that the results of the LCA heavily depend the system delimitation. However, adopting the one or the other approach does not change the overall conclusion that palm oil seems like a better environmental alternative than rapeseed oil concerning global warming, acidification and eutrophication, and that the opposite is the case concerning land use. But the contributions to the included impact categories vary with up to a factor 200 depending on the approach to system delimitation. The importance of adopting either the consequential or the attributional approach is tested for two issues: Marginal/average electricity and handling of co-products by system expansion/allocation. The most important factor concerning vegetable oils are identified as the handling of co-products. Using either marginal or average electricity is of less importance, since the emissions contributing to global warming, acidification and eutrophication mainly comes from the agricultural cultivation of crops.

The study of affected processes using either co-product allocation or system expansion shows significant differences. Using the attributional approach, the investigated system only includes the product systems for rapeseed oil and palm oil. Using the consequential approach, the product systems for four oil crops and five milling processes are included. Keeping the different LCA results in mind, the attributional LCA may be seen as a too simplified picture of reality, when dealing with decision support to political and regulatory decisions. On the other hand market forecasts, which are the prerequisite for system expansion, may also cause uncertainties in the result. As discussed in section 5.3 the assumptions that cause the differences within land use may be questioned due to difficulties in identifying the actual marginal affected land (nature type) and in collecting data on agricultural regulations in the affected regions.

This article shows that regulation of one commodity may affect several other commodities in the global market. Thus, applying regulation based on life cycle assessments may lead to undesired effects if not the consequential approach to system delimitation is taken into consideration. Hidden within the goal and scope definition, the attributional approach simply cuts off too many potential important side effects when dealing with global traded large material flows of substitutable commodities. On this background it is recommended to be extremely aware of the approach to system delimitation in LCA. In this respect it is of great importance to focus on the questions that the LCA is intended to answer. Thus, I see a need for more focus on the approach to system delimitation in the future - especially related to land use.

Appendix A: Inventory data for rapeseed oil – consequential system delimitation

This appendix provides the data and documentation of the life cycle inventory for rapeseed oil using the consequential approach to system delimitation.

Rapeseed - agricultural stage	Amount per 1 kg rapeseed	Source	Applied database/emission
Electricity	8.13 Wh	(LCAfood, 2003)	Electricity (natural gas) (LCAfood, 2003)
N-fertilizer	62.2 g	(LCAfood, 2003)	Fertilizer (N) (LCAfood, 2003)
P-fertilizer	8.49 g	(LCAfood, 2003)	Fertilizer (N) (LCAfood, 2003)
K-fertilizer	27.2 g	(LCAfood, 2003)	Fertilizer (P) (LCAfood, 2003)
Traction	1.21 MJ	(LCAfood, 2003)	Traction (LCAfood, 2003)
Ammonia	2.26 g	(LCAfood, 2003)	Emission to air
N_2O	2.62 g	(LCAfood, 2003)	Emission to air
Nitrate	129 g	(LCAfood, 2003)	Emission to water
Phosphate	7.78 g	(LCAfood, 2003)	Emission to water
Arable land use - occupied	3.8 m^2 a	(FAOSTAT, 2004)	Non-material emission
Arable land use – new land	0 m^2		Non-material emission

Table A.1: *Databases used to find emissions related to the included data categories in the product system for rapeseed oil – consequential system delimitation. The occupied land is calculated from a yield of 2633 kg rapeseed per hectare in Denmark 2003 (FAOSTAT, 2004).*

Rapeseed mill stage	Amount per 1 kg rapeseed oil and 1.4 kg rape meal	Source	Applied database/emission
Electricity	0,120 kWh	(LCAfood, 2003)	Electricity (natural gas) (LCAfood, 2003)
Heat	1.6 MJ	(LCAfood, 2003)	Heat (oil) (LCAfood, 2003)
Hexane	2.00 g	(LCAfood, 2003)	Chemicals inorganic (LCAfood, 2003)
Process water	0.200 l	(LCAfood, 2003)	Water (tap) (LCAfood, 2003)
Transport seeds from farm to oil mill	168 kgkm	(LCAfood, 2003)	Truck 28t (LCAfood, 2003)
Hexane	2.00 g	(LCAfood, 2003)	Emission to air

Table A.2: *Databases used to find emissions related to the included data categories in the product system for rapeseed oil – consequential system delimitation.*

Soybean agricultural stage	Amount per 1 kg soy beans	Source	Applied database/emission
P2O5-fertilizer	9.4	(LCAfood, 2003)	Fertilizer (P2O5) (LCAfood, 2003)
Traction	0.56 MJ	(LCAfood, 2003)	Traction (LCAfood, 2003)
N_2O	4.1 g	(LCAfood, 2003)	Emission to air
Nitrate	185 g	(LCAfood, 2003)	Emission to water
Phosphate	12 g	(LCAfood, 2003)	Emission to water
Arable land use - occupied	3.6 m^2 a	(LCAfood, 2003)	Non-material emission
Arable land use – new land	3.6 m^2		Non-material emission

Table A.3: *Databases used to find emissions related to the included data categories in the product system for rapeseed oil – consequential system delimitation. The occupied land is calculated from a yield of 2803 kg soy beans per hectare in Argentine 2003 (FAOSTAT, 2004).*

Soybean mill stage	Amount per 1 kg soy oil and 4.6 kg soy meal	Source	Applied database/emission
Hexane	0.376 g	(LCAfood, 2003)	Chemicals inorganic (LCAfood, 2003)
Transport of soy meal to Denmark	56 tkm	(LCAfood, 2003)	Freighter oceanic (LCAfood, 2003)
Heat	760 KJ	(LCAfood, 2003)	Heat (oil) (LCAfood, 2003)
	1480 KJ	(LCAfood, 2003)	Heat (gas) (LCAfood, 2003)
Electricity	64.7 Wh	(LCAfood, 2003)	Electricity (natural gas) (LCAfood, 2003)
Hexane	376 mg	(LCAfood, 2003)	Emission to air
CO_2	140 g	(LCAfood, 2003)	Emission to air
CO	22.7 mg	(LCAfood, 2003)	Emission to air
NO_x	169 mg	(LCAfood, 2003)	Emission to air
VOC	66.1 mg	(LCAfood, 2003)	Emission to air
SO_2	12.1 mg	(LCAfood, 2003)	Emission to air
Nitrate	0.02 mg	(LCAfood, 2003)	Emission to water

Table A.4: *Databases used to find emissions related to the included data categories in the product system for rapeseed oil – consequential system delimitation.*

Transport stage	Amount per 1 kg rapeseed oil	Source	Applied database/emission
Transport of oil from mill to further food processing	100 kgkm	Own estimate	Truck 28t (LCAfood, 2003)

Table A.5: *Databases used to find emissions related to the included data categories in the product system for rapeseed oil – consequential system delimitation.*

Appendix B: Inventory data for rapeseed oil – attributional system delimitation

This appendix provides the data and documentation of the life cycle inventory for rapeseed oil using the attributional approach to system delimitation.

Agricultural stage	Amount per 1 kg rapeseed	Source	Applied database/emission
Electricity in Denmark (8.13 Wh)	3.82 Wh (47% coal)	Data in these entries are based on table A.1. Data on electricity are described in appendix E.	Coal electricity and heat, energy content, 1997 (Eltra et al., 2000)
	2.03 Wh (25% natural gas)		Gas-CK energy content, 1997 (Eltra et al., 2000)
	0.894 Wh (11% wind)		Wind power electricity, 1997 (Eltra et al., 2000)
	0.894 Wh (11% oil)		Oil electricity and heat energy content, 1997 (Eltra et al., 2000)
	0.488 Wh (6% biomass/waste)		*Average of:* Waste electricity and heat (1997) energy content and Biomass electricity and heat (1997) energy content (Eltra et al., 2000)
	0.00 Wh (0% hydro)		-
	0.00 Wh (0% nuclear)		-
N-fertilizer	62.2 g		Fertilizer (N) (LCAfood, 2003)
P-fertilizer	8.49 g		Fertilizer (N) (LCAfood, 2003)
K-fertilizer	27.2 g		Fertilizer (P) (LCAfood, 2003)
Traction	1.21 MJ		Traction (LCAfood, 2003)
Ammonia	2.26 g		Emission to air
N_2O	2.62 g		Emission to air
Nitrate	129 g		Emission to water
Phosphate	7.78 g		Emission to water
Arable land use - occupied	3.8 m^2 a		Non-material emission
Arable land use – new land	0 m^2		Non-material emission

Table B.1: *Databases used to find emissions related to the included data categories in the product system for rapeseed oil – attributional system delimitation. Data in this table are based on the data presented in table A.1.*

Rapeseed mill stage	Amount per 1 kg rapeseed oil	Source	Applied database/emission
Electricity in Denmark (68.4 Wh)	32.1 Wh (47% coal)	The data in this table are based on table A.2. Data on electricity are described in appendix E.	Coal electricity and heat, energy content, 1997 (Eltra et al., 2000)
	17.1 Wh (25% natural gas)		Gas-CK energy content, 1997 (Eltra et al., 2000)
	7.52 Wh (11% wind)		Wind power electricity, 1997 (Eltra et al., 2000)
	7.52 Wh (11% oil)		Oil electricity and heat energy content, 1997 (Eltra et al., 2000)
	4.10 Wh (6% bio-mass/waste)		*Average of:* Waste electricity and heat (1997) energy content and Biomass electricity and heat (1997) energy content (Eltra et al., 2000)
	0.00 Wh (0% hydro)		-
	0.00 Wh (0% nuclear)		-
Heat	0.912 MJ		Heat (oil) (LCAfood, 2003)
Hexane	1.14 g		Chemicals inorganic (LCAfood, 2003)
Process water	0.114 l		Water (tap) (LCAfood, 2003)
Transport seeds from farm to oil mill	95.8 kgkm		Truck 28t (LCAfood, 2003)

Table B.2: *Databases used to find emissions related to the included data categories in the product system for rapeseed oil – attributional system delimitation. Data in this table are based on the data presented in table A.2 and allocation between rapeseed oil and meal according to economical co-product allocation as described in section 3.2.*

The LCI data for the transport stage are the same as for the consequential system delimitation, see table A.5.

Appendix C: Inventory data for palm oil – consequential system delimitation

This appendix provides the data and documentation of the life cycle inventory for palm oil using the consequential approach to system delimitation.

Oil palm - Agricultural stage	Amount per 1 kg fresh fruit bunch	Source	Applied database/emission
N-fertilizer (Urea)	4.7 g	(Unilever, 1990)	Fertilizer (N) (LCAfood, 2003)
P2O5-fertilizer	0.7 g	(Unilever, 1990)	Fertilizer (P2O5) (LCAfood, 2003)
KCl-fertilizer	11 g	(Unilever, 1990)	No LCI data available
MgSO4	1.0 g	(Unilever, 1990)	No LCI data available
Traction	0.62 MJ	(Zah and Hischier, 2003)	Traction (LCAfood, 2003)
N	0.47 g	(Unilever, 1990)	Emission to water
P	0.079 g	(Unilever, 1990)	Emission to water
Arable land use - occupied	0.55 m^2 a	(FAOSTAT, 2004)	Non-material emission
Arable land use – new land	0.55 m^2		Non-material emission

Table C.1: *Databases used to find emissions related to the included data categories in the product system for palm oil – consequential system delimitation. The occupied land is calculated from a yield of 18312 kg fresh fruit bunches per hectare in Malaysia 2003 (FAOSTAT, 2004).*

Palm oil mill	Amount per 1 kg palm oil and 0.27 kg palm kernels	Source	Applied database/emission
Process water	0.25 m^3	(Unilever, 1990)	Water (tap) (LCAfood, 2003)
Transport FFB from plantation to oil mill	0.1 MJ	(Unilever, 1990)	Traction (LCAfood, 2003)
PM > 10 μm	1.9 g	(Zah and Hischier, 2003)	Emission to air
PM > 2.5 μm & < 10 μm	2.6 g	(Zah and Hischier, 2003)	Emission to air
PM < 2.5 μm	1.5 g	(Zah and Hischier, 2003)	Emission to air
NOx	0.55 g	(Zah and Hischier, 2003)	Emission to air
NMVOC, unspecified	1.1 g	(Zah and Hischier, 2003)	Emission to air
SO_2	2.0 g	(Zah and Hischier, 2003)	Emission to air
CO	0.23 g	(Zah and Hischier, 2003)	Emission to air
CH_4	44 g	(Zah and Hischier, 2003)	Emission to air
N	0.19 g	(Zah and Hischier, 2003)	Emission to water

Table C.2: *Databases used to find emissions related to the included data categories in the product system for palm oil – consequential system delimitation. Data in this table from Zah and Hischier (2003) are based on Hirsinger et al (1995) where data are allocated by mass between palm oil, palm kernels and shells for road construction. Thus, the data in this table are found be calculating backwards using an allocation factor of 0.52 for palm oil.*

Palm kernel mill	Amount per 1 kg palm kernel oil and 1.15 kg palm kernel meal	Source	Applied database/emission
Mechanical energy (diesel motor)	0.072 MJ	(Unilever, 1990)	Traction (LCAfood, 2003)
Steam (produced from diesel)	0.74 MJ	(Unilever, 1990)	Heat (oil) (LCAfood, 2003)
Electricity from the grid	0.54 MJ	(Unilever, 1990)	Electricity (natural gas) (LCAfood, 2003)
Hexane	4.4 g	(Unilever, 1990)	Chemicals inorganic (LCAfood, 2003)
Transport from palm oil mill to palm kernel oil mill	-	No data available	-
Hexane	4.4 g	(Unilever, 1990)	Emission to air

Table C.3: *Databases used to find emissions related to the included data categories in the product system for palm oil – consequential system delimitation. Data in this table are based on the assumption that processing of 1 kg copra in a coconut oil mill is equal to the processing of 1 kg palm kernels in a palm kernel oil mill (Shonfield, 2004).*

Copra – agricultural stage	Amount per 1 kg copra	Source	Applied database/emission
N-fertilizer (Urea)	40.5 g	(Unilever, 1990)	Fertilizer (N) (LCAfood, 2003)
P2O5-fertilizer	40.5 g	(Unilever, 1990)	Fertilizer (P2O5) (LCAfood, 2003)
KCl-fertilizer	109 g	(Unilever, 1990)	No LCI data available
Traction	0.67 KJ	(Zah and Hischier, 2003)	Traction (LCAfood, 2003)
N	0.47 g	(Unilever, 1990)	Emission to water
P	0.079 g	(Unilever, 1990)	Emission to water
Arable land use - occupied	10.3 m^2 a	(FAOSTAT, 2004)	Non-material emission
Arable land use – new land	10.3 m^2		Non-material emission

Table C.4: *Databases used to find emissions related to the included data categories in the product system for palm oil – consequential system delimitation. The occupied land is calculated from a yield of 5843 kg coconuts per hectare in Indonesia 2003 since this is the most important supplier of coconuts (approx 30% of the world production) (FAOSTAT, 2004). According to Unilever (1990) there is an input of 6 kg coconuts per kg copra.*

Coconut mill	Amount per 1 kg coconut oil and 0.6 kg coconut meal	Source	Applied database/emission
Mechanical energy (diesel motor)	0.05 MJ	(Unilever, 1990)	Traction (LCAfood, 2003)
Steam (produced from diesel)	0.52 MJ	(Unilever, 1990)	Heat (oil) (LCAfood, 2003)
Electricity from the grid	0.38 MJ	(Unilever, 1990)	Electricity (natural gas) (LCAfood, 2003)
Hexane	3.1 g	(Unilever, 1990)	Chemicals inorganic (LCAfood, 2003)
Transport from coconut plantation to mill	0.03 MJ	(Unilever, 1990)	Traction (LCAfood, 2003)
Hexane	3.1 g	(Unilever, 1990)	Emission to air

Table C.5: *Databases used to find emissions related to the included data categories in the product system for palm oil – consequential system delimitation.*

Transport stage	Amount per 1 kg palm oil	Source	Applied database/emission
Transport of palm oil from mill to harbour in MY	100 kgkm	Own estimate	Truck 40t (LCAfood, 2003)
Transport of palm oil from Singapore to Hamburg	16,000 kgkm	www.distances.com	Freighter oceanic (LCAfood, 2003)
Transport of palm oil from Hamburg to Aarhus for further food processing	340 kgkm	www.krak.dk	Truck 28t (LCAfood, 2003)

Table C.6: *Databases used to find emissions related to the included data categories in the product system for palm oil – consequential system delimitation.*

For inventory data for rapeseed oil/meal and soy oil/meal, see appendix A.

Appendix D: Inventory data for palm oil – attributional system delimitation

This appendix provides the data and documentation of the life cycle inventory for palm oil using the attributional approach to system delimitation.

Oil palm - Agricultural stage	Amount per 1 kg fresh fruit bunch	Source	Applied database/emission
N-fertilizer (Urea)	4.7 g	The data in these entries are based on table C.1.	Fertilizer (N) (LCAfood, 2003)
P2O5-fertilizer	0.7 g		Fertilizer (P2O5) (LCAfood, 2003)
KCl-fertilizer	11 g		No LCI data available
MgSO4	1.0 g		No LCI data available
Traction	0.62 MJ		Traction (LCAfood, 2003)
N	0.47 g		Emission to water
P	0.079 g		Emission to water
Arable land use - occupied	0.55 m^2 a		Non-material emission
Arable land use – new land	0.55 m^2		Non-material emission

Table D.1: *Databases used to find emissions related to the included data categories in the product system for palm oil – attributional system delimitation. Data in this table are based on the data presented in table C.1.*

Palm oil mill	Amount per 1 kg palm oil	Source	Applied database/emission
Process water	0.21 m^3	The data in this table are based on table C.2.	Water (tap) (LCAfood, 2003)
Transport FFB from plantation to oil mill	0.084 MJ		Traction (LCAfood, 2003)
PM > 10 μm	1.6 g		Emission to air
PM > 2.5 μm & < 10 μm	2.2 g		Emission to air
PM < 2.5 μm	1.3 g		Emission to air
NOx	0.46 g		Emission to air
NMVOC, unspecified	0.92 g		Emission to air
SO_2	1.7 g		Emission to air
CO	0.19 g		Emission to air
CH_4	37 g		Emission to air
N	0.16 g		Emission to water

Table D.2: *Databases used to find emissions related to the included data categories in the product system for palm oil – attributional system delimitation. Data in this table are based on the data presented in table C.2 and allocation between palm oil and palm kernels according to economical co-product allocation as described in section 4.2.*

The LCI data for the transport stage are the same as for the consequential system delimitation, see table C.6.

Appendix E: Electricity technologies

The technologies applied for electricity differ with respect to the approach to system delimitation and the region of electricity production. When adopting the consequential approach marginal electricity is applied while average electricity is applied when adopting the attributional approach. The affected regions are Denmark, Malaysia and Argentina. In the following the differences are described.

E.1 Applied technology when the consequential approach is applied

The marginal technology/supplier of electricity of small and medium scale changes in the long term is characterized by:

- It is able to change its production volume. I.e. there are no constraints determining its production volume, e.g. CO_2 quotas
- It is the most competitive processes in increasing markets or the least competitive supplier in decreasing markets

The changes investigated in this study are on the small to medium scale. Large scale changes are characterized by that they may affect production costs and/or constraints. Thus, the marginal technologies may change as a function of the investigated change. Even though a total shift from the present composition of vegetable oils in the EU to either only rapeseed oil or palm oil, it would not affect the overall market trend of electricity consumption in any of the affected regions.

In all affected regions the overall market trend is increasing (IEA, 2004). In this respect, Denmark is considered as a part of the European Union, since its grid is connected to other EU countries.

Renewable energy (solar energy, wind power, biomass, waste incineration, hydro power etc.) in most cases are constrained by political regulations and the availability of renewable resources. Furthermore they do not represent the most competitive process. Thus, renewable energi is not considered as marginal technologies. The same is the case of nuclear power, which is constrained by political regulations. Thus the marginal technologies are based on fossil fuel. According to Weidema (2003) heavy fuel oil and natural gas in small plants represent the least competitive suppliers. Hence the marginal suppliers are either coal or natural gas (large plant) based.

In the EU the share of coal based electricity has been rather constant/decreasing from 1991 to 2001, while the production of natural gas based electricity has been increasing three fold (IEA, 2004). Hence, electricity based on natural gas is considered as the marginal technology for electricity in the long term in the EU.

In Malaysia the share of coal based electricity has been constant from 1991 to 2001 and is of only a minor importance. The production of natural based electricity has increased around six fold from 1991 to 2001 and amounts 78% of the total electricity production (IEA, 2004). Hence, the marginal technology for Malaysian electricity is considered as natural gas based.

In Argentina the share of coal based electricity has been constant from 1991 to 2001 and is of only a minor importance. The production of natural based electricity has increased two fold from 1991 to 2001 and amounts 47% of the total electricity production (IEA, 2004). Hence, the marginal technology for electricity in Argentina is also considered as natural gas based.

According to Weidema (2003) technologies that are co-producing heat with electricity are not relevant for marginal power plant. It is assumed that the marginal natural gas fired gas plants in Denmark, Malaysia and Argentina has the same energy efficiency. Thus, the applied electricity process from LCI database in SimaPro is the same for all three countries: Electricity (natural gas) (LCAfood, 2003).

E.2 Applied technology when the attributional approach is applied

Adopting the attributional approach imply that average technology is applied. The average technology for electricity production in Denmark, Malaysia and Argentina is given in table E1 below.

Technology	Denmark	Malaysia	Argentina
Coal	47%	3%	2%
Natural gas	25%	78%	47%
Wind	11%	0%	0%
Oil	11%	9%	2%
Biomass/waste	6%	0%	0%
Hydro	0%	10%	41%
Nuclear	0%	0%	8%
Total	**100%**	**100%**	**100%**

Table E1: *Share of different technologies for electricity in Denmark, Malaysia and Argentina in 2001. (IEA, 2004)*

Electricity production in Denmark is almost entirely based on CHP (combined heat and power) plants, where electricity is co-produced with heat (92% of the coal based energy plants are CHP and 96% of the natural gas based energy plants are CHP) (IEA, 2004). This increases the overall energy efficiency from 30-50% to 90-95% (Danish Energy Authority, 2004). In Malaysia and Argentina there are no CHPs in the energi system. Thus, different processes from LCI databases in SimaPro are to be applied for the same energy technology dependant of the region.

A LCA study of Danish electricity and heat has been conducted in 2000 (Eltra et al., 2000). The LCI data from this study can only be imported into the pc-tool EDIP. However PRè Consultants who is the vendor of SimaPro provides a conversion tool, so that the EDIP database can be converted into a SimaPro database. Eltra et al. (2000) provides the opportunity to perform co-product allocation between heat and electricity either by energy content or by exergy. In this study it is chosen to adopt the data allocated by the energy content method. Table E2 gives the LCI processes applied as Danish electricity.

Technology	LCI process (Denmark)
Coal	Coal electricity and heat, energy content, 1997 (Eltra et al., 2000)
Natural gas	Gas-CK energy content, 1997 (Eltra et al., 2000)
Wind	Wind power electricity, 1997 (Eltra et al., 2000)
Oil	Oil electricity and heat energy content, 1997 (Eltra et al., 2000)
Biomass/waste	*Average of:* Waste electricity and heat (1997) energy content and Biomass electricity and heat (1997) energy content (Eltra et al., 2000)
Hydro	Not used in Denmark
Nuclear	Not used in Denmark

Table E2: *Applied LCI data for Danish technology. CHP plants.*

Since the LCI data in Eltra et al. (2000) are based on co-producing heat and electricity plants, these data are not suitable for electricity in Malaysia and Argentina. Table E3 gives the data applied for electricity (non CHP) in these countries.

Technology	LCI process (Malaysia and Argentina)
Coal	Electricity coal power plant UCPTE (ETH, 1996)
Natural gas	Electricity gas power plant in UCPTE (ETH, 1996)
Wind	Not used in Malaysia and Argentina
Oil	Electricity oil UCPTE (ETH, 1996)
Biomass/waste	Not used in Malaysia and Argentina
Hydro	Electrcity hydropower in UCPTE (ETH, 1996)
Nuclear	Electrcity nuclear power plant UCPTE (ETH, 1996)

Table E3: *Applied LCI data for electricity in Malaysia and Argentina. Non CHP plants.*

Appendix F: Land use impact potentials

The calculations of land use impacts are based on Weidema and Lindeijer (2001).

The impact potential, I_{occ} is calculated from the formula:

$$I_{occ} = A \cdot t \cdot \frac{\left(Q_{pot} - Q_{act}\right)}{s}$$

Where A is the area occupied, t is the period of occupation also including relaxation period, Q_{pot} is the indicator value for the relaxation potential, Q_{act} is the indicator value during human activity and s is a slope factor to reflect that during the relaxation period Q_{act} gradually approach Q_{pot}.

In Weidema and Lindeijer (2001) I_{occ} is conducted for both ecosystem productivity and biodiversity. In this article only I_{occ} for biodiversity is calculated because of lack of data for calculating I_{occ} for ecosystem productivity. The impact potential for both types is calculated as the sum of impact during activity and impact during relaxation.

F.1 Land use in rapeseed cultivation

In the case of impacts from rapeseed the marginal production implies no transformation of natural biome. According to Weidema (2003) the European market is considered as closed geographical market due to border tariffs. Thus, increased demand for rapeseed can be met either by increased productivity by using additional fertilizer or occupation of set aside areas. The current trend is that agricultural land is taken out of cultivation in Europe. Due to limits on fertilizer per ha in some areas in the EU, rapeseed cultivation is considered a postponement of relaxation in the natural biome (temperate forest).

Table F1 gives the elements used in the calculation of the impact potential for rapeseed fields.

Elements in the calculation	**Impact on biodiversity**
	During activity
Area, A	1 m^2
Time, t	1 year
Potential quality, Q_{pot}	192
Actual quality, Q_{act}	0
Slope factor, s	1
Occupation impact, I_{occ}	**192 $Q_{biodiversity}$-weighted m^2**

Table F1: *Calculation of occupation impact, I_{occ}, from cultivation of rapeseed on 1 m^2. A yield of 263 g rapeseed per m^2a implies an occupied area of 3.8 m^2a per kg FFB. The value of each element is documented below.*

The duration of the activity is 1 year. As there is no transformation, there is no relaxation period allocated to the cultivation of rapeseed.

The potential quality for biodiversity, Q_{pot}, is calculated from the formula given below:

$$Q_{pot,biodiversity} = \frac{SR}{SR_{\min}} \cdot \frac{A_{pot,\max}}{A_{pot}} \cdot \left(\frac{A_{exi}}{A_{pot}}\right)^{-0.85} \quad \text{(Weidema and Lindeijer, 2001, p 28)}$$

SR = 1000 species/10,000 km^2 tropical forest (Weidema and Lindeijer, 2001, p 44)
SR$_{min}$ = 100 species/100 km^2 (Weidema and Lindeijer, 2001, p 43)
A$_{pot,max}$ = 25.3·10^6 km^2 (Weidema and Lindeijer, 2001, p 26)
A$_{pot}$ = 6.2·10^6 km^2 tropical rain forest (Weidema and Lindeijer, 2001, p 36)
A$_{exi}$ = 1.0·10^6 km^2 tropical rain forest (Weidema and Lindeijer, 2001, p 36)

F.2 Land use in oil palm plantations

An increase in the demand for palm oil is met by transformation of natural biome (tropical forest) into oil palm plantations.

Table F2 gives the elements used in the calculation of the impact potential for oil palm plantations.

Elements in the calculation	**Impact on biodiversity**	
	During activity	During relaxation
Area, *A*	1 m^2	1 m^2
Time, *t*	1 year	300 years
Potential quality, Q_{pot}	157	157
Actual quality, Q_{act}	0	0
Slope factor, *s*	1	2
Occupation impact, I_{occ}	**23.7·10^3 Q$_{biodiversity}$-weighted m^{2}a**	

Table F2: *Calculation of occupation impact, I_{occ}, from growing oil palms on 1 m^2. A yield of 1.83 kg FFB per m^{2}a implies an occupied area of 0.55 m^{2}a per kg FFB. The value of each element is documented below.*

Relaxation time for latitude 0° is 300 years for biodiversity. (Weidema and Lindeijer, 2001, p 41-42)

The potential quality for biodiversity, Q_{pot}, is calculated from the formula given below:

$$Q_{pot,biodiversity} = \frac{SR}{SR_{\min}} \cdot \frac{A_{pot,\max}}{A_{pot}} \cdot \left(\frac{A_{exi}}{A_{pot}} \right)^{-0.85}$$ (Weidema and Lindeijer, 2001, p 28)

SR = 2500 species/10,000 km^2 tropical forest (Weidema and Lindeijer, 2001, p 43)
SR$_{min}$ = 100 species/100 km^2 (Weidema and Lindeijer, 2001, p 43)
A$_{pot,max}$ = 25.3·10^6 km^2 (Weidema and Lindeijer, 2001, p 26)
A$_{pot}$ = 5.7·10^6 km^2 tropical rain forest (Weidema and Lindeijer, 2001, p 36)
A$_{exi}$ = 3.8·10^6 km^2 tropical rain forest (Weidema and Lindeijer, 2001, p 36)

F.3 Land use in soy cultivation

An increase in the demand for soy beans is met by transformation of natural biome (tropical forest) into agricultural land.

Table F3 gives the elements used in the calculation of the impact potential for oil palm plantations.

Elements in the calculation	**Impact on biodiversity**	
	During activity	During relaxation
Area, *A*	1 m^2	1 m^2
Time, *t*	1 year	360 years
Potential quality, Q_{pot}	157	157
Actual quality, Q_{act}	0	0
Slope factor, *s*	1	2
Occupation impact, I_{occ}	**$28.4 \cdot 10^3$ $Q_{biodiversity}$-weighted m^2a**	

Table F3: *Calculation of occupation impact, I_{occ}, from cultivation of soy beans on 1 m^2. A yield of 280 g soy beans per m^2a implies an occupied area of 3.6 m^2a per kg soybeans. The value of each element is documented below.*

Relaxation time for latitude 20° is 360 years for biodiversity (Soy cultivation in Argentina is situated approximate at latitude 30°. Weidema and Lindeijer (2001) consider 30° as dessert area. Thus, 20° are considered as a better estimate). (Weidema and Lindeijer, 2001, p 41-42)

The potential quality for biodiversity, Q_{pot}, is calculated from the formula given below:

$$Q_{pot,biodiversity} = \frac{SR}{SR_{\min}} \cdot \frac{A_{pot,\max}}{A_{pot}} \cdot \left(\frac{A_{exi}}{A_{pot}}\right)^{-0.85} \quad \text{(Weidema and Lindeijer, 2001, p 28)}$$

SR = 2500 species/10,000 km^2 tropical forest (Weidema and Lindeijer, 2001, p 43). The forest in north Argentina is sub tropical forest. No data for sub tropical forest are available. Thus, it is assumed to be the same as tropical forest.
SR_{min} = 100 species/100 km^2 (Weidema and Lindeijer, 2001, p 43)
$A_{pot,max} = 25.3 \cdot 10^6$ km^2 (Weidema and Lindeijer, 2001, p 26)
$A_{pot} = 5.7 \cdot 10^6$ km^2 tropical rain forest (Weidema and Lindeijer, 2001, p 36)
$A_{exi} = 3.8 \cdot 10^6$ km^2 tropical rain forest (Weidema and Lindeijer, 2001, p 36)

F.4 Land use in coconut plantations

An increase in the demand for coconuts is assumed to be met by transformation of natural biome (tropical forest) into oil palm plantations.

Table F4 gives the elements used in the calculation of the impact potential for oil palm plantations.

Elements in the calculation	**Impact on biodiversity**	
	During activity	During relaxation
Area, *A*	1 m^2	1 m^2
Time, *t*	1 year	300 years
Potential quality, Q_{pot}	157	157
Actual quality, Q_{act}	0	0
Slope factor, *s*	1	2
Occupation impact, I_{occ}	**$23.7 \cdot 10^3$ $Q_{biodiversity}$-weighted m^2a**	

Table F4: *Calculation of occupation impact, I_{occ}, from growing coconut palms on 1 m^2. A yield of 584 g coconuts from coconuts per m^2a implies an occupied area of 10.3 m^2a per kg copra. The value of each element is documented below.*

Relaxation time for latitude 0° is 300 years for biodiversity. (Weidema and Lindeijer, 2001, p 41-42)

The potential quality for biodiversity, Q_{pot}, is calculated from the formula given below:

$$Q_{pot,biodiversity} = \frac{SR}{SR_{\min}} \cdot \frac{A_{pot,\max}}{A_{pot}} \cdot \left(\frac{A_{exi}}{A_{pot}} \right)^{-0.85}$$ (Weidema and Lindeijer, 2001, p 28)

SR = 2500 species/10,000 km^2 tropical forest (Weidema and Lindeijer, 2001, p 43)
SR_{min} = 100 species/100 km^2 (Weidema and Lindeijer, 2001, p 43)
$A_{pot,max} = 25.3 \cdot 10^6$ km^2 (Weidema and Lindeijer, 2001, p 26)
$A_{pot} = 5.7 \cdot 10^6$ km^2 tropical rain forest (Weidema and Lindeijer, 2001, p 36)
$A_{exi} = 3.8 \cdot 10^6$ km^2 tropical rain forest (Weidema and Lindeijer, 2001, p 36)

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