Life cycle assessment of rapeseed oil and palm oil

Ph.D. thesis, Part 3: Life cycle inventory of rapeseed oil and palm oil

Schmidt, Jannick

Publication date:
2007

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Schmidt, J. (2007). *Life cycle assessment of rapeseed oil and palm oil: Ph.D. thesis, Part 3: Life cycle inventory of rapeseed oil and palm oil*. Department of Planning and Development, Aalborg University.

Life cycle assessment of rapeseed oil and palm oil

Ph.D. thesis, Part 3: Life cycle inventory of rapeseed oil and palm oil

Jannick H Schmidt

Department of Development and Planning
Aalborg University

Title: Life assessment of rapeseed oil and palm oil. Ph.D. thesis, Part 3: Life cycle inventory of rapeseed oil and palm oil

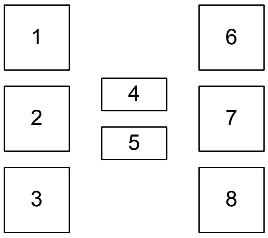
Author: Jannick Hoejrup Schmidt

Published by: Department of Development and Planning, Aalborg University

Distribution: http://vbn.aau.dk

Date: 15-jun-2007 (version for the assessment committe)

Cover: Fotos by:



1) Jannick H Schmidt, Rapeseed field near Aalborg, May 2007
2) Calle Schmidt, Rapeseed field in Northern Jutland, May 2007
3) Picture obtained from: http://jyndevad.okologgen.dk (Accessed May 2007)
4) Jannick H Schmidt, Rapeseed oil, June 2007
5) Jannick H Schmidt, Palm oil, May 2007
6) Jannick H Schmidt, United Plantations Berhad, Malaysia, November 2006
7) Jannick H Schmidt, United Plantations Berhad, Malaysia, November 2006
8) Jannick H Schmidt, United Plantations Berhad, Malaysia, August 2005

Preface

This report is published as part of the Ph.D. thesis: Life cycle assessment of rapeseed oil and palm oil. The thesis consists of three parts:

1. **Part 1: Summary report**
   The summary report describes the overall problem of the Ph.D. project, the research outline, summaries of the research and perspectives and recommendations.
2. **Part 2: Article collection (6 scientific articles)**
   The article collection presents the core of the scientific output of the Ph.D. project.
3. **Part 3: Life cycle inventory of rapeseed oil and palm oil**
   This life cycle inventory report provides and documents the background material for the scientific article: Comparative life cycle assessment of rapeseed oil and palm oil (published in part two of the thesis). This includes definition of system boundaries, the collected data, the modelling of the investigated system, sensitivity analyses and an evaluation of sensitivity, completeness and consistency. The inventory report has character of an appendix report to the life cycle assessment

The Ph.D. thesis was carried out at the Department of Development and Planning at Aalborg University. The project was initiated under the framework of the DUCED - I&UA project which is a Danish university consortium for environment and development. The thesis was supervised by professor Per Christensen and associate professor Eskild Holm Nielsen, Department of Development and Planning, Aalborg University.

Many people, companies and institutions have provided essential data, insights and great hospitality during meetings and longer stays which have made this study possible. Therefore, a special thanks goes to:

Carl Bek-Nielsen (Executive director of United Plantation), Dr. Gurmit Singh (Research director), Dr. Xaviar Arulandoo (Research controller), Dr. Mukesh Sharma (Research manager) and the rest of the Research Department at United Plantations Berhad, Teluk Intan, Malaysia

Jesper Korning (Quality manager), Lars Kronborg (Quality engineer), Anders Kromand Hansen (Engineer) and Anders Dahl (Trading Manager), AarhusKarlshamn, Aarhus, Denmark

Vijaya Subramaniam (Research officer), Engineering & Processing Division, Energy and Environment Unit, Malaysian Palm Oil Board (MPOB), Kajang, Malaysia

Prof. Dr. P Agamuthu (Professor) and the students at the Solid Waste Lab, Institute of Biological Science, University of Malaya, Kuala Lumpur, Malaysia

Randolph Jeremiah (Project officer), MUCED, Malaysian University Consortium for Environment and Development, University of Malaya, Kuala Lumpur, Malaysia

Sumiani Yusoff (Researcher), Department of Civil Engineering, University of Malaya, Kuala Lumpur, Malaysia

Peter Shonfield, LCA Team Leader, Chemistry & Environmental Protection Department, Safety and Environmental Assurance Centre, Unilever

Jannick Hoejrup Schmidt, June 2007

Contents

1 Introduction

This document is a complete life cycle inventory (LCI) for a comparative life cycle assessment of refined rapeseed oil from Denmark and palm oil from Malaysia and Indonesia. The inventory has been carried out following the reuirements in ISO 14040 (2006) and ISO 14044 (2006). The purpose of this report is to provide the basis for a comparative LCA of rapeseed oil and palm oil. Therefore, all four phases[1] of a life cycle assessment (LCA) is not fully included in this report. **Figure 1.4** (page 17) shows how the different sections in the document relate to the four phases.

1.1 Purpose of the life cycle inventory

The inventory provides the basis for a comparative life cycle assessment (LCA) of refined rapeseed oil and palm oil. This includes definition of system boundaries, data collection, the modelling of the investigated system, sensitivity analyses, identification of improvement options and an evaluation of sensitivity, completeness and consistency. The comparative LCA of rapeseed oil and palm oil is presented in Schmidt (2007a)[2]. According to Schmidt (2007a) the main purpose of the LCA is to assess the environmental impacts related to increasing supply of vegetable oils to the EU. The two main oils used in the EU are rapeseed oil and palm oil. The LCA analyses rapeseed oil from Denmarks as representative for the supply of rapeseed oil and palm oil from Malaysia and Indonesia as representative for the supply of palm oil. For futher details, see Schmidt (2007a).

1.2 Functional unit

The functional unit is defined as one tonne refined vegetable oil suitable for the most important food purposes delivered in central Europe (Amsterdam). The most important uses of vegetable oils and fats are in margarine, shortening and frying and salad oils (Bockisch, 1998). But since different oils and fats have different properties in terms of crystallization, stability to heat, health etc. care should be taken when determining the reference flow. In order to compare one tonne rapeseed oil with one tonne palm oil the oils have to be substitutable.

1.3 Method for system delimitation

Consequential system delimitation

The consequential approach to system delimitation has been applied, i.e. the system inventoried reflects the actually affected processes (Weidema, 2003). The core differences between consequential LCAs and so called attributional or traditional LCAs are summarised in **Table 1.1**.

---

[1] Phase 1: Goal and scope definition, Phase 2: Life cycle inventory, Phase 3: Life cycle impact assessment and Phase 4: Life cycle interpretation (ISO 14040 2006)

[2] Schmidt (2007a) is part of the Ph.D. thesis: ‘Life assessment of rapeseed oil and palm oil’ and it is published in the report ‘Life assessment of rapeseed oil and palm oil. Ph.D. thesis, Part 2: Article collection’.

Feature	Consequential modelling	Attributional modelling
Nature	Attempts to predict to responses to a change in demand	Describes how existing production is taking place
Included processes/suppliers	Marginal	Average
Co-product allocation	Co-product allocation is avoided by system expansion	Co-product allocation is treated by using allocation factors

Table 1.1: Main characteristics of and differences between consequential and attributional modelling in life cycle inventory (based on Weidema 2003; Schmidt and Weidema 2007[3]).

A marginal technology or supplier is defined as the one actually affected by a change in demand, and it is identified as the one most sensitive to changes in demand. A supplier or technology must be within the relevant market segment and among those which are flexible, i.e. not constrained by legal, physical or market conditions. When the relevant suppliers or technologies are identified, the marginal one can be identified as the most competitive in situations with an increasing or constant market trend and reversely the least competitive in situations with a decreasing market trend. The most or least competitive supplier or technology can be determined on the basis of the price relations between the technologies. Alternatively it can be assumed that the most competitive suppliers are those which are increasing with the highest rate.

The main argument for applying the consequential approach is that only the actual affected processes are included (Weidema, 2003). Technologies that are not likely to respond to a change in demand should not be included in an LCA since this will not reflect the actual change in environmental impact.

In order to keep the opportunity to compare results with other LCAs on vegetbale oils, results achived using attributional modelling are presented parallel to the other scenarios investigated.

System delimitation in the agricultural stage

According to Schmidt (2007b)[4] no agricultural LCAs which include the following three important aspects have been identified (i) the identification of the actually affected crops and regions, (ii) the identification of how increased demand for an agricultural product is met and (iii) when land under natural vegetation is transformed into agricultural land there are obvious some induced emissions from fertiliser inputs etc. But the emissions from the land under natural vegetation are also avoided. Relating to (i), increased demand for e.g. rapeseed in Denmark may lead to either increased import or increased cultivation or a combination. If cultivation is increased, it is important to clarify if this affects the area cultivated with other crops in the region. E.g. in Denmark where the total agricultural area has been declining the last decades it is likely that increased cultivation of rapeseed will cause less area available for other crops. Thus, the marginal crop will be displaced as a consequence of increased rapeseed cultivation. If it is assumed that increased production of rapeseed does not affect the overall food security in the world, the displaced crop will be compensated for in the region representing the marginal supplier of that crop. Relating to (ii) it is relevant to clarify if increased agricultural production is met by increased yield or by increased area, i.e. transformation of non-productive land into agricultural land. According to Schmidt (2007b) the differences between these two strategies is significant; increased cultivated area is associated with land use effects while increased yields may lead to significant effects relating to global warming and eutrophication. Relating to (iii), it is well known that even pristine nature causes undesirable emissions, though the level is commonly significant lower than the emission level from agricultural land. Thus,

---

[3] Schmidt and Weidema (2007) is part of the Ph.D. thesis: 'Life assessment of rapeseed oil and palm oil' and it is published in the report 'Life assessment of rapeseed oil and palm oil. Ph.D. thesis, Part 2: Article collection'.

[4] Schmidt (2007b) is part of the Ph.D. thesis: 'Life assessment of rapeseed oil and palm oil' and it is published in the report 'Life assessment of rapeseed oil and palm oil. Ph.D. thesis, Part 2: Article collection'.

the interventions from cultivation of crops should be represented by the difference between the actual interventions from the agricultural land and the interventions from the form the alternative land use, i.e. commonly land under natural vegetation.

Changes in agricultural production of a certain crop can principally be achieved by affecting one of or a combination of three different systems; 1) changes in agricultural productivity per unit of area (e.g. fertiliser, pesticides, organic/conventional), 2) transformation of land between agricultural land and non-cultivated land or 3) the change in cultivated area of the desired crop affect the area cultivated with other crops.

System 1) Changes by yield: When agricultural production is increased by a change in yield, there are no effects on land-use. Only the interventions per unit of area are affected. The interventions are calculated as the intervations from 1 hectare of intensified cultivation minus the interventions from 1 hectare of 'business as usual' cultivation. The principle is illustrated in **Figure 1.1**.

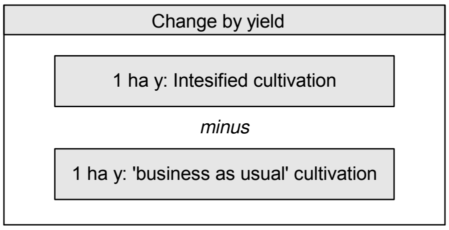


Figure 1.1: Principle in modelling of changes in agricultural production by a change in yield. The crop output from this system is equal to the difference in yields of the two processes. The abbreviation ha y refers to 1 hectare in one year.

System 2) Changes by area: When agricultural production is increased by a change in the cultivated area there are two different sources of interventions: Firstly, there are interventions related to cultivation of the transformed land. This includes occupation processes of the land and and emissions corresponding to 'business as usual' cultivation. Secondly, there are interventions related to the transformation process itself, i.e. transformation processes of land and the associated changes in the standing stocks of carbon and nitrogen. The principle is illustrated in **Figure 1.2**.

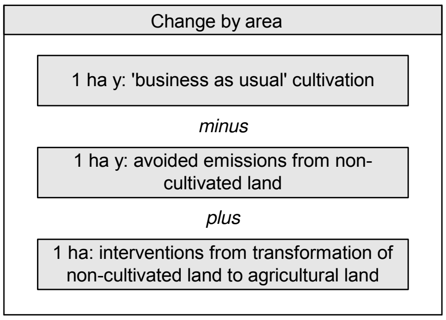


Figure 1.2: Principle in modelling of changes in agricultural production by a change in area. The crop output from this system is equal to the annual yield of the relevant crop. The abbreviation ha y refers to 1 hectare in one year.

In **Figure 1.2** it is easy to relate the interventions from cultivation and the avoided interventions from non-cultivated land to the functional unit, because the interventions are proportional with the annual yield. However, the interventions from transformation of 1 ha non-cultivated land into 1 ha agricultural land is difficult to relate to the functional unit, because it is difficult to predict how many functional units the land-transformation will support. Therefore, the interventions related to the transformation process itself are treated separately in the LCI and LCIA.

System 3) Displacement of other crops: When agricultural production of a crop x is changed at the expense of cultivation of another crop y, the displaced crop y must be produced somewhere else, i.e. in the region that represents the marginal supplier of crop y. The amount of displaced crop y per ha cultivation of crop x is determined as: ($\text{yield}_{\text{crop y}}$ / $\text{yield}_{\text{crop x}}$). The changes in production of crop y then have to be distributed on changes by area and changes by yield. The principle is illustrated in **Figure 1.3**.

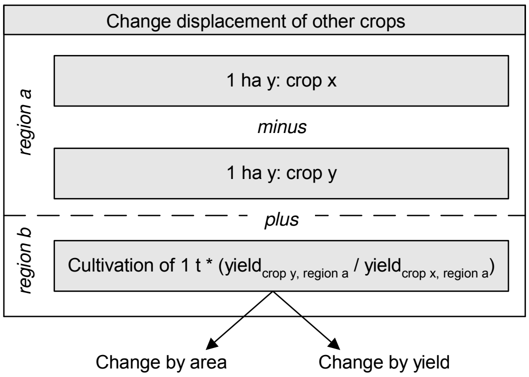


Figure 1.3: Principle in modelling of changes in agricultural production of crop a by displacement of crop b.

System delimitation in the oil mill stage and the refinery stage

There are two main product outputs from the oil mill stage; vegetable oil and the meal which is used for animal fodder. The meal has two functions as animal fodder; protein source and energy source. Thus, when inventorying the interventions relating to the oil, it must be taken into account that the meal substitutes the marginal sources of fodder protein and fodder energy. A method for avoiding co-product allocation by system expansion take these factors into account is presented in Schmidt and Weidema (2007).

In addition to the co-products from the oil mill there are also co-products from the refinery, i.e. vegetable oil and free fatty acids which are used as fodder energy. The system expansion related to that is also dealt with using the method presented in Schmidt and Weidema (2007).

1.4 Method applied for Life Cycle Impact Assessment (LCIA)

Though, this report is only a life cycle inventory, LCIA methods are used for some purposes. Firstly, when comparying different database LCI data for energy, transport, material or process inputs to the system, an LCIA method is used for selection of relevant comparable indicators (e.g. global warming), and for comparison. In the selection of relevant comparable indicators the weighted results using a LCIA method are used. In most cases global warming, eutrophication and toxicity turn out to be the three most relevant indicators to compare, i.e. these are the most significant potential environmental impacts related to the products/services compared. When the indicators have been selected the characterised results are compared. Hereby the most significant differences between the considered database LCI data are monitored. Secondly, LCIA methods are used when performing sensititity analyses of the significance of different assumptions and data uncertainties on the overall result. Hereby, the assumption's or selected data's contribution to the total potential environmental impact within some selected impact categories is analysed.

It is chosen to use the Danish EDIP97-method (Wenzel et al. 1997 and Hauschild and Wenzel 1998) as the default LCIA method in this study. The LCIA-methods Impact 2002+ and EcoIndicator are used as a sensitivity analysis on the level of LCIA methods (see section 21.1).

The EDIP97-method as available in SimaPro 7.0 is not applied directly in this study. The following modifications have been implemented in the EDIP97-method in SimaPro:

Modification 1) Updates: The original EDIP97-method has been updated continouosly since the release in 1996. The newest version of the updated EDIP97-method which includes addition of new substances and updates of characterisation factors as well as normalisation and weighting factors is available in (LCA-center 2007). The updates are implemented in the EDIP97-method in SimaPro. However, the updated version is not available in a format compatible with SimaPro and the work load for entering all updated factors is too big. Therefore, the EDIP97-method in SimaPro has only been partly updated focussing only on the most significant interventions. The partly update has been conducted in the following way:

1. Substances of pesticides and their characterisation factors have been included, see **Table 1.3**
2. The final LCI entered in SimaPro is analysed using the original version of EDIP97. The characterisation factors of the top-10 most significant substances are checked for updates (analysing rapeseed oil and palm oil in scenario 1). At the same time, in order to check for addition of new substances in the updated version of EDIP97, the top-10 list of substances obtained when using EcoIndicator and Impact 2002+ are also chcked for updates. See **Table 1.2**
3. The normalisation and weighting factors are updated

The characterisation factors for the added active ingredients of pesticides are given in **Table 1.3**. Besides, the pesticides given in **Table 1.3**, characterisation factors for the following substances have also been updated in accordance to LCA-center (2007):

EDIP97 (version in SimaPro) (ecotoxicity, water chronical/ ecotoxicity, water acute/ ecotoxicity, soil chronical)	**Impact2002+ (aquatic ecotoxicity/ terrestrial ecotoxicity)**	**EcoIndicator 99 (H) (ecotoxicity)**	**Total list of emissions checked for updates**
Acetone (air)	Aluminium (air)	Cadmium (soil)	Acetone (air)
Arsenic (water)	Aluminium (soil)	Chromium (air)	Aluminium (air)
Benzene (air)	Aluminium (water)	Chromium (soil)	Aluminium (soil)
Cadmium (air)	Arsenic (soil)	Copper (air)	Aluminium (water)
Cadmium, ion (water)	Cadmium (soil)	Copper (soil)	Arsenic (soil)
Chromium VI (water)	Chromium (soil)	Lead (air)	Arsenic (water)
Cobalt (water)	Copper (air)	Nickel (air)	Benzene (air)
Copper (air)	Copper (soil)	Nickel (soil)	Cadmium (air)
Copper, ion (water)	Copper, ion (water)	Zinc (air)	Cadmium (soil)
Cyanid (air)	Cypermethrin (air)	Zinc (soil)	Cadmium, ion (water)
Cyanid (water)	Cypermethrin (water)	-	Chromium (air)
Formaldehyd (air)	Glyphosate (soil)	-	Chromium (soil)
Hexane (air)	Mercury (water)	-	Chromium VI (water)
Hydrogen sulphide (water)	Nickel (air)	-	Cobalt (water)
Iron (soil)	Nickel (soil)	-	Copper (air)
Iron (water)	Selenium (soil)	-	Copper (soil)
Lead (water)	Zinc (air)	-	Copper, ion (water)
Magenese (soil)	Zinc (soil)	-	Cyanid (air)
Manganese (water)	Zinc, ion (water)	-	Cyanid (water)
Molybdenum (soil)	-	-	Cypermethrin (air)
Nickel (water)	-	-	Cypermethrin (water)
Selenium (soil)	-	-	Formaldehyd (air)
Strontium (water)	-	-	Glyphosate (soil)
Titanium, ion (water	-	-	Hexane (air)
Zinc, ion (water)	-	-	Hydrogen sulphide (water)
-	-	-	Iron (soil)
-	-	-	Iron (water)
-	-	-	Lead (air)
-	-	-	Lead (water)
-	-	-	Magenese (soil)
-	-	-	Manganese (water)
-	-	-	Mercury (water)
-	-	-	Molybdenum (soil)
-	-	-	Nickel (air)
-	-	-	Nickel (soil)
-	-	-	Nickel (water)
-	-	-	Selenium (soil)
-	-	-	Strontium (water)
-	-	-	Titanium, ion (water
-	-	-	Zinc (air)
-	-	-	Zinc (soil)
-	-	-	Zinc, ion (water)

Table 1.2: Lists of the 10 most significant emissions contributing to (eco)toxicity using different LCIA-methods when analysing the inventories of scenario 1 described in section 2.5. The right column shows the total list of emissions that are checked for updates in the EDIP-method.

Active ingredient (a.i.)	Compartment	ETWC (m^3/g)	ETWA (m^3/g)	ETSC (m^3/g)
Herbicide, Clomazone	air	0	0	0
	water	14.5	17.1	0
	soil	0	0	1.51
Herbicide, Propyzamid	air	0	0	0
	water	255	13.2	0
	soil	0	0	40
Herbicide, Clopyralid	air	7.25	0	18.1
	water	14.5	1.45	0
	soil	0	0	36.2
Herbicide, Glyphosate	air	0	0	0
	water	62.6	7.69	0
	soil	0	0	155
Herbicide, Tribenuron-methyl	air	625	0	3.00E3
	water	1.25E3	125	3.00E3
	soil	0	0	0
Herbicide, 2,4-D	air	154	0	188
	water	769	76.9	0
	soil	0	0	235
Herbicide, imazethapyr	air	No data, omitted from LCIA		
	water			
	soil			
Insecticide, Cypermethrin	air	0	0	0
	water	5.81E7	2.13E6	0
	soil	0	0	2.63E4
Insecticide, Alpha-cypermethrin	air	0	0	0
	water	3.33E5	1.00E5	0
	soil	0	0	244
Insecticide, Tau-fluvalinat	air	0	0	0
	water	1.00E5	1.00E4	0
	soil	0	0	4.94
Insecticide, Chlorpyrifos	air	0	0	0
	water	1.79E+08	5.00E+06	0
	soil	0	0	8.75E+05
Insecticide, Deltamethrin	air	No data, omitted from LCIA		
	water			
	soil			
Rodenticide, Warfarin	air	No data, omitted from LCIA		
	water			
	soil			

Table 1.3: Characterisation factors for pesticides applied to the EDIP97-method in SimaPro. The characterisation factors are obtained from LCA-center (2007).

Modification 2) Inclusion of land-use (biodiversity) as an impact category: The EDIP97-method does not include land-use. Therefore, this has been included. Since no sufficient methods for land-use impacts exist, a method has been developed for this reason: Schmidt (2007c)[5]. The existing methods are either too coarse (i.e. no distiguishing between crops, extensive/intensive etc.) or they are only covering a smaller part of the world, e.g. Europe.

Modification 3) Exclusion of characterisation factors for biogenic CO_2 emission and CO_2-uptake in biomass: In the EDIP97-method in SimaPro 7.0 the following two emissions are included as contributers to global warming: '*Carbon dioxide, biogenic*' (emission to air, characterisation factor 1 g CO_2-eq./g CO_2) and '*Carbon dioxide, in air*' (raw material, characterisation factor 1 g CO_2-eq./g CO_2). These emissions correspond to the emissions included in ecoinvent-processes in the case of oxydation (burning) of biomass and in the case of agricultural cultivation and forestry. However, since it is almost impossible to ensure that the uptake of car-

---

[5] Schmidt (2007c) is part of the Ph.D. thesis: 'Life assessment of rapeseed oil and palm oil' and it is published in the report 'Life assessment of rapeseed oil and palm oil. Ph.D. thesis, Part 2: Article collection'.

bon in agriculture and forestry is balanced with carbon emitted as biogenic CO_2, the characterisation factors are set to zero.

1.5 Data collection

The data collection for rapeseed cultivation in Denmark is among others based on cultivation guidelines for rapeseed oil (Dansk Landbrugsrådgivning 2005), the LCAfood database and background material (Nielsen et al. 2005; Dalgaard 2007). The life cycle inventory for the oil mill and refinery stages for rapeseed oil takes its point of departure in a detailed data collection at AarhusKarlshamns in Aarhus (Korning 2006; Kronborg L; Hansen 2006; Aarhus United 2005a; Aarhus United 2005b).

The data collection for oil palm cultivation as well as the oil mill and refinery stages takes its point of departure in a detailed data collection for palm oil at United Plantations in Malaysia (Bek-Nielsen 2006; Singh 2006; UPRD 2004). Other important data sources regarding palm oil are the Malaysian Palm Oil Board, MPOB (Subramaniam 2006a; Subramaniam 2006b; Subramaniam et al. 2005; Subramaniam et al. 2004) and various oil palm research (Corley and Tinker 2003).

The co-product from the oil mill process, the oil meal affects soybean meal and barley (see section 2). The data collection related to these commodities is based on Dalgaard et al. (2007) for soybean meal and Dansk Landbrugsrådgivning (2005), Nielsen et al. (2005) and Dalgaard (2007) for barley.

Inventory data for background processes, i.e. for energy production, fertiliser production, transportation, construction, maintenance and disposal of buildings etc. are largely based on the ecoinvent database (ecoinvent 2004). The latest available version of ecoinvent, available in the LCA software SimaPro, is used, i.e. ecoinvent v1.3 (Frischknecht et al. 2006). When data from databases are used, they modified in order to comply with the consequential approach to system delimitation in LCA.

1.6 Structure of the report

The structure of the report is summarised in **Figure 1.4**.

It appears from section 1.3 that changes in agricultural production can be achieved either by increasing the cultivated area or by increasing the yield. Changes in the production from oil milling and oil refineries are more simple, since changes in production here is achieved simply be scaling the whole product system of these life cycle stages. **Figure 1.4** shows how agricultural production, oil milling and refining can be changed and in which sections in the report the single affected elements are described.

Structure of the report				ISO 14040/44
System delimitation				Phase 1
Scoping	Definition of inventoried systems	System delimitation	Section 2	Definition of goal and scope
General inventory data				Phase 2
Energy	Different sources of energy	Electricity and district heat	Section 3	Life Cycle Inventory analysis (LCI)
Transport	Different means of transportation	Lorry, ocean tanker and traction	Section 4	
Agricultural stage				
Change by area	Cultivation of crop	Cultivation of rapeseed	Section 5	
		Cultivation of oil palm	Section 6	
	plus	Cultivation of soybean	Section 7	
	Transformation of land	Cultivation of barley	Section 8	
	minus	Emissions from transformation and from transformed land	Section 19	
	Emissions from transformed land			
Change by yield	Intensified cultivation of crop	Intensified cultivation of rapeseed	Section 18	
		Intensified cultivation of oil palm		
	minus	Intensified cultivation of soybean		
		Intensified cultivation of barley		
	Cultivation of crop	Cultivation of rapeseed	Section 5	
		Cultivation of oil palm	Section 6	
		Cultivation of soybean	Section 7	
		Cultivation of barley	Section 8	
Oil mill stage				
Change in prod.	Oil milling	Rapeseed oil mill	Section 9	
		Palm oil mill	Section 10	
		Palm kernel oil mill	Section 11	
		Soybean oil mill	Section 12	
Refinery stage				
Change in prod.	Refining	Rapeseed oil refinery	Section 13	
		Palm oil refinery	Section 14	
		Palm kernel oil refinery	Section 15	
		Soybean oil refinery	Section 16	
Transport stage				
Transport	Transport of oil to Central Europe	Transport of rapeseed oil and palm oil	Section 17	
Life cycle impact assessment (LCIA)				Phase 3
Results	Very brief presentation of characterised results of scenarios		Section 20	Life Cycle Impact Assessment (LCIA)
Sensitivity analyses and improvement options				
Sensitivity	Assessment of significanse of various assumptions, methods and data		Section 21	
Improvements	Identification of improvement options in the product chains		Section 22	
Sensitivity, completeness and consitency checks				Phase 4
Confidence	Evaluation of the confidence in LCA results		Section 23	Interpretation of results

Figure 1.4: Structure of the report. The right column shows how the different sections relate to the four phases of an LCA in accordance to the ISO 14040 and 14044 standards.

2 System boundaries of inventoried systems

The production of rapeseed oil and palm oil are divided into four stages; agricultural stage, oil mill stage, refinery stage and transport stage. The transport stage only includes transport of oil from the refinery to final use which is assumed to be in Mid-europe represented by Amsterdam. Other transport processes are included in the other life cycle stages. The LCA includes direct affected processes, overhead (operation of buildings, administration, marketing etc.) and capital goods (building, machinery and means of transportation). The determination of the system boundaries relating the oil mill stage and refinery stage is based on the methodology presented in Schmidt and Weidema (2007) and the determination of the system boundaries relating the agricultural stage is based on the methodology presented in Schmidt (2007b)

2.1 Marginal suppliers of affected crops

The system expansions required as described in section 2.2 implies that more crops than rapeseed and fresh fruit bunches (FFB) from oil palms are affected. In section 2.2 these secondary affected crops are identified to be barley and soybean. When the demand for any crop changes, the consequential approach to system delimitation prescribes that the included supplier should be the marginal one. Therefore, the marginal suppliers of the affected crops are identified. According to FAOSTAT (2006) the market trend for all these crops has been increasing (rapeseed, FFB and soybean) or relatively constant (barley) from 1995 to 2005 and FAPRI (2006) predict that the market trend will increase for all crops from 2005 to 2015. Thus, according to Weidema (2003) the marginal suppliers should be identified as the most competitive among those who are flexible. It is difficult to identify the most competitive supplier using price relations since the market prices for the crops mainly are determined by the world supply and demand and therefore are equal for all suppliers. For this reason, the marginal suppliers are identified as the ones who are predicted to face the largest annual increase in production in the near future (2005 to 2015) (see **Table 2.1**). For comparison, the average annual increase the last ten years (1995-2000 and 2000-2005) are also shown in **Table 2.1**.

Crop	Supplier	Annual change 1995-2000 (FAOSTAT 2006)	Annual change 2000-2005 (FAOSTAT 2006)	Annual change 2005/06-2015/16 (FAPRI 2006)
		1000 t	1000 t	1000 t
Rapeseed	EU25*	636	916	417
	China	273	422	151
	Canada	466	477	145
Palm oil	Indonesia*	449	1,251	965
	Malaysia*	598	840	552
	Nigeria	17	57	No data
Soybean	Brazil*	1,819	4,037	3,535
	Argentina	2,021	3,115	1,514
	US	2,947	1,586	149
Barley	Canada*	-198	182	229
	EU25	430	-443	181
	Russia	-1,015	19	162

Table 2.1: Identification of marginal suppliers of crops: Historical and predicted annual average increases among the leading suppliers, i.e. those who are predicted to face the largest annual increase in the future in FAPRI (2006). The suppliers that are assumed to represent the marginal suppliers are marked with *. No outlook data have been available for oil palm fruit (FFB). For this reason palm oil production is shown instead. However, palm oil production is to a large extent proportional to FFB and there is no international trade with FFB, thus production of palm oil always takes place in the same country as production of FFB.

The reason for choosing the marked (*) marginal suppliers of rapeseed, FFB and soybean appear to be quite obvious because these regions/countries are predicted to increase their production significantly more than the other suppliers. For barley the picture is not so clear. Nevertheless, looking at the development from 1995 to 2005 Canada seems to increase its production while the EU25 decreases its production. Therefore, it is regarded as more likely that Canada will represent the marginal supplier than the EU25. The uncertainties related to the identification of marginal suppliers of barley and palm oil are assessed in a sensitivity analysis in section 21.2.

2.2 System expansion – oil mill stage

As described in section 1.3 the consequential approach to LCA implies that system expansion has to be considered in the agricultural as well as the oil milling stage. Firstly, here in section 2.2, system expansion in the oil mill stage is considered and secondly, in section 2.3, system expansion in the agricultural stage is described.

From the processing of rapeseed as well as palm kernels[6] in the oil mills there are outputs of rapeseed oil meal and palm kernel cake (PKC) respectively which are used for fodder purposes. Thus, a change in demand for rapeseed oil or palm oil will affect the production of oil meals/cakes. According to section 1.1 the purpose of the inventory is to model the interventions related to increased supply of vegetable oils to the EU, i.e. to model a *change* in demand. It is assumed that changed production of oil meals, as a consequence of a change in demand for vegetable oils, does not affect the production of meat. Hence, the demand for animal fodder is not assumed to be affected as a consequence of a change in demand for vegetable oils. Therefore, increased production of oil meals will substitute the marginal animal fodder in the market. According to Schmidt and Weidema (2007) fodder mainly consists of two components, i.e. fodder energy and fodder protein. Dalgaard et al. (2007) and Nielsen et al. (2005) identify the marginal sources of protein and fodder energy as soybean meal and barley respectively. The marginal suppliers of the affected crops are identified in section 2.1.

Since soybean meal is co-produced with soybean oil and since soybean meal as well as barley contain proteins as well as fodder energy, the determination of the amounts of affected crops related to 1 tonne rapeseed oil or palm oil is more complex than just simple product substitutions. In addition, displacement of soybean meal causes a change in the supply of vegetable oil to the market. This change will then affect the marginal supplier of vegetable oil. According to Schmidt and Weidema (2007) the marginal vegetable oil is palm oil. Hence, three parameters must be balanced, i.e. oil, fodder protein and fodder energy. Balancing the affected commodities relating to a change in demand for 1 tonne vegetable oil the corresponding change in supply of fodder protein and fodder energy should be zero. In this respect, the relevant properties for of vegetable oils, oil meals and barley are given in **Table 2.2**.

In addition to the co-products from the oil mill stage (vegetable oil, fodder protein and fodder energy), there are also co-products from the refinery stage that affect the same systems. From the neutralisation process in the refining, there is an output of free fatty acids (FFA). According to Weidema and Wesnæs (2006) the FFA is e.g. used for animal feed, in rubber processing, in the flavour industry, for production of candles and cosmetics. Further, Weidema and Wesnæs (2006) regard it as likely that the use for animal feed is the marginal use where the FFA acts as energy source. Therefore, it is assumed that the FFA is used as fodder fat and that it displaces the marginal source of fodder energy, i.e. barley. Corresponding to the vegetable oils, oil meals and barley, the relevant properties of fodder fat are also given in **Table 2.2**.

---

[6] Palm kernels is a co-product from the processing of oil palm fruit (fresh fruit bunches, FFB) in the palm oil mill, see section 10.

Paramter	Vegetable oil, per kg oil	Rapeseed meal, per kg meal	Soybean meal, per kg meal	Palm kernel cake, per kg meal	Barley, per kg barley	Fodder fat, per kg fodder fat
Oil	1 kg oil	0 kg oil	0 kg oil	0 kg oil	0 kg oil	0 kg oil
Protein	0 g protein	340 g protein	436 g protein	149 g protein	91.8 g protein	0 g protein
Fodder energy*	0 SFU**	0.954 SFU	1.20 SFU	0.791 SFU	0.952 SFU	2.31 SFU

Table 2.2: Relevant properties of affected commodities related to the product system of rapeseed oil and palm oil. *Fodder energy is measured in SFU (Scandinavian Fodder Units). **The reason why there is no fodder energy in vegetable oil is that the aim of this LCA is to assess the environmental impacts from vegetable oils used for food purposes (some times vegetable oils are used as animal fodder).

In order to balance the product system it is necessary to know the ratio between the co-products from the involved processed. The product outputs from the rapeseed, palm oil, palm kernel oil and soybean oil mills are given in **Figure 9.2**, **Figure 10.1**, **Figure 11.1** and **Figure 12.1** respectively. In addition, the losses in refining of vegetable oils and the output of the co-product, fodder fat, must be taken into account. 1 tonne crude palm oil is not directly substitutable with 1 tonne crude rapeseed or soybean oil because of different losses in the refining process. The losses and outputs of fodder fat from refining of rapeseed oil, palm oil, palm kernel oil and soybean oil are given in **Figure 13.1**, **Figure 14.1**, **Figure 15.1** and section 16 respectively. The land-use requrements are calculated from the yields given in **Figure 5.4**, **Figur 6.13**, **Figure 7.1** and **Figure 8.2**. Based on these informations, it is possible to draw the overall product systems for the affected commodities, see **Figure 2.1** and **Figure 2.2**. In the bottom of the figures the product outputs from the systems are transformed into contents of oil, fodder protein and fodder energy. This is done by applying the figures provided in **Table 2.2** to the vegetable oil, meals/cakes, barley and fodder fat. The bottom line of the figures corresponds to the relevant outputs of co-products when considering system expansion and product displacement, see next section.

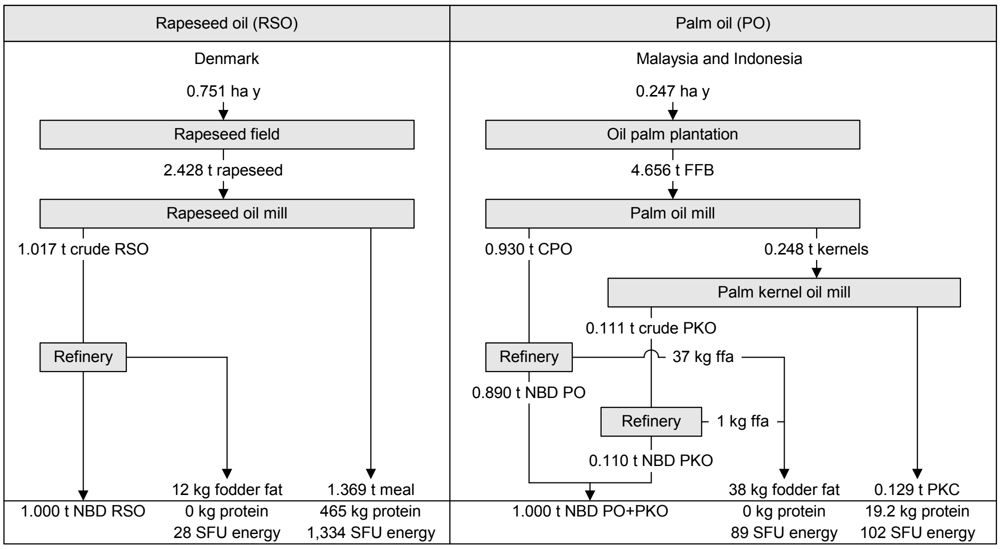


Figure 2.1: Product systems and their co-products for the directly affected systems (rapeseed oil and palm oil).

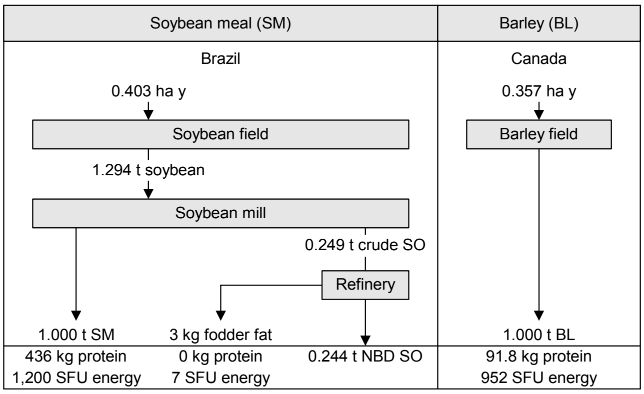


Figure 2.2: Product systems and their co-products for the indirectly affected systems in system expansion (soybean meal and barley).

Rapeseed oil

When performing system expansion in the product system of rapeseed oil and other related (affected) systems, the equation system described in Schmidt and Weidema (2007) is applied. By solving **Equation (1)** the amounts of rapeseed oil, palm oil, soybean meal and barley are balanced in order to provide a net output of 1 tonne oil, 0 kg protein and 0 SFU (right side of the equation). The left side of the equation represents the amount of the affected crops multiplied by vectors of co-products. Here the amount of rapeseed oil is 1 tonne and the other three commodities (palm oil, soybean meal and barley) are independent variables, each representing the marginal sources of vegetable oil, fodder potein and fodder energy respectively.

$$
\begin{gathered}
1\,\text{t RSO}\cdot\begin{bmatrix}1\text{ t oil/t RSO}\\465\text{ kg prot./t RSO}\\1{,}362\text{ SFU/t RSO}\end{bmatrix}+\text{t PO}\cdot\begin{bmatrix}1\text{ t oil/t PO}\\19.2\text{ kg prot./t PO}\\191\text{ SFU/t PO}\end{bmatrix}+\text{t SM}\cdot\begin{bmatrix}0.244\text{ t oil/t SM}\\436\text{ kg prot./t SM}\\1{,}207\text{ SFU/t SM}\end{bmatrix}+\text{t BL}\cdot\begin{bmatrix}0\text{ t oil/t BL}\\91.8\text{ kg prot./t BL}\\952\text{ SFU/t BL}\end{bmatrix}=\begin{bmatrix}1\text{ t oil}\\0\text{ kg prot.}\\0\text{ SFU}\end{bmatrix}\\
\Downarrow\\
\text{t RSO}=1.000\\
\text{t PO}=0.255\\
\text{t SM}=-1.045\\
\text{t BL}=-0.157
\end{gathered}
\qquad (1)
$$

It appears that a change in demand for rapeseed from Denmark at 1 tonne causes increased production of rapeseed oil in Denmark at 1 t, increased production of palm oil (PO+PKO) in Malaysia and Indonesia at 0.255 t, displacement of 1.045 tonne soybean meal in Brazil and displacement of 0.157 tonne barley in Canada. The reason, that a change in demand for rapeseed oil causes changed production of palm oil is that the displacement of soybean meal also causes displacement of soybean oil. This ‘missing’ vegetable oil then has to be compensated for by a change in production of the marginal oil which is palm oil.

Palm oil

Corresponding to the calculation of affected commodities related to a change in demand for rapeseed oil from Denmark, the calculation is done for a change in demand for palm oil, see **Equation (2)**.

$$
\begin{gathered}
\text{t PO}\cdot\begin{bmatrix}1\text{ t oil/t PO}\\19.2\text{ kg prot./t PO}\\191\text{ SFU/t PO}\end{bmatrix}+\text{t SM}\cdot\begin{bmatrix}0.244\text{ t oil/t SM}\\436\text{ kg prot./t SM}\\1{,}207\text{ SFU/t SM}\end{bmatrix}+\text{t BL}\cdot\begin{bmatrix}0\text{ t oil/t BL}\\91.8\text{ kg prot./t BL}\\952\text{ SFU/t BL}\end{bmatrix}=\begin{bmatrix}1\text{ t oil}\\0\text{ kg prot.}\\0\text{ SFU}\end{bmatrix}\\
\Downarrow\\
\text{t PO}=1.001\\
\text{t SM}=-0.00245\\
\text{t BL}=-0.198
\end{gathered}
\qquad (2)
$$

It appears from **Equation (2)** that a change in demand for palm oil at 1 tonne causes increased production of palm oil in Malaysia and Indonesia at 1.001 t, displacement of 0.00245 tonne soybean meal in Brazil and displacement of 0.198 tonne barley in Canada. The reason that production of more palm oil than demanded is required is that the displacement of soybean meal also causes displacement of soybean oil. Then, as explained in the case of rapeseed oil above, this missing oil has to be compensated for by a change in production of the marginal vegetable oil, i.e. palm oil.

System expansion in the oil mill stage - summary

Table 2.3 summarises the amount of agricultural crop inputs to the system and the corresponding land occupations. These inputs are determined from the product flows given in **Figure 2.1** and the results of **Equation (1)** and **(2)**. The data in **Table 2.3** only represent the immediate affected amounts of crops and land occupations. First when system expansion in the agricultural stage has been carried out, the actual amounts of crops and land occupations can be identified. The land occupations given in **Table 2.3** correspond to the traditional way of determining land use in the life cycle inventory phase, i.e. the land under the crop of interest determined from present crop yields (Schmidt 2007b).

	1 t rapeseed oil in Denmark		1 t palm oil in Malaysia and Indonesia	
Affected crops	**Amount**	**Land occupation**	**Amount**	**Land occupation**
Rapeseed in Denmark	2,428 t	0,751 ha y	0 t	0 ha y
Oil palm fruit (FFB) in Malaysia and Indonesia	1,187 t	0,063 ha y	4,661 t	0,247 ha y
Soybean in Brazil	-1,352 t	-0,421 ha y	-0,0032 t	-0,0010 ha y
Barley in Canada	-0,157 t	-0,056 ha y	-0,198 t	-0,071 ha y
Total immediate land occupation	**-**	**0.337 ha y**	**-**	**0.175 ha y**

Table 2.3: Affected commodities and suppliers related to a change in demand of 1 t rapeseed oil and 1 t palm oil.

2.3 System expansion – agricultural stage

The amounts of crops given in **Table 2.3** represent the immediate change in demand for crops related to demand for 1 tonne rapeseed oil from Denmark and 1 tonne palm oil from Malaysia/Indonesia. In the following the changes in demand for each of the crops in **Table 2.3** will be described regarding system expansion in the agricultural stage, i.e. the identification of how increased production is achieved (yield or area) and the identification of land constraints and its consequences for the actual affected crops. The description is based on the methodology presented in Schmidt (2007b).

Rapeseed in Denmark

The change in demand for rapeseed from Denmark can be met either by increasing the yield or by increasing the area cultivated or a combination. If the area cultivated is increased, there are arguments against as well as for that this will be likely to affect to total cultivated area in Denmark. An argument that supports that the total cultivated area will increase is related to the EU strategy on biofuel (The European Commission 2006a). The European Commission (2006a) specifies that set-aside areas can be grown with energy crops in order to help further facilitating energy crops. According to the European Commission (2006b) 8,500 km^2 set-aside area in the European Union has already been used for growing oilseeds for energy purposes. For comparison the total cultivated area with rapeseed in 2005 in EU25 is 47,600 km^2 (FAOSTAT 2006). On the other hand, an argument against that increased demand for rapeseed will affect the total cultivated area is, that the total agricultural area in Denmark has been slightly decreasing the last decades (Danmarks Statistik 2006) and in addition, a main goal in the Danish forestry action plan, is to double the forested area within the next 80 year (The Danish Government 2002). This will increase the total forested area in Denmark from 12% (FAO 2006) to 20-25% (The Danish Government 2002). For comparison the set-aside area in 2005 covered only 4% of the total area in Denmark (Danmarks Statistik 2006). Thus, even when including set-aside areas in agricultural production, the agricultural area in Denmark is likely to continue its decrease. Increased area cultivated with rapeseed in Denmark will therefore be likely to displace the marginal crop in Denmark. Schmidt (2007b) has identified the marginal crop in Denmark to be spring barley. The marginal supplier of barley is previously identified as Canada. Thus, the displaced barley in Denmark will most likely be compensated for by increased production in Canada. From 2005/06 to 2015/16 the average annual increase in rapeseed yield in Europe is predicted to be 1.01% (FAPRI 2006). The average annual increase in the rapeseed area in Europe is predicted to be 1.52% (FAPRI 2006). Hence, 40% of the future increase in production is predicted to be met by yield. It is assumed that the data for Europe in FAPRI are representative for Denmark. Thus, 40% of the increase in Danish rapeseed production is met by locally increasing the yields while the remaining 60% is met by increasing the area which displaces spring barley. The yield of Danish spring barley in 2005 (calculated by regression from 1990 to 2005 and substracted seed) is 5.120 t/ha (see **Figure 8.3**). Since the yield of rapeseed in Denmark is 3.231 t/ha and since 1.457 tonne rapeseed (60% of the desired 2.428 tonne in **Table 2.3**) is met by increased area, it can be calculated that 2.308 tonne spring barley is displaced in Denmark. Since Canada is regarded as the marginal supplier of barley, it is assumed that Canada will increase its barley production with 2.308 tonne.

If the purpose of the LCA was to compare rapeseed oil from the EU instead of Danish rapeseed oil with palm oil, it could be argued that the increased demand for rapeseed oil produced in the EU would be met by yield and area increases within the EU, i.e. no displacement of other crops in the EU. The reason for this is, that the total cultivated area in the EU is predicted to increase slightly (based on FAPRI 2006) and that set-aside areas may be included in cultivation of rapeseed. In addition EU is the region in the world that is predicted to face the largest annual increase in rapeseed production from 2005/06 to 2015/16 (FAPRI 2006). Therefore, a scenario where increased demand for rapeseed is met by 40% increased yield and 60% increased area in the EU is included. Since the aim of this scenario is to assess the differences between local expansion and abroad expansion of the agricultural area, it is in practise defined as the increases in yield and area took place in Denmark, i.e. data for Danish yield and Danish technology is applied.

It appears from the previous that when rapeseed cultivation is increased by area in Denmark, the corresponding changes in land use will not take place in Denmark since increased cultivation takes place at the expense of spring barley. Therefore, the changes in land use will most likely take place in Canada. In the case of the scenario describing increased rapeseed cultivation by area in the EU, the corresponding land use changes will be from set-aside area to rapeseed fields.

FFB in Malaysia and Indonesia

The change in demand for FFB in Malaysia and Indonesia is assumed to take place by 4% increased yield and 96% increased area. It has not been possible to identify any data on predicted yields and cultivated area for the future. Therefore, the distribution between yield and area is based on historical data from FAOSTAT (2006) from 1995 to 2005.

When oil palm cultivation is increased by area it is assumed that no displacements of other crops take place. It is often stated that a considerable share of the oil palm expansion has and is taking place on land released from other crops (Henson 2004, Corley and Tinker 2003 p 480 and Teoh 2000). According to Henson (2004) oil palm in Malaysia has largely been planted on land released from rubber, coconut and cocoa. This is in good accordince with data obtained from FAOSTAT (2006) for Malaysia where the planted area of rubber, cocoa and coconuts have been decreasing from around the year 1990 to the year 2005 while the planted area of oil palm has been increasing during the same period of time. However, looking at Malaysia and Indonesia as one marginal supplier of palm oil, there is a general increase in the cultivated area of rubber, coconut and cocoa, see **Figure 2.3**. Only an insignificant decrease in the cultivated area of cocoa is identified from 1994 to 1999.

Thus, no displacements between crops are considered when identifying how oil palm cultivation is increased by area.

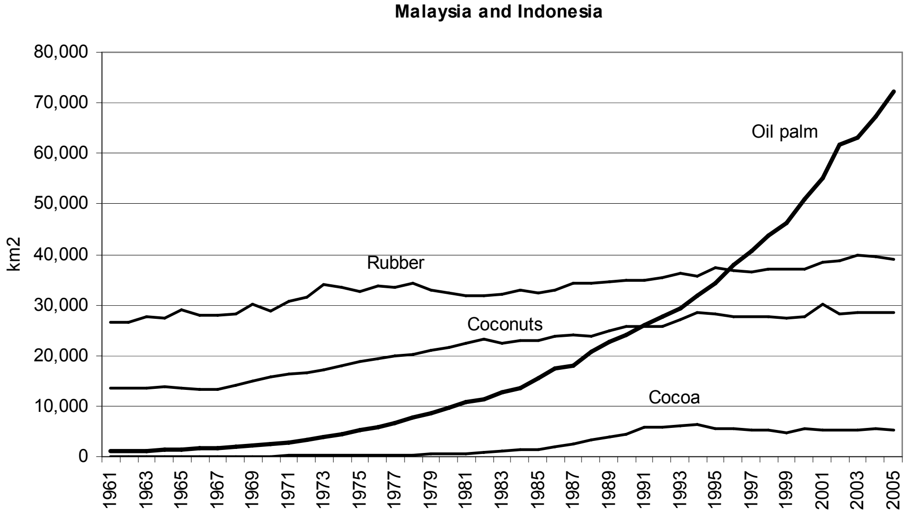


Figure 2.3: Planted area of oil palm, natural rubber, coconuts and cocoa in Malaysia and Indonesia 1961-2005. Based on FAOSTAT (2006).

Since no crop displacement is taking place when considering Malaysia and Indonesia together, it is presumed that a change in demand for oil palm affects the cultivation with 4% change in yield and 96% transformation of non-agricultural land into oil palm cultivation.

For changes achived by land transformation the question is then what kind of land that is transformed. Some NGO's refer to land transformation related to oil palm as clearing of primary forest, e.g. see Frese et al. (2006), Casson (2003) and Wakker (2004). However, oil palm is almost always established on already disturbed land (Glastra et al. 2002, ProForest 2003, Bek-Nielsen 2006).

Disturbed land may be either abandoned agricultural land, cleared forest (grassland/alang-alang land) or secondary forest. If oil palm is planted directly on transformed primary forest, the transformation from primary to degraded forest should be ascibed to logging since changes in demand for timber is the main driving force of logging. Thus, land use changes related to oil palm in this study is represented by either transformation of secondary/degraded forest to oil palm or transformation of grassland/alang-alang land to oil palm.

From 1993 to 2003 the agricultural area in Malaysia and Indonesia has been increasing in average 5,600 km^2 annually (FAOSTAT 2006). In the same period the area planted with oil palm has been increasing in average 3,400 km^2 annually. These data represents the newst data available for a ten years period.

For comparison the annual change in forest cover in Malaysia and Indonesia from 1990 to 2000 has been 19,500 km^2 (FAO 2006), 96% in Indonesia and 4% in Malaysia. This has only changed slightly looking at 2000 to 2005 where the annual deforestation rate in Malaysia and Indonesia together was 20,110 km^2. For comparison Pagiola (2000) specifies an annual deforestation rate in Indonesia at 16,420 km^2 from 1987 to 1997. In Malaysia the change in the extent of primary forest has not changed from 1990 to 2005 while the annual degradation of primary forest at 14,478 km^2 in Indonesia has been the same in 1990 to 2000 and 2000 to 2005. It appears that the annual deforestation in Malaysia and Indonesia is significant larger than the increase in agricultural area, also when looking at degradation of primary forest only. This underpins that it is not likely that oil palm is not the driving force of the logging of primary forest.

According to Garrity et al. (1997) and Corley (2006) large areas of grassland (also called alang-alang or imperata) is available for expanding the agricultural area in Indonesia. Garrity et al. (1997, p 20) estimate the area of alang-alang grass land in Indonesia as 75,000–130,300 km^2, i.e. 4-7% of the total area, while the area of grassland available for agricultural expansion in Malaysia is only 1,000–5,000 km^2, i.e. 0.3–1.5% of the total area. A suggested specific target in the WWF initiated Round Table on Sustainable Palm Oil (RSPO) is that at least 75% of the new oil palm plantings should be on degraded or abandoned, deforested land, rather than new clearings (Corley 2006; RSPO 2006)

From the figures presented above it is not possible to estimate the composition of land use types transformed into oil palm. It is assumed that 50% of oil palm expansions take place by transformation of grassland and the other 50% take place by transformation of degraded/secondary forest. However, this assumption associated with large uncertainties. Therefore, the uncertainties related to the determination of the affected land use types (grassland, degraded/secondary forest and primary forest) are assessed in a sensitivity analysis in section 21.3.

Soybean in Brazil

The change in demand for soybean in Brazil is presumed to take place by 19% increased yield and 81% increased area. This presumption is based on predictions from 2005/06 to 2015/16 in FAPRI (2006). According to Dros (2004) expansion of soybean cultivation in Brazil mainly takes place in the Cerrados and the Amazon forests. Dros (2004) specifies the annual expansion rates from 1995/96 to 2003/04 in the Cerrado as approximately 7,500 km^2/year, while the rate in the Amazon states in the same period is around 369 km^2/year. This is in good accordance with FAOSTAT (2006) from which an average increase in the soybean cultivated area from 1993 to 2003 can be determined as 7,812 km^2/year. Based on the figures provided by Dros (2004), it is assumed that changed soybean production by expanding the agricultural area in Brazil is achived by 95% transformation of the Cerrado savannah and 5% transformation of the Amazon rain forest. As in the case of oil palm in Malaysia and Indonesia, degradation of primary forest into degraded/secondary forest is ascribed to timer logging while transformation of degraded forest/secondary forest into soybean fields is ascribed to soybean cultivation. The transformation of the Cerrado savannah into soybean fields is fully ascribed to soybean cultivation.

From 1993 to 2003 the arable land in Brazil has been increasing in average 6,740 km^2 annually (FAOSTAT 2006). Thus, the increase in the area cultivated with soybean is larger than the total increase in arable land. An immidiate explanation of that could be that the increase in soybean has been taking place at the expense of displacement of other crops. However, that is not the case because the sum of change in the cultivated area of all crops in FAOSTAT (2006) shows a total increase at 10,951 km^2/year. The reason why this figure is larger than the total increase of arable land is because of increased cultivation of cropping systems with more than one crop anually. FAOSTAT (2006) distinguishes between ‘cultivated area’ and ‘arable land’. The ‘cultivated area’ is equal to the harvested area. And since some fields are harvested more than once a year, the ‘cultivated area’ is larger than the area of the ‘arable land’. According to Schnepf et al. (2001) three crops per year are in principple possible in some areas of Brazil. Double-croppping in Argentina and Brazil is often put forward as an important mean of increasing the cultivated area (the “virtually” area) (Jales et al. 2006 and USDA 2006).

Double-croppping in Argentina is refereed to as 37% of the soybean cultivated area in USDA (1997) and 25% in Dalgaard et al. (2007). No information on double-cropping in Brazil has been identified. Therefore, it is assumed that 25% of the soybean in Bazil is cultivated in a double-cropping system. The consequence of this is, that the yield of soybean obtained from FAOSTAT statistics should be multiplied by a factor of 1.25 (=0.25·2 + 0.75) in order to reflect the annual yield of one hectare of arable land.

Barley in Canada

From predictions in FAPRI (2006) it can be found that 31% of the future increase in production of barley in Canada is met by yield while the remaining 69% is met by increased area. However, since the total agricultural area in Canada has been decreasing in the period from 1993 to 2003 (FAOSTAT 2006) it is not assumed to be likely that 69% of future changes in demand for barley will be met by transformation of nature to agriculture. According to FAOSTAT (2006) there have been major increases in the cultivation of peas, rapeseed, soybeans, barley, oats, linseed, maize and lentils while there has been a corresponding decrease in the area cultivated with wheat. It could then be argued that the increased production of barley in Canada is achived by displacement of wheat. However, identifying the marginal supplier of wheat and then perform system expansion again would not add much acuracy to prediction of affected crops. The reason for that is that there is a considerable substitutability between different cereals (wheat, barley, oat, rye and to some extent maize and rice). It could then be asked if the marginal supplier of barley should be the same as the marginal supplier of cereals. In order to assess the uncertainties related to the identification of the marginal supplier of barley, a sensitivity analysis in section 21.2 assesses the effect on the results if other suppliers of barley are are marginal.

According to FAOSTAT (2006) the average annual increases in cereals production from 1990 to 2005 have taken place as 1.48% increase in yield and 0.36% decrease in cultivated area. Similar figures showing that yield increases are the dominant way of increasing cereal production can be found in FAPRI (2006). In FAPRI, the predicted increased production of cereals is achived by 1.02% increase in yield and only 0.12% increase in cultivated area. Based on that, an increase in the production of cereals is assumed to be achived by increase in yields only. However, in some of the included scenarios increases in production of barley are assumed to be achieved by increase in the cultivated area. In these cases it is assumed that the transformed land is prairie grassland.

System expansion in the agricultural stage - summary

Figure 2.4 and **Figure 2.5** summarises the product flows, and the affected crops and suppliers when performing system expansion in the agricultural stage. The yields of rapeseed and spring barley in Denmark, FFB in Malaysia and Indonesia, soybean in Brazil and barley in Canada are obtained from sections 5.1, 6.1, 7.1 and 8.1.

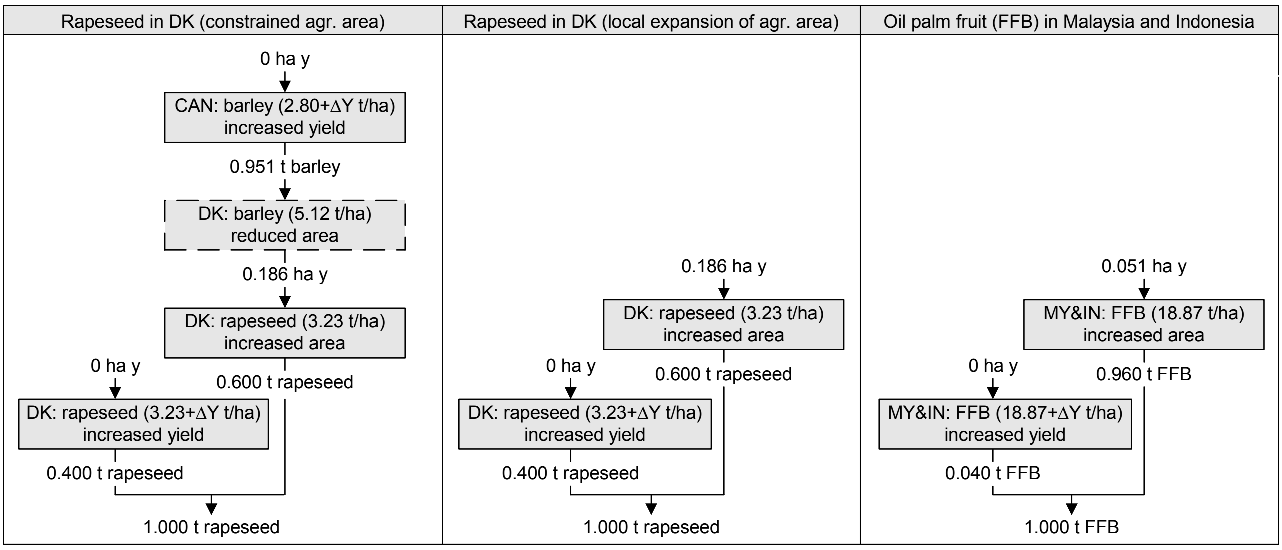


Figure 2.4: Expanded agricultural product systems related to 1 t rapeseed and 1 t FFB. Abbreviations: Canada (CAN), Denmark (DK) and Malaysia and Indonesia (MY&IN). ΔY represents the desired increase in yields when increased production is achieved that way.

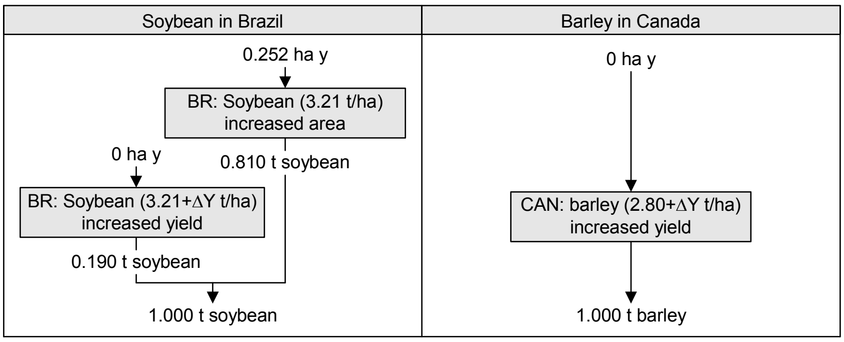


Figure 2.5: Expanded agricultural product systems related to 1 t soybean and 1 t barley. Abbreviations: Canada (CAN) and Brazil (BR). ΔY represents the desired increase in yields when increased production is achieved that way.

2.4 Scenarois related to system expansion

The system delimitation in the main scenario is described in the previous sections. However, most LCAs on products from oil crops are performed using attributional modelling in system delimitation and LCI, i.e. allocation is typically done by economic value (or by energy content/mass/100 percent/0 percent) and system expansion is not taken into account (Defra 2005; Beer et al. 2002; Mehlin et al. 2003; Wightman et al. 1999; McManus et al. 2004; Yusoff and Hansen 2005; Koch 2003; Althaus et al. 2003; Zah and Hischier 2003). Some LCAs on oil crop products have adopted consequential modelling in the oil mill stage (Dalgaard et al. 2007; Nielsen et al. 2005). However, no existing LCAs which include system expansion in the agricultural stage have been identified. Though, progress in that field is ongoing. A model including a case study on wheat is presented in Schmidt (2007b) and work is ongoing by Kløverpris (2007). See Kløverpris (2006) for a description of the work.

In order to make the results obtained from the present LCI transparent and comparable with other LCIs, the results are shown on all three levels of LCI-modelling: 1) Attributional modelling, i.e. traditional LCA with no system expansion, 2) semi-consequential modelling, i.e. only taking system expansion in the oil mill stage into account and 3) consequential modelling in the oil mill stage as well as in the agricultural stage.

Attributional modelling: The economic allocation factors applied in the attributional modelling are based on the product flows shown in **Figure 2.1** and the average prices on oils and meals from 1996/97 to 2003/04 provided in Oil World (2005). The allocation factors ascribing shares of the input of rapeseed to the two co-products from rapeseed milling are 73% for the oil and 37% for the meal. Two co-products are also considered from the palm oil mill together with the palm kernel oil mill (see **Figure 2.1**), i.e. palm oil (PO+PKO) and palm kernel meal. The allocation factors ascribing shares of the input of FFB to the co-products are 98% for the oil and 2% for the meal. From 1996/97 to 2003/04 the relative world market prices between oils and meals have been changing so that the allocation factor for palm oil would vary from 97.5% to 98.7% and the allocation factor for rapeseed oil would vary from 66% to 78%. Thus, relative variations between prices on oil and meals are not considered as a significant source of uncertainty.

Attributional modelling in the agricultural stage means that only the area under the immediate affected crops is affected. Attributional modelling describes how existing production takes place. Contrary to that, consequential modelling attempts to predict responses to changes in demand. Therefore, attributional modelling in this this study does not consider changes in yield as well as constraints on area available for agricultural cultivation are not considered.

Semi-consequential modelling (system expansion in oil mill stage only): The system defined by system expansion in the oil mill stage is presented in **Table 2.3**. Attributional modelling is applied in the agricultural stage, see above.

Consequential modelling (system expansion in oil mill stage as well as agricultural stage): The system inventoried is described as the system in **Table 2.3** (system expansion in oil mill stage) combined with the system in **Figure 2.4** and **Figure 2.5** (system expansion in agricultural stage). Since the determination of the share of changes in agricultural production achieved by area and yield is related to some uncertainty, three scenarios are assessed within the consequential modelling, i.e. i) changes in production achieved by a combination of area and yield (as described in section 2.3), ii) changes in production achieved by changes in area only, and iii) changes in production achieved by changes in yield only.

Hence, in total five scenarios are included: three consequential, one semi-consequential and one attributional. Additional to that, for the two consequential scenarios which include changes in the cultivated area, two alternative ways of increasing rapeseed production in Denmark are included, i.e. a) increased area cultivated with rapeseed causes displacement of the marginal crop in Denmark, spring barley, and b) increased area cultivated with rapeseed causes local transformation of set-aside area. These two alternative ways of increasing rapeseed production in Denmark are described in 'Rapeseed in Denmark' in section 2.3. **Table 2.4** provides an overview of the included five different scenarios relating to the system delimitation.

Scenarios: compositions of product systems	**Description of product system**	
	1 t rapeseed oil in Denmark	**1 t palm oil in Malaysia and Indonesia**
Sc 1) Consequential modelling in oil mill and agr. stages. Marginal increases are assumed to be achived by a combination of increase in agr. area and yields	a) RSO (constrained area) and b) RSO (flexible area)	PO+PKO
Sc 2) Consequential modelling (area only) in oil mill and agr. stages. Marginal increases are assumed to be achived by increase in agr. area only	a) RSO (constrained area) and b) RSO (flexible area)	PO+PKO
Sc 3) Consequential modelling (yield only) in oil mill and agr. stages. Marginal increases are assumed to be achived by increase in agr. yields only	RSO	PO+PKO
Sc 4) Semi-consequential modelling, system expansion in oil mill stage and attributional modelling in agr. stage	RSO	PO+PKO
Sc 5) Attributional modelling, i.e. economic allocation and no system expansion	RSO (73% allocated to oil)	PO+PKO (98% allocated to oil)

Table 2.4: Overview of the included scenarios relating to system delimitation.

2.5 Inventoried system – summary

Agricultural stage

Table 2.5 summarises the product flow in the agricultural stage in the included scenarios. The values are calculated on the basis of the descriptions in section 2.4 and the data presented in **Table 2.3** (system expansion in oil mill stage) and **Figure 2.4** and **Figure 2.5** (system expansion in agricultural stage).

			Affected crops, t				
Scenario 1	**Ref. flow**	**Increase**	**Rapeseed (DK)**	**FFB (MY&IN)**	**Soybean (BR)**	**Barley (CAN)**	**Barley (DK)**
Sc 1) Consequential modelling in oil mill and agr. stages. Marginal increases are assumed to be combined increase in agr. Area and yields	1 t RSO (constrained area)	Area	1.457 t	1.140 t	-1.096 t	0 t	-2.308 t
		Yield	0.971 t	0.0475 t	-0.257 t	2.151 t	0 t
	1 t RSO (local expansion)	Area	1.457 t	1.140 t	-1.096 t	0 t	0 t
		Yield	0.971 t	0.0475 t	-0.257 t	-0.157 t	0 t
	1 t PO+PKO	Area	0 t	4.475 t	-0.00257 t	0 t	0 t
		Yield	0 t	0.186 t	-0.000602 t	-0.198 t	0 t
Scenario 2	**Ref. flow**	**Increase**	**Rapeseed (DK)**	**FFB (MY&IN)**	**Soybean (BR)**	**Barley (CAN)**	**Barley (DK)**
Sc 2) Consequential modelling (area) in oil mill and agr. stages. Marginal increases are assumed to be increase in agr. area only	1 t RSO (constrained area)	Area	2.428 t	1.187 t	-1.352 t	3.690 t	-3.847 t
	1 t RSO (local expansion)	Area	2.428 t	1.187 t	-1.352 t	-0.157 t	0 t
	1 t PO+PKO	Area	0 t	4.661 t	-0.00317 t	-0.198 t	0 t
Scenario 3	**Ref. flow**	**Increase**	**Rapeseed (DK)**	**FFB (MY&IN)**	**Soybean (BR)**	**Barley (CAN)**	**Barley (DK)**
Sc 3) Consequential modelling (yield) in oil mill and agr. stages. Marginal increases are assumed to be increase in agr. yields only	1 t RSO	Yield	2.428 t	1.187 t	-1.352 t	-0.157 t	0 t
	1 t PO+PKO	Yield	0 t	4.661 t	-0.00317 t	-0.198 t	0 t
Scenario 4	**Ref. flow**	**Increase**	**Rapeseed (DK)**	**FFB (MY&IN)**	**Soybean (BR)**	**Barley (CAN)**	**Barley (DK)**
Sc 4) Semi-consequential modelling, system expansion in oil mill stage and attributional modelling in agr. stage	1 t RSO	Area	2.428 t	1.187 t	-1.352 t	-0.157 t	0 t
	1 t PO+PKO	Area	0 t	4.661 t	-0.00317 t	-0.198 t	0 t
Scenario 5	**Ref. flow**	**Increase**	**Rapeseed (DK)**	**FFB (MY&IN)**	**Soybean (BR)**	**Barley (CAN)**	**Barley (DK)**
Sc 5) Attributional modelling, i.e. economic allocation and no system expansion	1 t RSO	Area	1.772 t	0 t	0 t	0 t	0 t
	1 t PO+PKO	Area	0 t	4.568 t	0 t	0 t	0 t

Table 2.5: Overview of the affected crops in the different scenarios relating to the functional unit of 1 t vegetable oil. Each line represents the affected crops relating to the functional unit.

In addition to the affected crops in **Table 2.5** the changes achived by increased cultivated area will have correspondingly effects on transformation of non-cultivated area into agricultural land. Based on **Figure 2.4**, **Figure 2.5** and **Table 2.5** the transformation processes related to 1 tonne rapeseed oil and 1 tonne palm oil are calculated, see **Table 2.6**. It must be stressed that the transformations given in **Table 2.6** are for the first year of harvesting. E.g. a crop yielding 1 t/ha per year will have a correspondingly transformation process at 1 ha/t crop. However, the transformed area will continue yielding crops after the first year. Therefore, the figures given in **Table 2.6** are not directly related to the functional unit as in **Table 2.5**. **Table 2.5** represents processes proportional to the functional unit while **Table 2.6** represents processes that only occur one time, and the cultivation on the same area after that will not be associated with any transformation processes.

	DK	**MY&IN**		**BR**		**CAN**
Transformation from…	**Set-aside**	**Forest**	**Grassland**	**Savannah**	**Forest**	**Grassland**
Transformation to…	**Rapeseed field**	**Oil palm plantation**		**Soybean field**		**Barley field**
Sc 1) Consequential modelling in oil mill and agr. stages. Marginal increases are assumed to be combined increase in agr. area and yields						
1 t RSO (constrained area)	0 ha	0.0302 ha	0.0302 ha	-0.324 ha	-0.0171 ha	0 ha
1 t RSO (local expansion)	0.451 ha	0.0302 ha	0.0302 ha	-0.324 ha	-0.0171 ha	0 ha
1 t PO+PKO	0 ha	0.119 ha	0.119 ha	-0.000760 ha	-0.0000400 ha	0 ha
Sc 2) Consequential modelling (area) in oil mill and agr. stages. Marginal increases are assumed to be increase in agr. area only						
1 t RSO (constrained area)	0 ha	0.0315 ha	0.0315 ha	-0.400 ha	-0.0211 ha	1.318 ha
1 t RSO (local expansion)	0.751 ha	0.0315 ha	0.0315 ha	-0.400 ha	-0.0211 ha	-0.0561 ha
1 t PO+PKO	0 ha	0.124 ha	0.124 ha	-0.000938 ha	-0.0000494 ha	-0.0707 ha
Sc 3) Consequential modelling (yield) in oil mill and agr. stages. Marginal increases are assumed to be increase in agr. yields only						
1 t RSO	0 ha	0 ha	0 ha	0 ha	0 ha	0 ha
1 t PO+PKO	0 ha	0 ha	0 ha	0 ha	0 ha	0 ha
Sc 4) Semi-consequential modelling, system expansion in oil mill stage and attributional modelling in agr. Stage						
1 t RSO	0.751 ha	0.0315 ha	0.0315 ha	-0.400 ha	-0.0211 ha	-0.0561 ha
1 t PO+PKO	0 ha	0.124 ha	0.124 ha	-0.000938 ha	-0.0000494 ha	-0.0707 ha
Sc 5) Attributional modelling, i.e. economic allocation and no system expansion						
1 t RSO	0.549 ha	0 ha	0 ha	0 ha	0 ha	0 ha
1 t PO+PKO	0 ha	0.121 ha	0.121 ha	0 ha	0 ha	0 ha

Table 2.6: Overview of the transformed area (ha) in the different scenarios relating to the functional unit of 1 t vegetable oil. Each line represents the affected crops relating to the functional unit.

Since the figures in **Table 2.5** and **Table 2.6** are not related to the functional unit the same way, the LCIA results from transformation processes are treated seperately.

Oil mill and refinery stages

Based on **Figure 2.1** and the results of **Equation (1)** and **Equation (2)**, the affected processes in the oil mill and refinery stages are calculated, see **Table 2.7**.

	Rapeseed oil		**Palm oil**		**Palm kernel oil**		**Soybean oil**	
Scenario	**Oil mill (oil)**	**Refinery (oil)**	**Oil mill (oil)**	**Refinery (oil)**	**Oil mill (oil)**	**Refinery (oil)**	**Oil mill (meal)**	**Refinery (oil)**
Sc 1), 2), 3) and 4) Consequential modelling in oil mill and refinery stage								
1 t RSO	1.017 t	1.000 t	0.237 t	0.227 t	0.0283 t	0.0280 t	-1.045 t	-0.255 t
1 t PO+PKO	0 t	0 t	0.931 t	0.891 t	0.111 t	0.110 t	-0.00245 t	-0.000599 t
Sc 5) Attributional in oil mill and refinery stage								
1 t RSO	0.742 t	1.000 t	0 t	0 t	0 t	0 t	0 t	0 t
1 t PO+PKO	0 t	0 t	0.913 t	0.891 t	0.109 t	0.110 t	0 t	0 t

Table 2.7: Overview of the affected oil mill and refinery processes in the different scenarios relating to the functional unit of 1 t vegetable oil. Each line represents the affected processes relating to the functional unit.

3 Energy

Energy is used in many of the included processes in the life cycle of rapeseed oil and palm oil. Electricity supply is delivered from the grid which is supplied from a range of different power plants connected to the European grid. Heat is supplied either through the district heating system or through own production in a furnace. This section describes the used life cycle inventory data for the different types of energy used in the life cycle of rapeseed oil and palm oil. The amount of energy used in the different unit processes is described in the distinct sections which inventory the single stages in the life cycle of rapeseed oil and palm oil; sections 5 to 17.

3.1 Electricity from the grid in Denmark

Electricity supply to the grid in Denmark comes from a variety of different technologies. These mainly comprise centralized coal and natural gas power plants, wind mills, waste incineration plants, decentralized combined heat and power plants based on natural gas, coal or biomass. When the demand for electricity is changed only the marginal suppliers are affected. Hence, there is a range of suppliers that are not affected when the demand for electricity is changed. These technologies include; wind mills which are constrained by the wind available and capacity determined by energy policy, decentralized combined heat and power plants whose production is determined by the local demand for heat, electricity production in waste incineration plants is determined by the amount of waste available. Thus, the marginal source of electricity is either coal, gas or both.

Marginal energy source of electricity: Coal or natural gas?

According to Weidema (2003) the most competitive technology is coal followed by natural gas, heavy fuel oil and biomass in the mentioned order. Since the consumption of electricity is increasing, it is the most competitive suppliers that are affected. Thus, coal based technology seem to be the marginal technology. LCA-Center (2006) also suggests that coal based power production is most likely to be affected; even when hour by hour fluctuations are taken into account.

However, all new power plants projected in the Nordic countries are natural gas fired (Weidema 2003). Coal based technology is likely to cover the demand within existing capacity the next 10 years (Weidema 2003). Concerning central Europe, Weidema identifies a range of properties of gas based technology that indicate that this technology could be the marginal in the longer term; installation of natural gas requires lower costs than coal, political goals on reduction of SO_2-, NO_x- and CO_2-emissions are easier reached using natural gas, and finally it is possible to regulate the power output of natural gas fired plants on a minute basis. Hence, the marginal technology tend to be coal based in the short term and natural gas based in the longer term.

Nevertheless, it may be questioned if gas can be marginal in the longer term since the reserves in Denmark as well as Europe are getting scarce. According to Energistyrelsen (2005) the outlook prediction on possible Danish gas production the next 20 years shows a decline in annual production at 83% from approximately 23 mio m^3 in 2004 to approximately 4 mio m^3 in 2024. According to Bentley (2002) Europe has little way to go before its peak in production is reached. On the other hand, EIA (2005) expects gas to be the fastest growing fuel in European until 2025. The increased demand is expected to be met by import; thus the reliance on import is predicted to increase from ~33% in 2002 to ~50% in 2025 (EIA 2005).

If natural gas should be considered as the marginal source of electricity in the longer term it must be flexible (i.e. not constrained). There are some indications on that it may be constrained by available gas resources in the future. EIA (2005, p 39) estimates the global reserves-to-production ratio to be 67 years while the ratio in the former Soviet Union from where EU imports its natural gas is 77 years. However, the Kyoto mechanisms may speed up the consumption and prices of natural gas which may lead to constraints in the future.

Different studies suggest different marginal technologies for electricity and choosing either coal or gas as the marginal will be related to some uncertainty. It is chosen to apply coal based electricity as the marginal since this is regarded as the marginal in the short term. As indicated it can be questioned if the gas resources are adequate (not constrained) to be the marginal technology in the longer term. Therefore, coal is regarded more likely to be the marginal in the short term as well as in the longer term. However, since the identification of marginal electricity suppliers is related to some uncertainties, gas based technology is applied in a sensitivity analysis in section 21.4.

Marginal technology for electricity: Co-production of heat or not?

Many centralized power plants in Denmark are producing both heat and electricity and they are able to regulate the ratio by operating between condensation mode and back pressure mode. According to Weidema (2003) co-generating technology is constrained by local demand for heat. Thus, marginal electricity is produced without co-generation of heat.

Inventory data for electricity

Loss in the grid also has to be considered. When the power plant delivers its electricity, it is sent into the high voltage grid (150-400 kV). This grid connects the power plants with the distribution grid, also denoted as the low voltage grid (<60 kV). According to Energi E2 et al. (2000) the loss in the high voltage grid is 1% of the supply to the grid. In the transformation to <60 kV and distribution in the low voltage grid to the end-users the loss is 3.8% of the supply to the high voltage grid. **Figure 3.1** shows a flowchart of electricity per 1 MJ delivered.

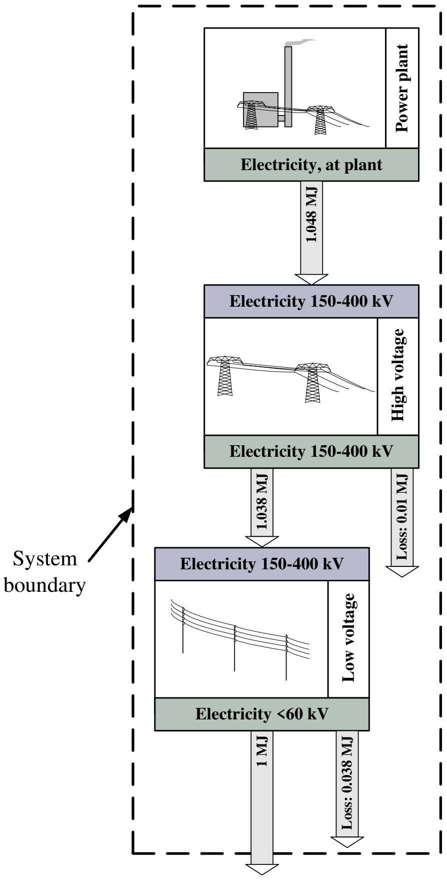


Figure 3.1: Flowchart of electricity from power plant to end-user.

Several life cycle inventories for coal and natural gas based electricity production have been identified. However, many of these are based on data for co-generation of heat and power and in these studies this is dealt with by co-product allocation based on either energy content or energy quality. These inventories, which among other include a detailed LCA of Danish electricity; (Energi E2 et al. 2000), are not considered in the following because they are not consistent with the used system delimitation described above.

Analysing existing inventories of electricity based on coal and gas available in SimaPro and using the EDIP97-method for LCIA, it appears that global warming, acidification and toxicity are the most significant impact categories. In **Table 3.1**, four relevant data sets are compared within these categories.

Coal: LCI-data for electricity	**CO2-eq.**	**SO2-eq.**	**ETWC, m3 water**	**Electricity efficiency**	**Description of data**
'Electricity coal power plant in NL', ETH-ESU database (Frischknecht et al., 1996)	274 g	0.79 g	105 m^3	No data	*Time:* Data from 1990-94 *Geography:* The Netherlands/UCPTE[7] *Technology:* Average gas fired plants *Co-product allocation*: Not relevant *Capital goods:* Machinery, buildings
'Electricity coal power plant in UCPTE', ETH-ESU database (Frischknecht et al., 1996)	302 g	1.45 g	119 m^3	No data	
'Electricity, hard coal at power plant/UCTE', ecoinvent database (Emmenegger et al. 2003)	298 g	1.38 g	37.3 m^3	36%	*Time:* Data from 2000 *Geography:* UCTE[7]/ NORDEL[8] *Technology:* Average gas fired plants *Co-product allocation*: Not relevant *Capital goods:* Machinery, buildings
'Electricity, hard coal at power plant/NORDEL', ecoinvent database (Emmenegger et al. 2003)	267 g	0.57 g	17.7 m^3	42%	

Natural gas: LCI-data for electricity	**CO_2-eq.**	**SO_2-eq.**	**ETWC, m^3 water**	**Electricity efficiency**	**Description of data**
'Electricity gas power plant in NL', ETH-ESU database (Frischknecht et al., 1996)	182 g	0.18 g	2.8 m^3	No data	*Time:* Data from 1990-94 *Geography:* The Netherlands/ UCPTE[7] *Technology:* Average gas fired plants *Co-product allocation*: Not relevant *Capital goods:* Machinery, buildings
'Electricity gas power plant in UCPTE', ETH-ESU database (Frischknecht et al., 1996)	256 g	0.35 g	11.5 m^3	No data	
'Electricity, natural gas, at power plant/UCTE', ecoinvent database (Emmenegger et al. 2003)	166 g	0.20 g	6.1 m^3	38%	*Time:* Data from 2000 *Geography:* UCTE[7]/ NORDEL[8] *Technology:* Average gas fired plants *Co-product allocation*: Not relevant *Capital goods:* Machinery, buildings
'Electricity, natural gas, at power plant/NORDEL', ecoinvent database (Emmenegger et al. 2003)	152 g	0.19 g	5.1 m^3	41%	

Table 3.1: Comparison of LCIs of 1 MJ electricity based on coal and natural gas technology. The comparison is shown as characterised results using the EDIP97-method for LCIA. The applied data are marked with a black dotted frame. The marked natural gas inventory is applied in a sensitivity analysis in section 21.4 while the coal inventory is applied in the baseline scenario.

Table 3.1 compares different inventories for coal as well as gas based electricity. In **Table 3.1** a data set is shown for Dutch plants because this is used in the LCAfood database (Nielsen et al. 2005) where it is assumed to represent Danish plants. Comparing of the data sets in **Table 3.1**, it appears that the environmental impacts from plants from the Netherlands and NORDEL seem to be smaller than from plants attached to the UCPTE/UCTE grid. Furthermore, it appears that the contributions to global warming from the power plants in ecoinvent are smaller than the ones from ETH-ESU. The reason for the smaller contributions to global warming in the ecoinvent data is probably that these data represent 6-10 years newer power plants.

It is chosen to use the data for NORDEL from ecoinvent because these data best represent the technology in Denmark and because these data are the most updated. In case of electricity consumption outside Denmark ecoinvent data for UCPTE are used. The data in ecoinvent includes particle removal, DeNOx, DeSOx, waste water treatment, disposal/recycling of ash, transport of fuels and ancillaries and capital goods such as production maintenance and disposal of the power plant[9] (Röder 2003).

---

[7] UCPTE/UCTE includes: Austria, Belgium, Germany, Spain, Luxembourg, Italy, the Netherlands, Greece and Portugal.

[8] NORDEL: Denmark, Finland, Norway and Sweden.

[9] Interventions related to production, maintenance and disposal of the power plant has due to an error in ecoinvent not been included in the original database entry (Bauer 2006). Therefore, this module has been manually applied to the data set in SimaPro.

The data described above only comprises environmental interventions related to electricity ex plant. Therefore, loss in the grid and production, maintenance and disposal of the grid also have to be taken into account. Data on loss in the grid is described above. Only one life cycle inventory on production, maintenance and disposal of the grid have been identified. The data are related to transmission and distribution of 1 kWh and are available in SimaPro in the ecoinvent database and they are described in Emmenegger et al. (2003). The data from ecoinvent distinguishes between high voltage grid (>150 kV), medium voltage grid (50-60 kV) and low voltage grid (<1 kV). As described in the above this study only distinguishes between high and low voltage grids. Therefore the medium voltage grid in ecoinvent is included in the low voltage grid in this study. The ecoinvent data are based on transmission and distribution of electricity in Switzerland and loss in the grid is 13%. Since loss in the Danish grid is 4.8% this value is used instead. The used data are shown in **Table 3.2**.

Grid	Database	Loss
High voltage grid (150-400 kV)	'Electricity, high voltage, at grid/DK' (ecoinvent 2004)	1,0% of electricity at plant
Low voltage grid (<60 kV)	'Electricity, medium voltage, at grid/DK' (ecoinvent 2004) plus 'Electricity, low voltage, at grid/DK' (ecoinvent 2004)	3,8% of electricity at plant

Table 3.2: Used LCI data on production, maintenance and disposal of transmission and distribution grid in Denmark. The losses in the grid in the ecoinvent data are deleted and the given values in the table are used instead.

The applied inventory data for marginal electricity in all relevant countries are summarised in **Table 3.3**.

3.2 Electricity from the grid in Malaysia and Indonesia

Malaysia

The electricity mix in Malaysia is constituted by 28% coal, 3% oil, 62% natural gas and 7% hydro (IEA 2007). The marginal source of electricity in Malaysia is regarded as coal. The reason for that is that the share of coal based electricity in Malaysia has increased rapidly the last few years and will continue to increase in the future (see below) and that coal based elctricity is the cheapest and thereby the most competitive (Mohammed and Lee 2006). The share of coal based electricity has increased from ~7% in 2000 to 28% in 2004 (IEA 2007). According to Mohammed and Lee (2006) the share is expected to increase futher to around 40-45%. At the same time the share of natural gas is expected to decrease to less than 50% (Mohammed and Lee).

According to IEA (2007) the Malaysian coal based electricity production in 2004 was 83.3 PJ while the use of coal in the coal power plants was 197.9 PJ. This corresponds to an average efficience of coal power plants in Malaysia at 42%. The use of coal in Malaysia's coal power plants in 2004 was 8,819 kt (IEA 2007). Comparing use of coal in terms of mass with the use of coal in terms of calorific units given above, this corresponds to energy content of coal at 22.4 MJ/kg.

The efficiency at 42% is relatively high. According to **Table 3.1** the efficiency of coal power plants (condensing mode) in Central Europe and Scandinavia are 36% and 42% respectively which is lower than Malaysian average. The reason for this is that the coal fired plants in Malaysia are newer than the ones in Europe and Scandinavia. Since the share of coal fired plant in Malaysia has faced a drastic increase the last few years, the plants in use are relatively new. According to Weidema (2003) no new planned power plants in Scandinavia have been based on coal since the mid 1990ies. Also in Central Europe, not many new coal fired plants have been buildt[10]. Therefore, the coal power plants in Central Euroepe and Scandinavia are older than the ones in

---

[10] This statement is based on the fact that the coal based share of electricity production in Central and Eastern Europe has been almost constant from around mid 1990ies to 2004 (IEA 2007).

Malaysia, and consequential it is not unlikely that the Malaysian coal power plants have a higher efficiency than European plants.

Since the efficiency of Malaysian and Scandinavian plants is the same, it is chosen to apply the same inventory data for electricity from the grid in Malaysia as in Denmark. Inventory data for electricity in Denmark are described in section 3.1, **Table 3.1**.

In addition to the inventory data for production of electricity loss in the grid and the production, maintenance and disposal of the transmission grid also are to be included. According to IEA (2007) the loss in the grid in Malaysia in 2004 was 4.9% of the produced electricity.

The same inventory data on production, maintence and disposal of the grid as for Danish electricity is applied, see **Table 3.2**.

The applied inventory data for marginal electricity in all relevant countries are summarised in **Table 3.3**.

Indonesia

The electricity mix in Indonesia is constituted by 40% coal, 30% oil, 16% natural gas, 6% geothermal and 8% hydro (IEA 2007). According to APERC (2006, p 36) 54% of the new capacity requirements for electricity generation is predicted to be coal while natural gas accounts for 40%. This combined with the fact that coal based electricity is the cheapest source of electricity lead to the assumption that coal is the marginal source of electricity in Indonesia.

According to IEA (2007) the Indonesian electricity production based on coal in 2004 was 173.6 PJ while the use of coal in the coal power plants was 589.2 PJ. This corresponds to an average efficience of coal power plants in Indonesia at 29%. The use of coal in Indonesia's coal power plants in 2004 was 22,882 kt (IEA 2007). Comparing use of coal in terms of mass with the use of coal in terms of calorific units given above, this corresponds to energy content of coal at 25.7 MJ/kg.

Losses in the grid are 13% (IEA 2007)

The inventory data for coal based electricity in Denmark are adjusted in order to reflext electricity in Indonesia, i.e. adjusting the input of coal burned to fit an efficiency at 29%. The same inventory data on production, maintence and disposal of the grid as for Danish electricity is applied, see **Table 3.2**.

The applied inventory data for marginal electricity in all relevant countries are summarised in **Table 3.3**.

Malaysia and Indonesia

When electricity is used in Malaysia and Indonesia regarded as one region, the marginal source of electricity is assumed to be represented as the average of the margnal sources of electricity in the two countries.

3.3 Electricity from the grid in Brazil

The electricity mix in Brazil in 2004 is constituted by 3% coal, 3% oil, 5% natural gas, 3% biomass, 83% hydro (IEA 2007). The marginal source of electricity in Brazil is regarded as natural gas. The reason for that is that the share of the most important source of electricity, hydro, is predicted to decrease from 2002 to 2030 to the benefit of natural gas (EIA 2004, p 224).

According to IEA (2007) the Brazilian electricity production based on natural gas in 2004 was 59.4 PJ while the use of natural gas in the gas fired power plants was 180.9 PJ. This corresponds to an average efficience of gas fired power plants in Brazil at 33%.

Distribution losses in the grid in Brazil in 2004 were 17% (IEA 2007).

The inventory data for gas based electricity in Denmark are adjusted in order to reflext electricity in Brazil, i.e. adjuting the input of coal burned to fit an efficiency at 33%. The same inventory data on production, maintence and disposal of the grid as for Danish electricity is applied, see **Table 3.2**.

The applied inventory data for marginal electricity in all relevant countries are summarised in **Table 3.3**.

3.4 Electricity from the grid in Canada

The electricity mix in Canada in 2004 is constituted by 17% coal, 4% oil, 5% natural gas, 1% biomass, 15% nuclear, 57% hydro (IEA 2007). According to APERC (2006, p 12) the share of coal, nuclear and hydro will decrease from 2002 to 2030 while the share of natural gas will increase. Therefore, natural gas is regarded as the marginal source of electricity in Canada.

Since a considerable share of the gas fired power plants in Canada are combined heat and power plants, it is not possible calculating the efficiency from statistics in IEA (2007).

The distribution losses in the grid in Canada were 6.6% in 2004 (IEA 2007).

Due to lack on data on the efficiency of gas fired power plants in Canada, it is chosen to apply inventory data for Canadian gas based electricity as the same as Danish gas fired power plants, see section 3.1, i.e. applying an efficiency at 41%. The same inventory data on production, maintence and disposal of the grid as for Danish electricity is applied, see **Table 3.2**.

The applied inventory data for marginal electricity in all relevant countries are summarised in **Table 3.3**.

3.5 Electricity in different countries, summary

Based on the efficiencies and losses in the grid described in section the previos sections, **Table 3.3** summarises the applied inventory data for marginal electricity in Denmark (DK), Malaysia (MY), Indonesia (IN), Brazil (BR) and Canada (CAN).

1 MJ electricity, coal/gas, at plant	**DK**	**MY**	**IN**	**BR**	**CAN**	**Applied LCI data**
Coal burned in power plant	2.38 MJ	2.38 MJ	3.45 MJ	-	-	Hard coal, burned in power plant/NORDEL
Gas burned in power plant	-	-	-	3.03 MJ	2.44	Natural gas, burned in power plant/NORDEL
1 MJ electricity, coal/gas, at user	**DK**	**MY**	**IN**	**BR**	**CAN**	**Applied LCI data**
Electricity, coal, at plant	1.048 MJ	1.049 MJ	1.130 MJ	-	-	see 'Electricity, coal, at plant' above
Electricity, gas, at plant	-	-	-	1.170 MJ	1.066 MJ	see 'Electricity, gas, at plant' above
High voltage grid (capital goods)	1 MJ	1 MJ	1 MJ	1 MJ	1 MJ	Modified version of 'Electricity, high voltage, at grid/DK' , (ecoinvent 2004), see **Table 3.2**
Low voltage grid (capital goods)	1 MJ	1 MJ	1 MJ	1 MJ	1 MJ	Modified version of 'Electricity, medium voltage, at grid/DK' (ecoinvent 2004), see **Table 3.2**
	1 MJ	1 MJ	1 MJ	1 MJ	1 MJ	Modified version of 'Electricity, low voltage, at grid/DK' (ecoinvent 2004), see **Table 3.2**

Table 3.3: Summary of the applied inventory data related to 1 MJ marginal electricity at user in different countries.

3.6 District heating in Denmark

In both the agricultural, oil mill and refinery stages heat is used and produced. The main part of this heat is produced on-site on the farm when drying crops, in the biomass plant that burnes straw, and in the power centrals of the oil mill and refinery. The emissions from on-site production of heat are dealt with in the respective processes. In addition to on-site heat production sometimes district heating is used or displaced. This is mainly for heating of administration buildings and laboratories in the rapeseed oil mill and refinery, and processes that displace district heat; energy production from straw in agriculture substitutes district heating. Interventions from marginal district heating in Denmark vary from region to region or even from town to town since different heat plants are used and a variety of local circumstances determine which supplier that is the marginal. Therefore point of departure is taken in district heating in Aarhus where the oil mill AarhusKarlshamn is situated. However, this may not be representative for substituted district heating from straw in agriculture. Therefore, a sensitivity analysis of this assumption is presented in section 21.5.

The supply of heat (hot water) to the district heating system in Aarhus is distributed on supply from the central power plant, Studstrupværket (~86%), waste incineration (~10%), excess heat from industry (~2%), peak load oil boilers (<1%) and other minor suppliers (Århus Kommunale Værker 2005). According to Århus Kommunale Værker (2005) changes in demand for heat is regulated through the heat production at Studstrupværket. Heat from waste incineration is constrained by waste generation, the minor supply from industry is constrained by its production and the boiler plants are only used in a fraction of the time in situations with peak load or in cases of failure of supply from other sources. Thus, Studstrupværket is considered as the marginal supplier of heat to the district heating system in Aarhus. Studstrupværket regulates the ratio in which it produces electricity and heat by continuously switching between condensation pressure and back pressure. In pure condensation pressure mode the energy efficiency is ~40% (only electricity) and in pure back pressure mode its ~80% (Andersen 2005), see **Figure 3.2**. In back pressure mode the 80% efficiency is distributed on ~52% points heat and ~28% points electricity, see **Figure 3.2**.

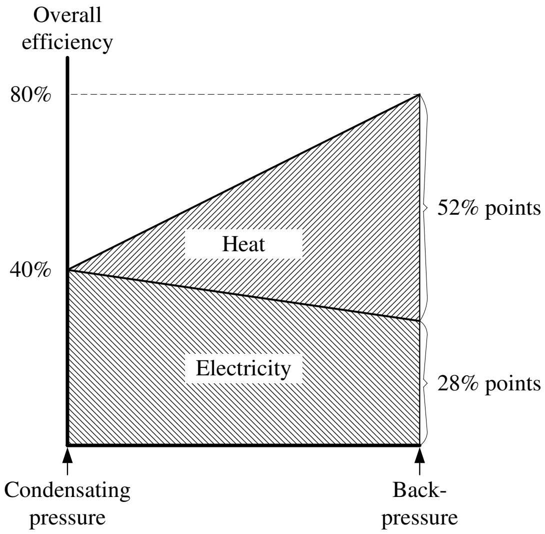


Figure 3.2: Relation between heat and electricity efficiencies and pressure mode for a combined heat and power plant that can continuously switch between condensation pressure and back pressure.

If demand for heat increases 1 MJ, this can be met in two ways: 1) the position on the scale between condensation pressure and back pressure is mowed towards back pressure, or 2) by increasing the power input of coal. Meeting the demand by 1), the total energy input at Studstrupværket is unchanged, the electricity output decreases and the heat output increases – but the heat production increases more than the electricity production decreases. The other way around, meeting the demand by 2), both the total energy input at Studstrupværket and the output of heat and electricity increase. The marginal energy input in order to produce 1 MJ heat is calculated assuming a situation combining 1) and 2) keeping the production of electricity constant. Since the two product outputs (heat and electricity) at Studstrupværket can be varied independently, the interventions from the product of interest should be found by including the consequences of changing the output of this co-product while keeping the other output constant (Weidema, 2003, p 87, 90). The calculation takes its point of departure in two different positions on the scale between condensation pressure and back pressure. According to Andersen (2005) the output of electricity decreases approximately linear by increased heat production, see **Figure 3.2**. Since the heat and electricity efficiencies are linear with the position on the scale, it does not matter where on the scale the change takes place. Therefore, the calculation takes its point of departure in heat production at 100% back pressure. Electricity production in back pressure mode is 0.54 MJ per 1 MJ heat. Keeping the total output of electricity constant, the interventions from marginal production of 0.54 MJ electricity must be subtracted from the intervention related to co-production of 1 MJ heat and 0.54 MJ electricity. In section 3.1, marginal electricity is identified as coal based electricity produced in condensation pressure with approximately 40% efficiency, which is the same as at Studstrupværket. If the marginal technology for electricity production is the same as the technology at Studstrupværket (coal), it makes no difference if this electricity is produced at Studstrupværket or another marginal electricity supplier. Thus, the energy input related to production of 1 MJ marginal heat at Studstrupværket can be determined by the difference between (1) the energy input for producing 1 MJ heat and 0.54 MJ electricity in back pressure mode at Studstrupværket and (2) the energy input for producing 0.54 MJ electricity in condensation pressure mode at a marginal power plant. Using the energy efficiencies shown in **Figure 3.2**, (1) can be determined as 1.93 MJ and (2) as 1.35 MJ. Thus, the marginal energy input related to production of 1 MJ heat is 0.58 MJ. However, in order to keep the inventory open for sensitivity analysis with other technologies as marginal, the inventory shown in **Table 3.4** is based on 1.93 MJ burned coal at Studstrupværket and displacement of 0.54 MJ marginal electricity.

According to Andersen (2005) there is not excess heat from waste incineration and industry at any time at the year. Thus, the calculated energy input related to production of 1 MJ marginal heat is valid as well in summer as winter seasons.

Studstrupværket is fired with ~92% coal, ~7% straw and 1% fuel oil (Elsam 2005). According to Elsam (2005) the amount of straw used is constrained by capacity at the plant. Thus coal is the marginal source of fuel to Studstrupværket. In section 3.1 inventory data on marginal electricity based on coal is described; 'Hard coal, burned in power plant/NORDEL' (ecoinvent 2004). However, the ecoinvent database also contains inventories on coal burned in power plants in other countries, but this is of minor interest since power plants connected to the NORDEL grid is most representative for Studstrupværket.

Furthermore 5.8 kJ electricity per MJ delivered heat is used. The inventory data for 1 MJ district heating in Aarhus is summarised in **Table 3.4**. Water consumption for compensation of loss of water in the grid and production, maintenance and disposal of the district heating grid is not included.

LCI-data for district heating in Aarhus	Amount	LCI data used in this study
Coal burned at Studstrupværket	1.93 MJ	'*Hard coal, burned in power plant/NORDEL*' (ecoinvent 2004)
Displaced electricity (electricity at plant)	-0.54 MJ	Electricity, see **Table 3.3**
Electricity (electricity at user)	0.0058 MJ	Electricity, see **Table 3.3**

Table 3.4: LCI of 1 MJ district heating in Aarhus.

4 Transport

Transport processes are used in several processes in the agricultural, oil mill, refinery and transport stages. This chapter describes inventory data for transport, either per tkm (transportation of 1 tonne at a distance of 1 kilometre) or per MJ diesel burned. Transport distances are described together with the processes that use transport, i.e. transport of the materials used in the relevant process. Transport types included are transport by truck, by oceanic freighter and burning of diesel in agricultural machinery (traction).

4.1 Transport with lorry

Several inventories are available for transport with lorry. There are also inventories for different sizes of lorry available. In this study three different lorries are applied; 10-16t, 25-28t and 40-48t trucks.

Different data sources operate with different assumptions on load factor, i.e. the effective transported load over one kilometre. Two factors determine the load factor; share of a round-trip where the truck is empty and the actual working load compared to load capacity. In a literature review in Spielmann et al. (2004) load factors in the interval 0.25 – 0.62 have been identified. Load factors exceeding 0.5 means that cargo is transported on both the outward journey and on the return trip.

The load factors applied in the ecoinvent database (Spielmann et al. 2004) and the EDIP database (EDIP 2000) are shown in **Table 4.1**.

Lorry	Load factor	
	Ecoinvent (Spielmann et al. 2004)	EDIP (2000)
Lorry 10-16 t (load capacity 5-8 t)	0.42	0.48
Lorry 17-28 t (load capacity 10-17 t)	0.47	0.48
Lorry 29-48 t (load capacity 18-32 t)	0.46	0.70

Table 4.1: Load factors in the ecoinvent and EDIP databases. (Spielmann et al., 2004 and EDIP 2000)

Regarding transport of oil seeds, vegetable oils and ancillary materials it is assumed that load factors above 0.5 are unrealistic. This is because this study concerns products (oil crops to oil mill, oil to market) and ancillary material to agriculture and oil mills where it is assumed that no cargo is sent back from the place of delivery. Thus, it is assumed that the lorries make the return trip empty. Therefore, the load factors from ecoinvent are applied in this study.

Analysing existing inventories for transport with lorry from the EDIP and ecoinvent databases in SimaPro and using the EDIP97-method for LCIA it appears that global warming, acidification and ecotoxicity are the most significant impact categories. However, the contributions to ecotoxicity, which mainly originates from strontium emissions from discharged water from crude oil production, are considered as either very uncertain or as related to an error in the LCIA-method; EDIP97 (Wenzel et al., 1997 and Hauschild and Wenzel 1998). Therefore, contributions to ecotoxicity when analysing the different inventories are not included in a comparison of the inventories. Since the contribution to global warming and acidification is mainly related to the amount of diesel burned, this is used for comparison of the inventories. Also in order to assess the comprehensiveness of the inventories, the number of included emissions from operation of the vehicles is included in the comparison. In **Table 4.2** inventories for 29-48 tonne lorries are compared from three different sources. The figures for different inventories of 10-16 tonne and 17-28 tonne lorries vary somehow in the same ratio as for 29-48 tonne lorries. Therefore, these data are not shown.

LCI-data for transport	Number of included emissions to air	Diesel consumption	Description of data
Truck 40-48t EU2 70%, kgkm, mixedDK (EDIP 2000)	14	336 g/km	*Time:* Data from late 1990ies *Geography:* Denmark *Technology:* Average; 80% motorway, 15% highway and 5% city, EURO class 2 engine *Co-product allocation*: Not relevant *Capital goods:* Not included
Truck 40-48t EU2 70%, kgkm, motorway (EDIP 2000)	14	319 g/km	*Time:* Data from late 1990ies *Geography:* Denmark *Technology:* Average; 100% motorway, EURO class 2 engine *Co-product allocation*: Not relevant *Capital goods:* Not included
Truck 40t (ETH-ESU, 1996)	13	-	*Time:* Data from early 1990ies *Geography:* USA, Switzerland and Germany *Technology:* Average, not specified *Co-product allocation*: Not relevant *Capital goods:* Construction, maintenance and disposal of trucks and roads are included
Transport, lorry 40t (ecoinvent 2004)	21	348 g/km	*Time:* Data from early 2000s *Geography:* Switzerland *Technology:* Average, fleet composition according to EURO classes *Co-product allocation*: Not relevant *Capital goods:* Construction, maintenance and disposal of trucks and roads are included

Table 4.2: Comparison of LCIs of transport with truck 29-48 tonne. The inventories are compared within the number of included emissions from operation and diesel consumption per kilometre. The applied data are marked with a black dotted frame.

It appears from **Table 4.2** that the difference in fuel consumption is not significant; it varies from 319 g/km to 348 g/km. The compared data sets represent different geographical regions. EDIP represent Denmark, ecoinvent represent Switzerland and ETH-ESU represent USA, Switzerland and Germany. The most comprehensive data are the ones from ecoinvent; they include 21 emissions to air from operation of vehicle and include inventories on production, maintenance and disposal of vehicles as well as roads. It is chosen to apply transport inventories from ecoinvent. The applied inventories for transport with lorries from ecoinvent comprises three different lorry sizes: 16t, 28t and 40t. The applied data are shown in **Table 4.3** for different transport distances and for different amounts of annual goods to the considered production unit. The distribution of lorry sizes as a function of distance and annual transported goods is based on rough estimates.

Distance/transported goods	0 – 9 tonne/year	10 – 99 tonne/year	≥100 tonne/year
0 - 99 km	Transport, lorry 16t	Transport, lorry 28t	Transport, lorry 28t
100 – 999 km	Transport, lorry 16t	Transport, lorry 28t	Transport, lorry 40t
≥1000 km	Transport, lorry 28t	Transport, lorry 28t	Transport, lorry 40t

Table 4.3: Applied inventories for transport with lorry from ecoinvent (2004). The lorry sizes applied vary dependent on the distance and annual transported goods.

4.2 Transport with ocean tanker

The only processes in this study that include transport with ship are transportation of palm oil from Malaysia to Europe and transportation of agricultural chemicals (fertilisers and pesticides). It is presumed that this is done in large tankers. Two inventories for oceanic ship transport with tanker have been identified. These are compared in **Table 4.4** within diesel consumption and number of included emissions for operation.

LCI-data for transport	Number of included emissions to air	Diesel consumption	Description of data
Tanker oceanic ETH U (ETH-ESU)	24	1.8 g/tkm	*Time:* Data from early 1990ies *Geography:* Not relevant *Technology:* Average, ship size not specified. Bilge oil waste and anti fouling agents are included. *Co-product allocation*: Not relevant *Capital goods:* Construction, maintenance and disposal of ship are included. Harbour not included.
Transport, transoceanic tanker/OCE (ecoinvent 2004)	25	1.3 g/tkm	*Time:* Data from early 2000s *Geography:* Not relevant *Technology:* Average, 150,000 t capacity. Bilge oil waste and anti fouling agents are included. *Co-product allocation*: Not relevant *Capital goods:* Construction, maintenance and disposal of ship and harbour are included. Harbour operations are also included.

Table 4.4: Comparison of LCIs of transport with tanker ship. The inventories are compared within the number of included emissions from operation and fuel consumption per tkm. The applied data are marked with a black dotted frame.

It appears from the table that the difference between the two inventories is not significant within the compared factors. It is chosen to apply the inventory from ecoinvent since this data set is the newest, most well documented and most comprehensive; it includes harbour operations and harbour related capital goods.

4.3 Traction

The term traction covers burning of diesel in agricultural machinery and it is measured in MJ. Traction includes production, transport and burning of diesel and use of lubricants. Life cycle inventories for traction are identified in the ecoinvent database (Nemecek et al. 2003) and the LCAfood database (Nielsen et al. 2005). **Table 4.5** compares the two inventories.

Since, no of the two inventories include lubricants, this has been added. According to Dalgaard et al. (2001) the use of lubricants is proportional with the use of diesel. Dalgaard et al. (2001) specifies the use of lubricants as 3.6 MJ/litre diesel burned in tractor. Assuming same density and calorific value for lubricant as for diesel (see Appendix 1: Data on fuels), the use of lubricants can be calculated as 0.099 kg lubricant/kg diesel, or 0.0024 kg lubricant/MJ diesel. The inventory on production of lubricants '*Lubricating oil, at plant/RER*' (ecoinvent 2004) has been applied. The ecoinvent data on lubricants do not include emissions related to the fate of the lubricant after it is used. It is assumed that lubricants end as emissions to air (when burned or heated up in the motor) and soil (when dripping). In both cases the oil will degrade into mainly CO_2 and water. Traces of heavy metals, SO_2, NO_x, NMVOC and other additives in the oil will also be emitted. However due to lack of data and uncertainties in determining the fate, it is chosen only to account for CO_2-emissions. According to Meyer et al. (1994) the CO_2 emission from burning of diesel is 74 g/MJ (This is also in accordance with the ecoinvent data in **Table 4.5**). 74 g CO_2/MJ lubricant corresponds to 3.1 kg CO_2/kg. Hence, this is added to the ecoinvent data on lubricants.

Interventions for traction	**Amount (g/MJ diesel)**		**LCAfood compared to Ecoinvent, factor**
	Ecoinvent (Nemecek et al. 2003, p 56-59)	**LCAfood (Nielsen et al. 2005)**	
Fuel consumption			
Diesel	23.1	28.0	Diesel
Emission			
Carbon dioxide (CO_2)	74.5	87	1.2
Sulphur dioxide (SO_2)	2.41E-02	2.50E-02	1.0
Methane (CH_4)	3.08E-03	4.10E-03	1.3
Benzene	1.74E-04	-	-
Cadmium (Cd)	2.39E-07	-	-
Chromium (Cr)	1.19E-06	-	-
Copper (Cu)	4.06E-05	-	-
Dinitrogen monoxide (N_2O)	2.86E-03	9.10E-03	3.2
Nickel (Ni)	1.67E-06	-	-
Zink (Zn)	2.39E-05	-	-
Benzo(a)pyrene	7.16E-07	-	-
Ammonia (NH_3)	4.77E-04	-	-
Selenium (Se)	2.39E-07	-	-
PAH (poly cyclic hydrocarbons)	7.85E-05	-	-
Hydro carbons (HC, as NMVOC)	6.80E-02(11)	1.17E-01	1.7
Nitrogen oxides (NO_x)	1.06(11)	1.10	1.0
Carbon monoxide (CO)	1.50E-01(11)	2.80E-01	1.9
Particulates (<2.5 μm)	1.07E-01(11)	7.10E-02	0.7

Table 4.5: Comparison of life cycle inventory data for 1 MJ traction in ecoinvent and LCAfood.

It appears from **Table 4.5** that ecoinvent includes more emissions than LCAfood and for most interventions the amount in LCAfood is higher than in ecoinvent. Most of this difference can be ascribed to difference in the applied calorific values in the two data sources. Comparing with other data sources, the calorific value at 43.3 MJ/kg diesel in ecoinvent seems more correct than the 35.7 MJ/kg which is used in LCAfood (see also Appendix 1: Data on fuels', where a calorific value at 41.9 MJ/kg is given).

Since the data in ecoinvent, shown in **Table 4.5** are the most comprehensive regarding the number of emissions included and uses the most normally applied calorific value for diesel, it is chosen to apply these data in this study. The use of lubricant at 0.0024 kg lubricant/MJ diesel and an emission of 3.1 kg CO_2/kg lubricant are added to the ecoinvent data. The applied inventory data for production of diesel is: ‘Diesel, at regional storage/RER’ (ecoinvent 2004).

4.4 Transport with passenger car

The use of transport with passenger car in this study is insignificant compared to the other means of transportation. The applied inventory data is ‘Transport, passenger car/RER’ (ecoinvent 2004). Beside burning and production of petrol, the following processes are also included in the data set: construction, maintenance and disposal of cars and roads. Since this data set is in the unit of personkm, it is transformed into the unit of km. According to ecoinvent (Spielmann et al. 2004), 1 personkm corresponds to 0.629 km. Thus, the ecoinvent data are transformed into the unit of km by multiplying with 0.629 km/personkm.

---

[11] Emission of HC, NO_x, CO and particles in ecoinvent are not related to kg or MJ diesel burned. Instead it is related to engine speed, engine power and operation time. Anyhow, in order to estimate the emissions, they are calculated as the average per amount of diesel from the five most significant field work processes which are: Combine harvesting, ploughing, fertilising (by broadcaster), harrowing (tine harrow) and rolling (see **Table 5.10**). The emissions for different field work processes are given in Nemecek et al. (2003).

5 Agricultural stage: Rapeseed

The rapeseed plant (Brassica napus) is an annual crop, it grows to a height of approximately 140 cm and the rapeseeds contain around 44% oil and 23% protein (Møller et al. 2000; Dansk Landbrugsrådgivning 2007).

The agricultural stage includes activities related to cultivation of rapeseed. The inventory takes its point of departure in cultivation of 1 hectare of rapeseed in Denmark. Most data are from 2002 - 2005. Two types of rapeseed exist; spring and winter rapeseed. The inventory is based on average production of conventional rapeseed in Denmark in 2004 where spring rapeseed constitutes approximately 1% of the rapeseed cultivated area. In 2004 an area of 1,218 km^2 was planted with rapeseed in Denmark (FAOSTAT 2006). That corresponds to 3% and 5% of the total land area and the arable land in Denmark respectively.

The following description of rapeseed cultivation is mainly based on Dansk Landbrugsrådgivning (2005a and 2005b).

The production target for rapeseed is a high yield of seed with a high content of oil and protein and a low content of glucosinolate and euricic fatty acids. Rapeseed can be grown on sandy as well as clay soils. In order to avoid fungus attack there should be at least four years between two rapeseed crops (and other crops with hollow stem). Normally 50 – 100 plants per m^2 are appropriate. Before sowing the soil should be sprayed with herbicides to control weeds, ploughed and compacted. The seeds are normally treated in order to avoid pest attack during seed germination. Winter rapeseed is sown between the 10th and 25th of August and spring rapeseed is sown in the beginning of April or later if there is a risk of night frost. The need for nitrogen fertilisers depends on the crop (winter/spring rapeseed), soil type and previously crop and application of manure. Other fertilisers include phosphorus (P), potassium (K), manganese (Mg), sulphur (S), and possibly boron (B) on sandy soils. Weeding of the rows between the rapeseed plants (inter-row tillage) are typically done twice during autumn for winter rapeseed and twice for spring rapeseed during spring. In addition weed and pest control can be done applying several different herbicides and insecticides. Harvesting typically takes place between 2nd of July and 5th of August for winter rapeseed and between 5th and 20th of August for spring rapeseed. Harvesting can be done either by laying in swaths or by a conventional harvester. Both methods are used. When harvesting by laying in swaths the harvested crop is drying and possible ripening in the field and is picked up later. This method is appropriate if ripeness is not the same all over the field (Dansk Landbrugsrådgivning, 2005a). By conventional harvesting the rapeseed and possible straw are picked up from the field immediately. This method is appropriate if ripeness is equal all over the field.

Figure 5.1 , **Figure 5.2** and **Figure 5.3** show a flowering rapeseed field, harvesting of rapeseed and harvested rapeseed respectively.

Figure 5.1: Flowering rapeseed field. Picture taken by Jannick H Schmidt near Aalborg in 2007.

Figure 5.2: Harvesting of rapeseed. Picture obtained from: http://jyndevad.okologgen.dk (May 2007)

Figure 5.3: Harvested rapeseed. Picture taken by Jannick H Schmidt in 2007. Samples provided by Nordic Folkecenter for Renewable Energy.

According to Dansk Landbrug (2004) rapeseed from Danish agriculture must maintain the specifications given in **Table 5.1**.

Specifications for rapeseed	Content
Oil	40%
Water	8-9%
Pure commodity	100%
Pure seed	98%
Glucosinolate	25 micro mol/mol
Euricic fatty acids	<2%
Free fatty acids	<2%

Table 5.1: Specifications for rapeseed from Danish agriculture. If the seed do not maintain the specifications the transfer price is adjusted. (Dansk Landbrug 2004). The water content in Dansk Landbrug (2004) (9%) vary slightly from the water content given in Møller et al. (2000) which is 8%.

5.1 Product flow in agricultural stage

The inventory of the agricultural stage is divided into the unit processes shown as shaded boxes in **Figure 5.4**. The product flow is determined per hectare from statistical data on Denmark's production of rapeseed from Statistics Denmark (Danmarks Statistik 2006), see descriptions below the figure.

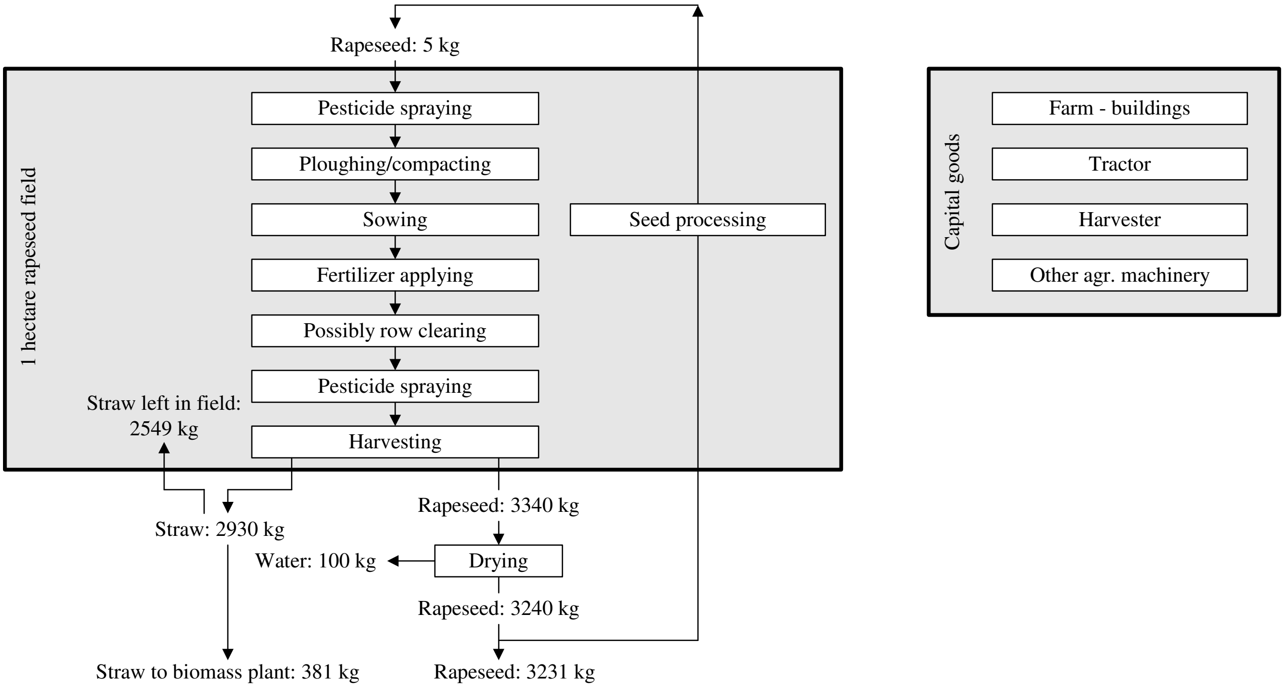


Figure 5.4: Product flow related to cultivation of 1 ha rapeseed field in 1 year. The grey shaded boxes represent the unit processes in the agricultural stage.

Seed input: According to Dansk Landbrugsrådgivning (2005a) 4-6 kg seed/ha is needed in order to achieve the desired plant density. 5 kg seed/ha is applied in this study.

Rapeseed output for seed production: According to section 5.4 the land use related to production of 5 kg seed corresponds to the lands use related to production of 9 kg conventional rapeseed.

Water loos in drying: According to section 5.3, 100 kg of water is lost in the drying process per ha.

Yield: The rapeseed yield is applied as the yield in 2005 calculated from linear regression of yields from 1990 to 2005, see **Table 5.2**. Yields are obtained from FAOSTAT (2006). The expected yield in 2005 can be calculated as 3.24 t/ha using the equation in **Figure 5.5**. For comparison with yields determined using other methods see **Table 5.2**.

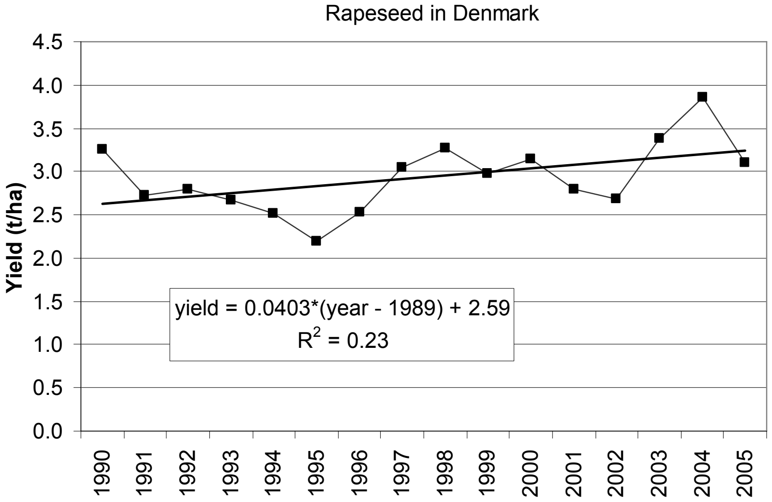


Figure 5.5: Rapeseed yields in Denmark 1990 to 2005. The linear regression line and its corresponding equation and R^2 are also shown. The yields are obtained from Danmarks Statistik (2006).

Region	Yield 2005 (based on regression 1990-2005)	Average yield 1990-2005	Average yield 2000-2005	Yield 2003	Yield 2004	Yield 2005
Denmark	3.24 t/ha	2.93 t/ha	3.16 t/ha	3.38 t/ha	3.86 t/ha	3.10 t/ha

Table 5.2: Rapeseed yield in Denmark determined using different methods. The applied yield is marked with a dotted line.

In order to clarify calculations and to perform sensitivity analysis for cultivation of different soils the yield is also determined for sand and clay soils. This is based on averages of yields for four soil types in Plantedirektoratet (2005a) which specify the expected yield. The calculation of averages is clarified and explained in **Table 5.14** and **Table 5.16**. **Table 5.3** shows the applied yields in this study.

The distribution of agricultural soil types in Denmark is determined to be 41% sand and 59% clay, see **Table 5.13**. Applying these numbers to the yields given in Plantedirektoratet (2005a) it appears that the calculated yields for average soil is in surprisingly good accordance with the yield in **Table 5.2**. Sine only 1% of the rapeseed grown in Denmark is spring rapeseed, **Table 5.3** only shows data for winter rapeseed. As it appears in in **Figure 5.5** there are great yield variations from year to year. Thus, the good accordance may be a coincidence. Therefore, the yields from Plantedirektoratet for sand and clay soils are adjusted to meet the level estimated in Danmarks Statistik (2006), see the lower part of **Table 5.3**.

Calculated yields based on Plantedirektoratet (2005a) (tonne/ha)	Average soil (41% sand / 59% clay)	Sand	Clay
	(Plantedirektoratet, 2005a)		
Winter rape	3.30	2.85	3.62
Applied yield in this study (tonne/ha)	**Average soil (41% sand / 59% clay)**	**Sand**	**Clay**
	(Danmarks Statistik 2006)		
Winter rape	3.24	2.79	3.55

Table 5.3: Yields based on Plantedirektoratet (2005a) and Danmarks Statistik (2006).

Comparing to yields in the major rapeseed producing countries shown in **Table 5.4**, it appears that the yield in Denmark is similar to the yield in other major rapeseed producing countries; Germany, France and the UK. However, the yields in Poland and Czech Republic seem to be lower.

Country	Yield: 2002-2004 (tonne/ha)	Average applied artificial N-fertiliser (kg N/ha)
Germany	3.3	153
France	3.3	156
Poland	2.4	100
United Kingdom	3.2	112
Czech Republic	2.5	91
Denmark	3.2	119

Table 5.4: Average yields of rapeseed during 2002 to 2004 in the six major rapeseed producing countries in Europe. Data on yield based on Eurostat (2006), see **Table A2.2** in Appendix 2: Rapeseed production in Europe in 2004. Data on fertiliser is based on Eurostat (2006) (for consumption of artificial N-fertiliser) and FAOSTAT (2006) (for agricultural land).

There may be several reasons for varying yield in the different countries. Climate, fertiliser application and weed control are considered as important factors. It appears from **Table 5.3** that the input of artificial fertiliser in Poland and Czech Republic is lower than in the other countries. The yields in Germany, France, UK and Denmark are almost equal even though the input of artificial fertilizer in UK and Denmark is lower than in Germany and France. The reason for that may be due to difference in input of manure. **Figure 5.6** illustrates the effect of manue application. It appears from the figure, that application of manue one year has effect on the yield the following year. Above explanation can only be used for illustration because several factors influence the yield.

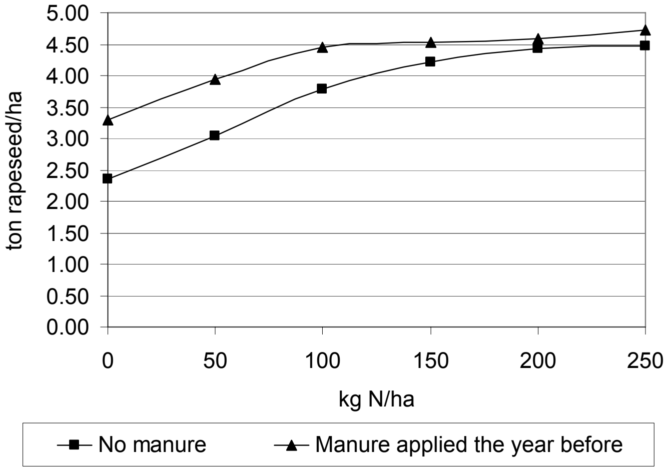


Figure 5.6: Correlation between fertiliser input (kg N/ha) and yield. The numbers are shown for fields with and without application of manure the previous season. The difference between the two graphs shows that application of manure provides nutrients available for crops the following season. Based on Pedersen (2005, p 162).

Straw: Rapeseed straw is co-produced with rapeseed. Different values for straw production have been identified. Jensen et al. (2005) specify a straw to crop ratio at 0.83 for high yield winter rapeseed cultivation on clay (3,600 kg rapeseed/ha) soils and 1.04 for low yield cultivation on sandy soils (2,300 kg rapeseed/ha). Brandt (2003) specifies a straw to crop ratio at 2.2 which represent production in Canada. A lower yield in Canada may explain some of the high ratio for production in Canada compared to Denmark (see data from Jensen et al 2005 above). According to FAOSTAT (2006) the average yield for rapeseed cultivation in Canada during 2003 to 2005 is only 1,550 kg /ha. Danmarks Statistik (2006) also uses a straw to crop ration in the annual statistic on straw production in Denmark. During 1997 to 2004 the applied straw to crop ratio for rapeseed has been within the interval between 0.85 and 0.94. The average during this period is 0.89.

It is chosen to apply the data from Jensen et al. (2005). The reason for not using data from Danmarks Statistik is that this source applies an average straw to crop ratio and thus, it does not take into account that the straw to crop ratio decreases as the yield increase. **Table 5.16** in section 5.4 specifies the soils cultivated with rapeseed in Denmark as 41% sand and 59% clay. **Table 5.3** specifies a yield at 2.79 tonne/ha on sandy soils and 3.55 tonne/ha on clay soils. Thus the straw production on average soils can be determined as 2.80 tonne straw per ha. The produced straw is shown in **Table 5.5**.

Soil type	Share of Denmark's agricultural soil	Straw to crop ratio	Winter rapeseed	
			Yield norm, t/ha	Straw production, t/ha
Sand	41%	1.04	2.79	2.90
Clay	59%	0.83	3.55	2.95
Total	**100%**			**2.93**

Table 5.5: Straw production for different yields (soil types) and winter/spring rapeseed. The applied data are marked with a dotted black frame.

According to section 5.5, 13% of the straw is utilised for energy purposes and 87% is left in the field.

5.2 Omitted inventory data in agricultural stage

Magnesium (Mg), Sulphur (S) and Boron fertilisers and dust emissions and soil erosion have not been taken into account. These interventions are regarded as insignificant.

5.3 Energy use

It appears from **Figure 5.4** that several different field work processes are included in rapeseed production. In this section the energy use for each of these field work processes is determined. In addition to the field work processes there are two other energy comsuming processes, i.e. drying of harvested rapeseed and miscellaneus transport (typically in person car), e.g. inspection of field.

Drying of seed

According to Jensen et al. (2005) the water content in rapeseed is dried 3 percent points. Nemecek et al. (2003, p 121) and Dalgaard et al. (2001) assume 2 percent points for unspecified grains. This study applies 3 percent point since the data from Jensen et al. (2005) concerns rapeseed and the other two data sets relate to drying of unspecified grains. **Table 5.6** below shows the energy consumption related to drying from two different identified data sets. The functional unit for drying is selected as 10 g water dried equalling 1 percent point water of 1 kg crop.

Drying of 1 % point of 1 kg crop/ Drying of 10 g water	Nemecek et al. (2003)	Dalgaard et al. (2001)
Electricity	36 KJ	-
Heat (fuel oil) (50-70 KJ in source; assuming 6 KJ)	60 KJ	-
Unspecified	-	50 KJ

Table 5.6: Comparison energy consumption related to drying of 1% point of 1 kg crop equalling drying of 10 g water from two data sources.

The inventory from ecoinvent described in Nemecek et al. (2003) is applied in this study; '*Grain drying, low temperature/CH*'. However, the electricity in the inventory is displaced by marginal electricity as described in **Table 3.3**. This inventory also includes construction, maintenance and disposal of machinery and buildings for the drying process.

The yield from one hectare is 3,240 kg dried rapeseed. Since the rapeseed is dried 3 percent points, the undried yield is 3,340 kg. Thus, 100 kg water is dried per hectare. This correspons to an energy use at 3.6 MJ electricity/ha and 6.0 MJ heat (fuel oil)/ha.

Miscellaneaus transport (person car)

Energy for miscellaneaus transport, e.g. inspection of field, is 6.1 litre diesel/ha (Dalgaard 2007). This is the applied energy use for miscellaneaus transport in LCAfood. Applying the data on fuels in Appendix 1: Data on fuels, 6.1 litre diesel corresponds to 222 MJ diesel/ha. The applied inventory data for inspection of field is: '*Transport, passenger car/RER*' (ecoinvent 2004). This data set includes burning of petrol, production maintenance and disposal of car and construction of road. In the data from ecoinvent there is an energy input of 0.00465 kg diesel and 0.0615 kg petrol per km. Applying the data in Appendix 1: Data on fuels, this corresponds to 2.82 MJ/km. Thus, miscellaneaus transport is 79 km/ha. The LCAfood assumes that all miscellaneus transport is in diesel cars. In this study the distribution given in ecoinvent (2004) is applied instead.

Specific diesel consumption for different field work processes

Two data sources on diesel consumption for different field work processes have been identified; applied data in ecoinvent (Nemecek et al. 2003) and applied data in LCAfood (Dalgaard et al., 2006 and Dalgaard et al. 2001).

Table 5.7 shows fuel consumption for different field work processes obtained from ecoinvent and LCAfood. Data from Nemecek et al. (2003) represents Swiss agriculture and are based on measurements as well as literature studies. Data from the LCAfood project represent Danish agriculture and are also based on measurements as well as literature studies. The specific diesel consumptions for different field work processes applied in the LCAfood project are given in Dalgaard et al. (2001). However an aggregation of these data to the overall agricultural sector in Denmark, described in Dalgaard et al. (2006), showed that the calculated diesel consumption was 18% lower than the total diesel consumption in the Danish agricultural sector. Therefore, Dalgaard et al. (2006) suggests to add 22% extra diesel to the data given in Dalgaard et al (2001). The data shown in **Table 5.7** from the LCAfood project include 22% extra diesel compared to Dalgaard et al. (2001). These data are referred to as LCAfood.

There are two methods for harvesting; combine harvesting or laying by swathes. It has not been possible to identify appropriate data on fuel consumption for laying in swathes. Firstly, it requires a swath operation with rotary windrower. This requires approximately 68 MJ/ha (Dalgaard et al., 2001 and Dalgaard et al. 2006). Next it requires combine harvesting with rough estimated energy consumption 90% of conventional combine harvesting; 560 MJ/ha (90% of the energy consumption obtained from Dalgaard et al., 2001 and Dalgaard et al. 2006). The total very rough estimated energy use for laying by swathes is 628 MJ/ha. The energy use for combine harvesting obtained from Dalgaard et al. (2001) and Dalgaard et al. (2006) is 622 MJ/ha which is much similar to the estimated energy consumption for laying in swathes. Therefore, it is presumed suitable to apply the energy use related to combine harvesting for all rapeseed harvesting.

Specific diesel consumption for different field work process		**Unit**	**Ecoinvent**	**LCAfood**	
				Sandy soil	**Clay soil**
Tillage	Ploughing	MJ/ha	1,086	919	1,124
	Harrowing, by tine harrow/disc harrow	MJ/ha	185	279	342
	Packing	MJ/ha		81	98
	Rolling	MJ/ha	132	81	98
	Seed bed harrowing	MJ/ha		160	195
	Seed bed harrowing, heavy	MJ/ha		240	293
	Inter-row tillage/weeding	MJ/ha	67	133	133
	Straw chopping[12]	MJ/ha	0	0	0
Sowing	Sowing	MJ/ha	159	120	146
Fertilising	Fertilising, by broadcaster	MJ/ha	220	89	89
	Fertilising, lime application	MJ/ha		67	67
	Slurry spreading	MJ/tonne	9	13	13
	Solid manure loading and spreading	MJ/tonne	22	24	24
Pesticide	Application of plant protection products, by field sprayer	MJ/ha	73	67	67
Harvesting	Combine harvesting	MJ/ha	1,386	622	622
Transport	Transport, tractor and trailer (including empty return trip)	MJ/tkm	1.7	8.9	8.9
	Machine transport	MJ/km		1.8	1.8

Table 5.7: Specific fuel consumption for different field work processes in the ecoinvent (Nemecek et al., 2003, p 181-182) and LCAfood (Dalgaard et al., 2001 and Dalgaard et al. 2006). Ecoinvent data are based on a yield at 3.15 tonne/ha (Nemecek et al., 2003, p 247). Conversion from litre and kg diesel is based on energy content given in Appendix 1: Data on fuels.

It appears from **Table 5.7** that the differences between data from ecoinvent and LCAfood are relatively small. However, significant differences > factor 2 are identified for three processes: 1) transport with tractor and trailer (difference = factor 5.2), 2) fertiliser application (difference = factor 2.5), and 3) harvesting (difference = factor 2.2).

---

[12] It is assumed that straw chopping is done with combine harvesting (Jensen et al 2005)

Field work operations: which and how many times?

In the following fuel consumption for rapeseed cultivation for different data sets are described. Firstly, the number of different field work processes are estimated, see **Table 5.8**. Next, the number of field work processes for rapeseed cultivation for different existing data sets are described, see **Table 5.9**. **Table 5.10** summarises the diesel use for all investigated data sets. The data set from LCAfood represents normal practice for rapeseed cultivation in Denmark.

Inventorying the fuel consumption it is important to be aware of differences between LCIs conducted applying the attributional versus the consequential approach for system delimitation. In Denmark most plant production takes place at farms which also produces animals. Therefore, a significant share of the fertilizer applied is manure. The data on plant production in ecoinvent, which is conducted applying the attributional approach, is based on average shares of artificial fertiliser and manure. On the other hand, data in LCAfood, which is conducted applying the consequential approach, only account for artificial fertiliser. This is because manure is presumed constrained by the production of animals and not production of plants. Therefore, all interventions related to slurry spreading (including traction for spreading and emissions of N from manure), have been disregarded. The need for nutrients is purely met by artificial fertilisers, because a change in crop production will affect the marginal supply of fertiliser which is artificial fertiliser and consequential traction for spreading and emissions.

In this study the consequential approach is applied. Therefore, the need for fertiliser is met by artificial fertilisers, traction and spreading is for artificial fertilisers and also the nutrient loss from the field is calculated based on a nutrient balance using artificial fertiliser. Thus, in **Table 5.8**, there are no operations related to spreading of slurry.

Field work process		Estimated number of operations		References
		High	Low	
Tillage	Ploughing	1	1	Dansk Landbrugsrådgivning (2005a), Jensen et al. (2005)
	Harrowing, by tine harrow/disc harrow	2	1	Several harrowing is recommended in order to reduce the number of snails in the soil (Dansk Landbrugsrådgivning, 2005a). Jensen et al. (2005) specify one treatment
	Packing	1	0	Packing after ploughing is recommended in Dansk Landbrugsrådgivning (2005a) No packing in Jensen et al. (2005)
	Rolling	1	1	Rolling after ploughing is recommended in Dansk Landbrugsrådgivning (2005a). Jensen et al. (2005) also specify one treatment.
	Seed bed harrowing	2	0	Packing and seed bed harrowing is recommended in (Dansk Landbrugsrådgivning, 2005a). Two light seed bed harrowing followed by one heavy seed bed harrowing is used in LCAfood. Jensen et al. (2005) do not include this process.
	Seed bed harrowing, heavy	1	0	
	Inter-row tillage/weeding	2	2	2 treatments recommended in Dansk Landbrugsrådgivning (2005a). Jensen et al. (2005) do not include this process.
	Straw chopping	1	0	If the straw is not removed from the field it should be chopped in order to improve germination of lost seeds (Dansk Landbrugsrådgivning, 2005a). Jensen et al. (2005) include this process with combine harvesting.
Sowing	Sowing	1	1	Dansk Landbrugsrådgivning (2005a), Jensen et al. (2005)
Fertilising	Fertilising, by broadcaster	2	2	This is specified in LCAfood, ecoinvent and Jensen et al. (2005)
	Fertilising, lime application	1	0	This is used in LCAfood. . Jensen et al. (2005) do not include this process.
	Slurry spreading	0	0	Since manure and slurry is constrained to animal production, only artificial fertiliser is ascribed to plant production
	Solid manure loading and spreading	0	0	
Pesticide	Pesticide, by field sprayer	4	3	In LCAfood the number of pesticide spraying operations is 5. According to Kristensen (2006) two inter-row tillage/weeding operations substitute one spraying in the autumn, thus 4. Jensen et al. (2005) specify 3 treatments.
Harvesting	Combine harvesting	1	1	The energy consumption in combine harvesting and laying by swathes is estimated to be similar. Therefore, combine harvesting is applied for all rapeseed.). Jensen et al. (2005) include straw chopping with combine harvesting.
Transport	Transport, tractor and trailer (including empty return trip)	3.2 tkm	3.2 tkm	Transport of the harvested rapeseed (yield at 3.1 tonne/ha and dried 3 percent points). Dalgaard et al. (2001) estimates an average distance at 1 km between the field and the farm.
	Machine transport	40 km	24 km	This is calculated as the sum of field work processes multiplied with the distance to the field (round-trip). The distance is 1 km each way; see transport, tractor and trailer.

Table 5.8: Description and documentation of estimated number of field work operations applied in this study.

Table 5.9 summarises the number of field work operations in different studies. The diesel consumption related to the estimate shown in **Table 5.8** is calculated using specific diesel consumption from ecoinvent as well as LCAfood. However, in the case of ecoinvent there are no data for seed bed harrowing. Therefore, two operations of tillage, rolling are applied instead of the one given in **Table 5.8**. Also there is no data for 'tillage, packing'. Therefore, there is applied an extra operation of 'tillage, rolling' instead. 'Tillage, straw chopping' has been left out since there is no data for that in ecoinvent. Furthermore, there is no field work process for lime application in ecoinvent. Therefore, this is applied as an extra 'fertiliser, by broadcasting' operation instead.

Adjusted to available processes in;		**ecoinvent**			**LCAfood**		
Estimate;		**ecoinvent**	**Own high**	**Own low**	**LCAfood**	**Own high**	**Own low**
Tillage	Ploughing	1	1	1	1	1	1
	Harrowing, by tine harrow/disc harrow	2	2	1	2	2	1
	Packing				1	1	
	Rolling		3	2	1	1	1
	Seed bed harrowing				2	2	
	Seed bed harrowing, heavy				1	1	
	Inter-row tillage/weeding		2			2	2
	Straw chopping				1	1	
Sowing	Sowing	1	1	1	1	1	1
Fertilising	Fertilising, by broadcaster	3	3	2	2	2	2
	Fertilising, lime application				1	1	
	Slurry spreading	8.55 t					
	Solid manure loading and spreading	5.55 t					
Pesticide	Pesticide, by field sprayer	3.5	4	3	5	4	3
Harvesting	Combine harvesting	1	1	1	1	1	1
Transport	Transport, tractor and trailer (including empty return trip)		3.2 tkm	3.2 tkm		3.2 tkm	3.2 tkm
	Machine transport	-	34 km	22 km	48 km	40 km	24 km

Table 5.9: Number of field work processes in different calculations of the diesel consumption in rapeseed cultivation. The number of field work operations for different processes in the LCAfood project is obtained from Dalgaard (2007).

Diesel consumption related to cultivation of rapeseed

The diesel consumption related to cultivation of rapeseed is shown in **Table 5.10**. The numbers are calculated from data in **Table 5.7** and **Table 5.9**.

Specific diesel consumption based on;		**Ecoinvent**			**LCAfood**						
Number of field work processes based on;		**Ecoin-vent**	**Own, high**	**Own, low**	**LCAfood**		**Own, high**	**Own, low**	**Own, high**	**Own, low**
Soil type;		**avg.**	**avg.**	**avg.**	**sand**	**clay**	**sand**	**sand**	**clay**	**clay**
Tillage	Ploughing	1,086	1,086	1,086	919	1,124	919	919	1,124	1,124
	Harrowing, by tine harrow/disc harrow	370	370	185	559	683	559	559	683	683
	Packing	0	0	0	81	98	81	0	98	0
	Rolling	0	396	264	81	98	81	81	98	98
	Seed bed harrowing	0	0	0	320	390	320	0	390	0
	Seed bed harrowing, heavy	0	0	0	240	293	240	0	293	0
	Inter-row tillage/weeding	0	134	0	0	0	266	266	266	266
	Straw chopping	0	0	0	178	178	178	0	178	0
Sowing	Sowing	159	159	159	120	146	120	120	146	146
Fertilising	Fertilising, by broadcaster	660	660	440	178	178	178	178	178	178
	Fertilising, lime application	0	0	0	67	67	67	0	67	0
	Slurry spreading	77	0	0	0	0	0	0	0	0
	Solid manure loading and spreading	122	0	0	0	0	0	0	0	0
Pesticide	Pesticide, by field sprayer	256	292	219	336	336	268	201	268	201
Harvesting	Combine harvesting	1,386	1,386	1,386	622	622	622	622	622	622
Transport	Transport, tractor and trailer (including empty return trip)	0	5	5	0	0	28	28	28	28
	Machine transport	0	0	0	88	88	73	48	73	48
Total		**4,116**	**4,488**	**3,744**	**3,787**	**4,301**	**4,000**	**2,738**	**4,513**	**3,049**

Table 5.10: Diesel consumption (MJ) in agricultural field work processes for 1 ha rapeseed cultivation based on different data.

It appears from **Table 5.10** that the diesel consumption varies between 2,738 MJ/ha and 4,513 MJ/ha depending on the assumptions applied and the data used. In order to provide a better overview of the influence of the different assumptions and data, **Table 5.11** shows different averages based on **Table 5.10**.

1	***Specific diesel consumption***	Average								
	Number of field work processes	Average								
	Soil type	Average								
	Total diesel consumption	3,860								
2	**Specific diesel consumption**	Ecoinvent			LCAfood					
	Number of field work processes	Average								
	Soil type	Average								
	Total diesel consumption	4,116			3,731					
3	**Specific diesel consumption**	Ecoinvent			LCAfood					
	Number of field work processes	Ecoin-vent	Own, high	Own, low	LCAfood		Own, high		Own, low	
	Soil type	Average								
	Total diesel consumption	4,116	4,488	3,744	4.044		4,256		2,894	
4	**Specific diesel consumption**	Ecoinvent			LCAfood					
	Number of field work processes	Ecoin-vent	Own, avg.		LCAfood		Own, avg.			
	Soil type	Average			sand	clay	sand		clay	
	Total diesel consumption	4,116	4,116		3,787	4,301	3,369		3,781	
5	**Specific diesel consumption**	Ecoinvent			LCAfood					
	Number of field work processes	Ecoin-vent	Own, high	Own, low	LCAfood		Own, High	Own, low	Own, high	Own, low
	Soil type	Average			sand	clay	sand	sand	clay	clay
	Total diesel consumption	4,116	4,488	3,744	3,787	4,301	4,000	2,738	4,513	3,049

Table 5.11: Five different averages of fuel consumption (MJ) in agricultural field work processes for 1 ha rapeseed cultivation based on different data. For each of the five averages, the parameters that are kept constant (average) are italic and underlined. The applied data are marked with a black dotted frame; the other data are used in a sensitivity analysis in section 21.6.

According to **Table 5.13** Danish agricultural land is distributed on 41% sand and 59% clay. Thus the average diesel consumption for traction can be calculated as 3,612 MJ.

The uncertainty related to the difference in energy use determined from data in ecoinvent and from data in LCAfood (average 4 in the table) is assessed in a sensitivity analysis, see section 21.6.

Difference in diesel consumption related to number of field work operations: It appears from **Table 5.11** (average 3 in the table) that the difference between the total diesel consumption based on standard number of field work processes in ecoinvent and LCAfood compared to the fuel consumption based on own estimate are between high and low of own estimates. However, the average of own estimates (average 4 in the table) differ from the ecoinvent data with 0% and for the LCAfood data the difference is 9-11%.

Difference in diesel consumption related to use of specific diesel consumption based on either ecoinvent or LCAfood: It appears from **Table 5.11** (average 2) that diesel consumption based on specific fuel consumption data from ecoinvent is 10% higher than if based on LCAfood. The main reason for this difference is higher specific diesel consumption for harvesting and fertiliser application.

Overall there is good coherence between the different data sources on diesel consumption related to cultivation of rapeseed. It is chosen to base the fuel consumption on specific fuel consumption data from LCAfood. The reason for this is that these data are based on Danish agriculture. Furthermore it is chosen to base the number of field work operation on an average of own high and low estimates, see dotted frame in **Table 5.11**.

Inventory data for burning of diesel in tractor and production, maintenance and disposal of tractor and is described in section 4.3.

5.4 Materials

The materials used for rapeseed growing include seed, artificial fertiliser and pesticides.

Seed

According to **Figure 5.4** there is an input of 5 kg seed per ha. The interventions related to the agricultural stage in production of seed are accounted for by subtracting an amount of seed from the yield. According to Nemecek et al. (2003, p 103) the yield of seed production is 43% less than for conventional cultivation of rapeseed. Thus, it requires 75% more land to produce seed than conventional rapeseed. Therefore, the use of 5 kg seed requires the interventions as cultivation of 8.75 kg ~ 9 kg conventional rapeseed.

Only one life cycle inventory of seed has been identified; '*Rape seed IP, at regional storehouse/CH*' (ecoinvent 2004). This inventory is shown in **Table 5.12** below. The inventory has been modified applying interventions for electricity as described in section 3.1 instead of average Swiss electricity as in ecoinvent.

LCI-data for production of 1 kg seed	Amount	LCI data used in this study
Rapeseed from agriculture	1.75 kg	This is accounted for by subtracting 1.75 kg from the yield at 3.24 tonne/ha per kg seed used, see **Figure 5.4**.
Electricity	0.21 MJ	Electricity, see **Table 3.3**
Building for storage	$2.0 \cdot 10^{-5}$ m^3	Building, multi-storey/RER (ecoinvent 2004)
Transport from farm to warehouse	0.13 tkm	Transport, lorry 28t/CH (ecoinvent 2004)

Table 5.12: Inventory data for production of 1 kg seed for rapeseed cultivation (ecoinvent 2004).

Fertilisers

Fertilisers used for rapeseed cultivation encompass nitrogen fertilisers, phosphorus, potassium, manganese, sulphur and possibly boron on sandy soils. The need for nitrogen fertilisers is described in Plantedirektoratet (2005a) and depends on the crop (winter/spring rapeseed), soil type, irrigation, previously crop and application of manure.

Life cycle inventories have been identified for straight fertilisers (N, P and K respectively) as well as for mixes. All the applied inventories are for straight fertilisers since these are considered as the marginal affected. The mixes often consist of mixes of the straight fertilisers.

Nitrogen (N): When determining the soil types on which rapeseed are grown, it is assumed that rapeseed is equally distributed on the soil types in Denmark. The argument for this assumption is that rapeseed does not require any special physical conditions on soil quality (Dansk Landbrugsrådgivning, 2005a).

The distribution of soil types in Denmark is shown in **Table 5.13**, also see Appendix 3: Soil types and adjustments to different sources. However, the soil types in Plantedirektoratet (2005a) which is used for determination of the fertiliser input do not fit with the soil types in **Table 5.13**. In addition Plantedirektoratet distinguishes whether the sandy soils are irrigated or not. No information on share of irrigated rapeseed on sandy soils has been identified. It is assumed that 50% is irrigated. In order to overcome differences in soil type terminology in different sources used, a conversion of the soil types has been carried out, see Appendix 3: Soil types and adjustments to different sources.

Soil type	Area, km^2	Share of agricultural soils	Sand/clay
Coarse sandy soil	10,548	26%	Sand
Grinding sand	4,233	10%	Sand
Sandy soil with clay	11,523	28%	Clay
Clay soil with sand	9,817	24%	Clay
Clay soil	2,390	6%	Clay
Heavy clay soil	303	1%	Clay
Humus soil	2,090	5%	Sand
Calcareous soil	87	0%	Sand
City	1,704	-	-
Total	**42,694**	**100%**	**Sand (41%)/clay (59%)**

Table 5.13: Distribution of soil types in agricultural soils in Denmark. See Appendix 3: Soil types and adjustments to different sources.

Table 5.14 shows the N-norm for winter rapeseed on different soils. Furthermore, the share of Denmark's agricultural land is given for the different soil types. This is based on **Table 5.13**.

Soil type	Share of Denmark's agricultural soil	Winter rapeseed	
		Yield norm, tonne/ha	N-norm, kg N/ha
Average of: Non-irrigated coarse sandy soil (JB 1+3) *and* Irrigated sandy soil (JB 1-4)	26%	2.7	159
Average of : Non-irrigated grinding sand (JB 2+4 and 10-12) *and* Irrigated sandy soil (JB 1-4)	16%	3.1	164
Mixed sand and clay soil (JB 5-6)	52%	3.6	171
Clay soil (JB 7-9)	7%	3.8	174
Total	**100%**	**3.3**	**169**

Table 5.14: Norms for yield and application of N-fertiliser for different soil types (Plantedirektoratet, 2005a, p 47).

When determining the application of N ascribed to rapeseed, its effect on N application on the next crop the following year should be credited for (Hvid et al., 2004, p 25). Also the available N from the previous crop should be accounted for. Rapeseed cultivation always enters into a crop rotation scheme including other crops. Since these crops have different 'previous crop' values it is necessary to estimate a typical crop rotation scheme from where the typical 'previous crop' value for crops before rapeseed can be determined. In Jacobsen et al., (2002) the most common crop rotation scheme for plant cultivation/pig production farms have been determined. The crop rotation scheme and 'previous crop' values are shown in **Table 5.15**. It is stressed that the 'previous crop' values given in **Table 5.15** do not necessarily reflect the actual effect on the nitrogen cycle. The 'previous crop' values given are those used in regulation of Danish agriculture which is not purely based on natural science, i.e. the values are politically agreed.

Field no	Crop rotation	'Previous crop' value, kg N/ha
1	Spring barley, with second crop	17-25
2	Spring barley, with second crop	17-25
3	Set-aside	0
4	Winter wheat	0
5	Peas	23
6	Winter wheat	0
7	Winter rye	0
8	Winter barley	0
9	Winter rapeseed	27
10	Winter wheat	0

Table 5.15: 'Most common' crop rotation scheme for plant cultivation/pig production farms (Jacobsen et al., 2002, p 95). The 'previous crop' values are from (Plantedirektoratet, 2005a)

It appears from **Table 5.15** that the 'previous crop' value for crops before rapeseed typically is 0 and the 'previous crop' value for rapeseed is 27 kg N/ha. Thus, no N from crops before rapeseed has to be considered, and the application of N fertiliser on the crop after rapeseed should be 27 kg/ha less than prescribed by the norm (Plantedirektoratet, 2005a, p 13). Therefore, the 27 kg N/ha is subtracted from the N-norm when determining the application of N on rapeseed.

In order to simplify the distinction between sandy soil and clay soil, **Table 5.14** is divided into two soil types; sandy soils (weighted average of the three first rows) and clay soils (weighted average of the two last rows).

The applied N-fertiliser on sandy, clay and average soils is shown in **Table 5.16**, which also take into account credit from the 'previous crop'-value for rapeseed.

Soil type	Share of Denmark's agricultural soil	Winter rapeseed	
		Yield norm, tonne/ha	N-application, kg N/ha
Sand	41%	2.85	134
Clay	59%	3.62	144
Total	**100%**	**3.30**	**140**

Table 5.16: Applied N-fertiliser in the study. The numbers are based on **Table 5.14** and N-application is subtracted a 'previous crop'-value at 27 kg N/ha. The applied data are marked with a dotted black frame.

It appears from **Table 5.16** that 140 kg N/ha is applied to rapeseed. In reality 140 + 27 ('previous-crop'-value) = 167 Kg N/ha is applied, but 27 kg N/ha can be saved for the crop after rapeseed. Therefore, the 27 kg N/ha is credited to rapeseed.

According to Nielsen et al. (2005) and Weidema (2003), the consumption of N-fertiliser in Europe is decreasing. This is also supported in IFA (2007a), where the consumption of N-fertiliser in Western Europe, Central Europe, Eastern Europe and Central Asia has been decreasing from around 27 million tonne in 1986/87 to 14 million tonne in 2002/03. According to IFA (2007a) the same decreasing tendency can be identified for P- and K-fertilisers. The affected supplier in a deceasing market is, according to Weidema (2003) the least competitive supplier. Nielsen et al. (2005) have identified the affected supplier to be less efficient ammonium plants in Eastern Europe. Thus, Nielsen et al. (2005) assume that the market is geographical limited to Europe and that the market trend is decreasing.

But is the geographical market limited to Europa? According to IFA (2007a) the import share of the supply to EU25 in 2005 was 20% for ammonia, 25% for ammonia nitrate and 39% for calcium ammonia nitrate. The import share of triple super phosphate was almost 100% and the import share of potash was 44% in 2005 (IFA

2007a). Based on these figures, it is assumed that the geographical markets for nitrogen, phosphate and potash fertilisers are global.

The World market for nitrogen fertilisers have been constant or slightly increasing from 1993/04 to 2005/06 (IFA 2007a). The increasing world market for nitrogen fertilisers is expected to continue in a 30 year outlook (IFA 2007b). According to IFA (2007a) the same increasing tendency can be identified for P- and K-fertilisers on the world market. Thus, the market trend on the global market is increasing.

Since the market trend then is increasing, the marginal suppliers are then, according to Weidema (2003), the most competitive. All identified LCI-data on production on fertilisers represents average suppliers to the European market. It is assumed that these data represents the marginal suppliers.

According to EFMA (2004) the most frequently used straight N-fertilisers in Europe are; Calcium ammonium nitrate (23% of all inorganic N applied in Europe), Ammonium nitrate (21%), Urea (16%) and Urea ammonium nitrate (12%). N-fertilisers in mixed fertilisers (also containing P and K) constitute 22% of the inorganic nitrogen applied in Europe. It is assumed that the affected type of N-fertiliser is the most commonly used straight N-fertiliser; calcium ammonium nitrate.

Several life cycle inventories for nitrogen fertilisers have been identified. Analysing the data sets in SimaPro and using the EDIP97 for LCIA, it appears that global warming, acidification and toxicity are the most significant impact categories. In **Table 5.17** inventories for the most widely applied N-fertilisers are compared within these categories.

LCI-data for N-fertiliser	CO$_2$-eq.	SO$_2$-eq.	ETWC, m^3 water	Description of data
'*Fertiliser (N)*', LCAfood database (Nielsen et al. 2005)	9.62 kg	32 g	0.9 m^3	*Time:* Data from early 1990ies *Geography:* Former West Germany *Technology:* Average, SNG marginal electricity *Co-product allocation*: Not relevant *Capital goods:* No
'*Calcium ammonium nitrate, as N, at regional storehouse/RER*', (ecoinvent 2004)	9.05 kg	33 g	2,480 m^3	*Time:* Data from mid to late 1990ies *Geography:* Western Europe *Technology:* Average, European average electricity *Co-product allocation*: Not relevant *Capital goods:* Machinery, buildings
'*Ammonium nitrate, as N, at regional storehouse/RER*', (ecoinvent 2004)	8.95 kg	28 g	2,300 m^3	
'*Ammonium sulphate, as N, at regional storehouse/RER*' (ecoinvent 2004)	2.68 kg	8.3 g	1,340 m^3	
'*Urea, as N, at regional storehouse/RER*', (ecoinvent 2004)	3.29 kg	13 g	1,670 m^3	

Table 5.17: Comparison of LCIs of N-fertiliser. The comparison is shown as characterised results using the EDIP97-method for LCIA. All the life cycle inventories are for 1 kg fertiliser, as N. The applied data are marked with a black dotted frame.

It appears from **Table 5.17** that the difference in contributions to global warming and acidification is not significant among ammonium nitrate fertilisers. The difference in contribution to ecotoxicity is mainly due to emissions of strontium related to diesel for transport in ecoinvent and copper related to disposal of metals in chemical plant. These emissions are not included in the inventory in LCAfood. The contribution to global warming, acidification and ecotoxicity is smaller for ammonia sulphate and urea. Electricity from the grid for N-fertiliser production is relative small (Nemecek et al. 2003). Therefore, it has almost no effect on the results that the data in ecoinvent uses data for average electricity from grid in Europe and not marginal electricity.

Since the data from ecoinvent include capital goods and thus are more complete, it is chosen to apply these data in the study. It is chosen to apply data for calcium ammonium nitrate since this fertiliser type is the most frequently applied N-fertiliser.

The European Commission (2006d) presents a range of different technologies to be considered in order to reduce N_2O emissions from production of nitric acid which is used in the production of ammonium nitrate fertilisers. Examples of technologies are alternative oxidation catalysts, extension of reactor chamber, catalytic N_2O decomposition in the oxidation reactor, combined NO_x and N_2O abatement in tail gases and non-selective catalytic reduction of NO_x and N_2O in tail gases. The presented technologies reduce the N_2O emission from 30-50% up to 98-99%. Section 21.8 presents a sensitivity analysis where BAT has been applied in the production of nitric acid.

Phosphorus (P): The application of P-fertiliser is determined from the soil's P-value (Dansk Landbrugsrådgivning, 2005a). However, the application of P-fertiliser in this study is based on average numbers given in Dansk Landbrugsrådgivning (2005a and 2005b). This is shown in **Table 5.18**. In Dansk Landbrugsrådgivning (2005a and 2005b) the use of P-fertiliser is given for two types of sandy soil; '*non irrigated sand, JB 1+3*' and '*Grinding sand, JB 2+4*'. The use of P-fertiliser on sandy soil is regarded as the average of these two.

Soil type	Share of Denmark's agricultural soil	Winter rapeseed kg P/ha
Sand	41%	21
Clay	59%	28
Total	**100%**	**25**

Table 5.18: Applied P-fertiliser in the study. The applied data are marked with a black dotted frame. 25 kg P corresponds to 57 kg P_2O_5.

In the section where N-fertiliser is described it appears that the market for P- and K-fertilisers is global and increasing. Thus, the affected suppliers are those who are most competitive. All identified LCI-data on production on fertilisers represents average suppliers to the European market. It is assumed that these data represents the marginal suppliers.

According to EFMA (2006) the most frequently applied straight P-fertilisers are; triple super phosphate (8% of all applied inorganic P in the EU) and double/single super phosphate (3%). P-fertilisers in mixed fertilisers (also containing N and K) constitute 86% of the inorganic phosphate applied in the EU. It is assumed that the affected type of P-fertiliser is the most commonly used straight P-fertiliser; triple super phosphate.

Three life cycle inventories for straight phosphorus fertilisers have been identified. Analysing the inventories on P-fertiliser available in Simapro and using the EDIP97 for LCIA, it appears that global warming, acidification and toxicity are the most significant impact categories. In **Table 5.19** the inventories are compared within these categories. The electricity consumption for production of triple super phosphate is relative higher than for production of N-fertiliser (Nemecek et al. 2003). Therefore, it has some effect on the emission levels that the data in ecoinvent uses data for average electricity in Europe and not marginal electricity. Thus, a modified version of triple super phosphate where electricity produced from coal instead of average electricity in Europe has been applied to the LCI in ecoinvent is analysed. This is shown in **Table 5.19**.

LCI-data for P-fertiliser	CO_2-eq.	SO_2-eq.	ETWC, m^3 water	Description of data
'*Fertiliser (P_2O_5)*', (triple super phosphate), LCAfood database (Nielsen et al. 2005)	1.19 kg	18 g	0.9 m^3	*Time:* Data from early 1990ies *Geography:* Former West Germany *Technology:* Average, European average electricity *Co-product allocation*: Not relevant *Capital goods:* No
'*Single superphosphate, as P_2O_5, at regional store-house/RER*', ecoinvent database (Nemecek et al. 2003)	2.64 kg	42 g	4,170 m^3	*Time:* Data from mid to late 1990ies *Geography:* Western Europe *Technology:* Average, European average electricity *Co-product allocation*: Not relevant *Capital goods:* Machinery, buildings
'Triple superphosphate, as P_2O_5, at regional storehouse/RER', ecoinvent database (2004) (Nemecek et al. 2003)	2.02 kg	34 g	5,110 m^3	
Modified version of: *'Triple superphosphate, as P_2O_5, at regional storehouse/RER*', ecoinvent database (2004) (Nemecek et al. 2003)	2.46 kg	35 g	5,040 m^3	*Time:* Data from mid to late 1990ies *Geography:* Western Europe *Technology:* Average. Electricity; marginal (coal) *Co-product allocation*: Not relevant *Capital goods:* Machinery, buildings

Table 5.19: Comparison of LCIs of P-fertiliser. The comparison is shown as characterised results using the EDIP97-method for LCIA. All the life cycle inventories are for 1 kg fertiliser, as P_2O_5. For conversion to kg P; 1 kg P corresponds to 2.29 kg P_2O_5. The applied data are marked with a black dotted frame.

It appears from **Table 5.19** that contribution to global warming and acidification differs with a factor 2.2 to 2.3. The difference between the two data sets for triple super phosphate is not as significant as the difference between single super phosphate and triple super phosphate – they only vary with a factor 1.6 to 1.8. As in the case of N-fertilisers in the ecoinvent database the difference in contribution to ecotoxicity is mainly due to emissions of cadmium from phosphoric acid production, strontium related to diesel for transport in ecoinvent and copper related to disposal of metals in chemical plant. These emissions are not included in the inventory in LCAfood. Since the data from ecoinvent include capital goods and thus are more complete, it is chosen to apply these data in the study. It is chosen to apply data for triple super phosphate since this fertiliser type the most widely used P-fertiliser type in EU. Furthermore it is chosen to apply the modified version of the ecoinvent data on triple super phosphate where average electricity has been replaced by marginal electricity produced from coal.

Potassium (K): The application of K-fertiliser is determined from the soil's K-value (Dansk Landbrugsrådgivning, 2005a). However, the application of K-fertiliser in this study is based on average numbers given in Dansk Landbrugsrådgivning (2005a and 2005b). This is shown in **Table 5.20**. In Dansk Landbrugsrådgivning (2005a and 2005b) the use of K-fertiliser is given for two types of sandy soil; '*non irrigated sand, JB 1+3*' and '*Grinding sand, JB 2+4*'. The use of K-fertiliser on sandy soil is regarded as the average of these two.

Soil type	Share of Denmark's agricultural soil	Winter rapeseed kg K/ha
Sand	41%	68
Clay	59%	91
Total	**100%**	**82**

Table 5.20: Applied K-fertiliser in the study. The applied data are marked with a black dotted frame. 82 kg K corresponds to 99 kg K_2O.

In the section where N-fertiliser is described it appears that the market for P- and K-fertilisers is global and increasing. Thus, the affected suppliers are those who are most competitive. All identified LCI-data on production on fertilisers represents average suppliers to the European market. It is assumed that these data represents the marginal suppliers.

According to EFMA (2006) the most frequently applied straight K-fertilisers are; potassium magnesium sulphate (51% of all applied inorganic K in the EU), potassium chloride (27%) and potassium sulphate (6%). K-fertilisers in mixed fertilisers (also containing N and P) constitute 16% of the inorganic potassium applied in the EU. It is assumed that the affected type of K-fertiliser is the most commonly used straight K-fertiliser; potassium magnesium sulphate. However, no inventory data have been identified for that type of K-fertiliser. Therefore, the type of K-fertiliser applied in this study is potassium chloride.

Three life cycle inventories on straight potassium fertiliser have been identified. One unspecified type in the LCAfood database (Nielsen et al. 2005) and two in the ecoinvent database (Nemecek et al. 2003); potassium chloride and potassium sulphate. The data sets are compared in **Table 5.21**.

LCI-data for K-fertiliser	CO_2-eq.	SO_2-eq.	ETWC, m^3 water	Description of data
'*Fertiliser (K_2O)*', LCAfood database (Nielsen et al. 2005)	0.67 kg	1.1 g	0.3 m^3	*Time:* Data from early 1990ies *Geography:* Former West Germany *Technology:* Average, European average electricity *Co-product allocation*: Not relevant *Capital goods:* No
'*Potassium chloride, as K_2O, at regional storehouse/RER*', ecoinvent database (Nemecek et al. 2003)	0.50 kg	1.9 g	402 m^3	*Time:* Data from mid to late 1990ies *Geography:* Western Europe *Technology:* Average, European average electricity *Co-product allocation*: Not relevant *Capital goods:* Machinery, buildings
'*Potassium sulphate, as K_2O, at regional storehouse/RER*', ecoinvent database (Nemecek et al. 2003)	1.42 kg	22.1 g	1,630 m^3	

Table 5.21: Comparison of LCIs of K-fertiliser. The comparison is shown as characterised results using the EDIP97-method for LCIA. All the life cycle inventories are for 1 kg fertiliser, as K_2O. For conversion to kg K; 1 kg K corresponds to 1.21 kg K_2O. The applied data are marked with a black dotted frame.

The comparison in **Table 5.21** shows that there is only little difference between data from the LCAfood database and '*Potassium chloride*' in the ecoinvent database regarding global warming and acidification. The contribution to ecotoxicity is significant higher in the inventories from ecoinvent. The difference in contribution to ecotoxicity is mainly due to emissions of strontium related to diesel for transport in ecoinvent and copper related to disposal of metals in chemical plant. These emissions are not included in the inventory in LCAfood. The electricity use for K-fertiliser production is produced by co-production of heat and electricity on the factory's own cogeneration units (Nemecek et al. 2003). Therefore, it has almost no effect on the results that the data in ecoinvent uses data for average electricity from the grid in Europe and not marginal electricity. Since the data from ecoinvent include capital goods and thus are more complete, it is chosen to apply these data in the study. It is chosen to apply data for potassium chloride since this fertiliser is the most frequently applied in the EU of the fertiliser types for which LCI data are available.

Magnesium (Mg), Sulphur (S) and Boron fertilisers: The average consumption of Mg, S and B fertilisers is shown in **Table 5.22**. No life cycle inventories have been identified for these fertilisers. Therefore, they are not included in the study. The total amount of N, P and K fertiliser equals 235 kg while the total amount of Mg, S and B fertilisers equals around 36 kg. Thus, the not included Mg, S and B fertilisers constitutes approximately 13% of the total application of fertilisers.

Fertiliser	Fertiliser application, kg/ha
Magnesium	8-9
Sulphur	20-30
Boron (sandy soils)	0-5

Table 5.22: Applied other fertilisers in rapeseed cultivation. These fertilisers are not included in the study because of lack of inventory data.

Pesticides

Data on pesticide use in rapeseed cultivation is based on data provided in Dalgaard et al. (2007) and Dalgaard (2007). The data in Dalgaard et al. (2007) are based on the total national sales and the distribution of crops. The use of pesticides per hectare is given in **Table 5.23** and reflects averages of cultivation in Denmark.

Pesticide	kg/ha	kg a.i./ha
Herbicide (clomazone)	0.14	0.050
Herbicide (propyzamid)	0.36	0.18
Herbicide (clopyralid)	0.20	0.020
Insecticide (Pyrethroid, cypermethrin)	0.070	0.0070
Insecticide (Pyrethroid, alpha-cypermethrin)	0.040	0.0020
Insecticide (Pyrethroid, tau-fluvalinat)	0.030	0.0072
Total	**0.84**	**0.27**

Table 5.23: Use of pesticides per hectare per year in rapeseed cultivation in Denmark. The amount and type of pesticides used are based on data provided in Dalgaard et al. (2007) and Dalgaard (2007).

Inventory data for production of the pesticides in **Table 5.23** have only been identified for pyrethroid: ‘Pyretroid-compounds, at regional storehouse/RER’ (ecoinvent 2004). The data set includes energy use, transport to regional storehouse and capital goods, i.e. machinery and buildings. Analysing the data in Simapro and using the EDIP97 method use of electricity appears to be significant within several impact categories. Therefore, European average electricity is replaced by marginal electricity based on coal technology. Production of the other pesticides has been applied as ‘Pesticide unspecified, at regional storehouse/RER’ (ecoinvent 2004). Also in this case, European average electricity is replaced by marginal electricity based on coal technology.

5.5 Co-products

Rapeseed is co-produced with straw from field. The utilisation of straw from winter rapeseed in Denmark is given in **Table 5.24** below.

Straw uses	1997	1998	1999	2000	2001	2002	2003	2004
Straw for energy	10%	7%	9%	9%	9%	15%	13%	10%
Straw for fodder	0%	0%	0%	0%	0%	0%	0%	0%
Straw for bedding etc.	3%	5%	2%	3%	4%	4%	3%	3%
Straw left in the field	87%	88%	89%	88%	87%	81%	84%	87%
Straw, total	100%	100%	100%	100%	100%	100%	100%	100%

Table 5.24: Production and uses of winther rapeseed straw in Denmark. (Danmarks Statistik 2006)

In average 87% of the straw is left in the field, 10% is used for energy purposes and 3% is used for bedding. In order to avoid co-product allocation the marginal application of straw is identified. The demand for bedding is determined by animal production. Hence, this cannot be the marginal use. It is assumed that the marginal use of straw is distributed on 87% left in the field and 13% for energy purposes. According to Energistyrelsen (2006) 29% of the potential for straw for energy purposes was utilised in 2002. This may increase in the future, but no clear tendency can be identified in **Table 5.24**. In this study 87% left in the field and 13% used for energy purposes is applied. The interventions related to the 87% straw left in the field are dealt with in section 5.6.

According to Danish Energy Authority et al. (2004), a typical small 5-15 MW modern straw fired combined heat and electricity power plant in Denmark has an overall efficiency at 88-90% and electricity efficiency at 29-30%. Thus it is assumed that straw used for energy purposes are fired in a co-generating heat and power plant with overall energy efficiency at 89% and electricity efficiency at 29%. Straw has a calorific value at 13.5 MJ/kg. It is assumed that the produced energy displace marginal electricity and heat. Inventory data for marginal electricity and heat are described in section 3.1 and 3.6.

No inventory data on burning of straw has been identified. Instead burning of softwood is assumed to represent the emissions that occur from burning of straw. The inventory: '*Wood chips, from forest, softwood, burned in furnace 1000kW/CH*' (ecoinvent 2004) has been applied for this purpose. This inventory includes the emissions, production of wood, transport of wood, disposal of slag and ashes and production, maintenance and disposal of the plant. Since the interventions related to production of the straw are included in the rapeseed cultivation, the corresponding production of wood is left out from the data. In addition the use of electricity in the ecoinvent process has been displaced by marginal Danish electricity (see **Table 3.3**). The inventory for 1 kg straw used for energy purposes is shown in **Table 5.25**.

LCI-data for 1 kg straw used for energy purposes	**Amount**	**LCI data used in this study**
Wood chips burned in furnace	13.5 MJ	'*Wood chips, from forest, softwood, burned in furnace 1000kW/CH*' (ecoinvent 2004). Modified: Production of wood is left out and marginal electricity has been applied instead of average electricity.
Displaced electricity	-3.92 MJ	Electricity, see **Table 3.3**
Displaced heat	-8.10 MJ	Heat, see section 3.6

Table 5.25: LCI of 1 kg straw used for energy purposes.

5.6 Emissions

Emissions from cultivating rapeseed include emissions to air, water and soil from the field. Emissions related to the energy use are described section 4.3 and 5.3. Emissions to water from agricultural soils are determined as substances that leave the root zone of the plants. Thereby, the topsoil is regarded as a part of the technosphere. E.g. nutrients are added to the soil and most of it is assimilated and harvested by the crops. Emissions are only related to the surplus, i.e. the difference between inputs to and removals from the field.

All emissions are inventoried for average, sand and clay soil. According to **Table 5.13** average soil consist of 41% sand and 59% clay. Data for average soil are applied in the baseline scenario while inventories for sand and clay are applied as sensitivity analyses described in section 21.7.

Emissions related to N-balance

Calculating N related emissions, the point of departure is a N-balance on the field scale. Known inputs and outputs related to seed, fertiliser, changes in N in soil matter and harvested crop and straw are balanced in order to determine the N surplus. This surplus is then distributed on different emissions. The balance is mainly based on the data given in **Table 5.26**. The data in **Table 5.26** are described under the table. The N-balance is shown in **Table 5.27**.

Parameter	Average soil	Sand	Clay
Yield	3,240 kg/ha	2,790 kg/ha	3,550 kg/ha
Crop residue	6,480 kg/ha	5,580 kg/ha	7,100 kg/ha
Straw removed (13%)	381 kg/ha	377 kg/ha	383 kg/ha
Crop residue left in field	6,099 kg/ha	5,203 kg/ha	6,717 kg/ha
N-content in rapeseed	0.0293 kg/kg		
N-content in crop residue	0.0053 kg/kg		

Table 5.26: Parameters for rapeseed and rapeseed cultivation used when establishing N-balance on the field level. N-content in rapeseed and crop residue is given as kg N per kg plant material fresh weight matter: Rapeseed (92% DS) and crop residue (85% DS).

Yields for rapeseed cultivation are given in **Table 5.3**. The amount of crop residue is assumed to be 2 which is the default value suggested in IPCC (2000, p 4.58). However this is related to some uncertainty. Other identified data used for rapeseed vary between 1.2 and 3. The factor 1.2 is applied in the LCAfood database where it is assumed to be of same value as winter barley, data delivered by Dalgaard (2007). The factor 3 is used in the Finnish national greenhouse gas emission account to the EU (Statistics Finland 2006). Straw removed from the field is calculated as 13% of the produced straw. Straw production is given in **Table 5.5** and the share of straw production that is removed from the field (13%) is given in section 5.5. N-content in rapeseed is based on Møller et al. (2000) and N-content in crop residue is from Clausen (2002).

N-deposition on land areas in Denmark were 10-20 kg N/ha in 2004 (Ellermann et al. 2005). According to Ellermann et al. (2005) there are not observed any remarkable changes in the level of deposition from 2003 to 2004. The value for deposition used in this study is assumed to be represented by the average deposition which is 15 kg/ha. The seed input in **Table 5.27** is determined in section 5.4. The fertiliser input is given in **Table 5.16**.

N changes in soil matter: The organic nitrogen pool in the soil matter is considered as consisting of two types of nitrogen; 1) easy available nitrogen which is dealt with as the ‘previous crop’ value determining the amount of N applied with fertiliser; and 2) more difficulty accessible nitrogen bound in organic matter (Petersen and Berntsen 2002). There is also a third type of organic nitrogen which is bound in humus with turnover times at thousands of years (Petersen and Berntsen 2002). This is considered as constant and thus is not accessible. As mentioned, the fluxes of the easily available nitrogen are accounted for when adjusting the fertiliser input for the ‘previous crop’ value, see description of fertilisers in section 5.4. The more difficult accessible organic bound nitrogen may be building up or decomposed in the soil matter depending on the cultivation practice (Wiggers et al. 2005). The nitrogen pool in the soil matter is a product of several years of cultivation practice. Application of large amounts of organic material (straw, ‘second crop’ and animal manure) contributes to accumulation of organic bound nitrogen (Wiggers et al. 2005). According to Wiggers et al. (2005) a change in cultivation practice will have significant importance on the leaching of nitrogen the first years, but after a period of years (20-100 years) the changes in nitrogen content will be of minor importance. Petersen and Berntsen (2002) have modelled the changes in N in the soil pool for three different simplified farms; a cattle farm, a pig farm and a plant farm having normal crop rotations. **Figure 5.7** shows the changes in N in the soil when establishing an average pig farm and an average plant farm on a hypothetic old cattle farm. The model calculation in Petersen and Berntsen (2002) is based on soil type JB4 (8% clay).

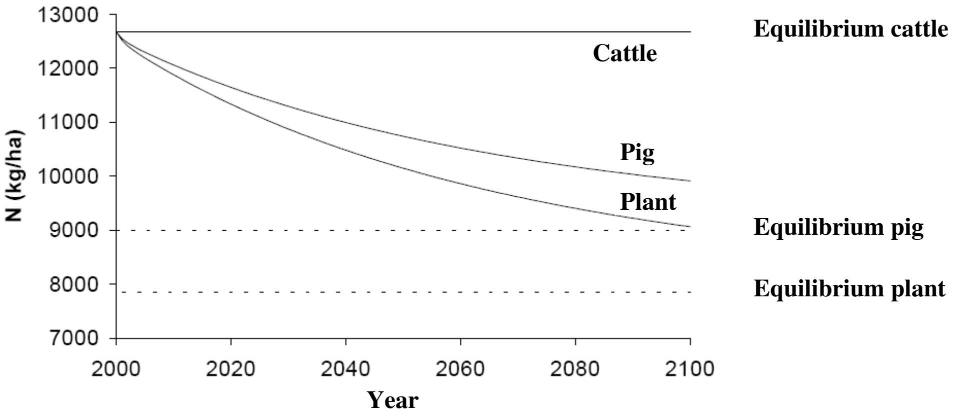


Figure 5.7: Model calculation of changes in organic N in the soil for three farm types all established on hypothetic old cattle farm soil (Petersen and Berntsen, 2002, p 16).

It appears from **Figure 5.7** that cattle farms have the highest level of organic N in soil. Plant farms have the lowest level. The equilibrium for cattle farms and plant farms is 12,700 kg N/ha and 7,900 kg N/ha respectively. After a 100 year period, the organic N in soil under a plant farm established on a hypothetic old cattle farm will have only reached a level at 9,000 kg N/ha. If the cattle and the plant farm are assumed to represent the extremes the difference is 4,800 kg N/ha. If equilibrium is achieved in 200 years (this can not be seen in the figure), the difference at 4,800 kg N/ha corresponds to 24 kg N/ha per year.

Changes in rapeseed cultivation in the EU will take place as a shift between crops or as changes in the set-aside area or nature.

It is assumed that the change of N in the soil pool is zero. The reason for that is: 1) No data on N in the soil under nature and set-aside areas have been identified. 2) shifting from one crop to another crop is assumed to have neglicible effect on the N content in the soil pool, 3) any change will have a maximum effect at 24 kg N/ha per year (assuming that plant farms and cattle farms represent the extremes and that equilibrium is achieved in 200 years) and 4) According to Petersen and Berntsen (2002) the main reason for changes in the soil N in agricultural soil is due to manure from animal production – rapeseed cultivation does not affect the production of animal and consequential manure spreading.

In the case of transformation of other land use types into agricultural cultivation the effect on the soil N may be positive or negative. Some land use types such as nitrogen poor ecosystems (heath land and commons) possibly have less N in the soil pool than agricultural soils and some meadows and forests may have more N in the soil pool. Set-aside areas may be somewhere in between. No data have been identified on that. Therefore, changes in the soil pool as a consequence of land use transformation are assumed to be zero.

In order to evaluate the effect of N changes in soil matter, a sensitivity analyses is carried out where it is assumed that N decomposition in soil matter is 24 kg/ha per year, see section 21.8.

N-balance: The N-balance is summarised in **Table 5.27**.

Input, kg N/ha	Average soil	Sand	Clay
Deposition	15	15	15
N in seed	0.2	0.2	0.2
N-fertiliser	140	134	144
N from changes in N in soil matter	0	0	0
Total	**155.2**	**149.0**	**159.5**
Output, kg N/ha			
N in harvested rapeseed	94.8	81.6	103.8
N in removed straw	2.0	2.0	2.0
Total	**96.8**	**83.6**	**105.9**
Balance			
N surplus (input – output)	**58.4**	**65.4**	**53.6**

Table 5.27: N-balance for 1 hectare rapeseed field; sandy soil clay soil and average soil (41% sand and 59% clay).

The N surplus is distributed on different emissions. The determination of each emission is described in the following.

Ammonia from crop: There are two sources to ammonia emission; crops and fertiliser application. According to Andersen et al. (2001, p 34) the generalised ammonia emission from crops is 3 kg N/ha for grass and 5 kg N/ha for other crops. Thus, the ammonia emission from rapeseed is 5 kg NH_3-N/ha.

Ammonia from fertiliser application: The ammonia emission from fertiliser depends on the fertiliser applied. According to Andersen et al. (2001, p 35) the ammonia emission from fertilisers based on ammonia is 2% of the N content in the fertiliser. Thus the ammonia emission as NH_3-N can be calculated as 2% of the applied fertiliser in **Table 5.16**.

Denitrification (total): The total denitrification (gaseous N oxides and molecular N_2) is calculated using the model; SimDen (Vinther and Hansen 2004). The reason why the total denitrification is calculated is that this is the only way of estimating N-loss as N_2. N_2 is determined as the total denitrification minus N_2O and NO. The model also calculates the N_2O-emission.

The model is developed for Danish soils. The model calculates denitrification as the sum of background denitrification, denitrification from application of artificial fertiliser, denitrification related to application of manure and denitrification from fixed nitrogen. Since marginal plant production does not affect manure and since rapeseed does not fix nitrogen these two sources to denitrification is not considered. The background denitrification depends on the past history of organic matter content in the soil and the soil type (Vinther and Hansen, 2004, p 30). The model includes calculations for eight different soil types and three levels of organic content. Average organic content in soil is assumed. The actual soil types are accounted for. Denitrification from application of artificial fertiliser depends on the amount of N applied with fertiliser, a factor describing the ratio between applied N and N_2O-emission and the N_2/N_2O-ratio (Vinther and Hansen, 2004, p 31). The fertiliser application for different soil types is described in **Table 5.14**. The soil type terminology in SimDen does not fit into the soil types for which data for Danish agriculture are available (see **Table 5.13**). Therefore the soil types in SimDen are adjusted in order to fit with the available data. This is described in Appendix 3: Soil types and adjustments to different sources.

The total denitrification is calculated as 14.1 kg N/ha for average soil, 6.0 kg N/ha for sand and 19.8 kg N/ha for clay.

Direct N_2O: The direct N_2O emission is calculated using a model described in IPCC (2000). The calculated emissions are then compared with the results using two other models described in FAO and IFA (2001) and

Vinther and Hansen (2004). The results obtained using these models are due to consistency not applied in this study. The model described in Vinther and Hansen (2004) is developed for Danish conditions and may therefore not be applicable under conditions in Malaysia, Indonesia, Brazil and Canada which are affected regions in this life cycle inventory. The model in FAO and IFA (2001) does not include peat soils which is relevant in Malaysia and Indonesia.

IPCC (2000): According to IPCC (2000, p 4.54) the direct N_2O emission is calculated as:

$$N_2O_{Direct}\text{-}N = [(F_{SN} + F_{AM} + F_{BN} + F_{CR}) \cdot EF_1] + (F_{OS} \cdot EF_2) \tag{3}$$

The parameter values used in **Equation (3)** are described in **Table 5.28**.

Parameter	Description	Parameter value
F_{SN}	Annual amount of synthetic fertiliser nitrogen applied to soils adjusted to account for the amount that volatilises as NH3 and NOx	Fertiliser application, see **Table 5.16**. 2% volatises
F_{AM}	Annual amount of animal manure nitrogen intentionally applied to soils adjusted to account for the amount that volatilises as NH3 and NOx	No manure
F_{BN}	Amount of nitrogen fixed by N-fixing crops cultivated annually	**No N-fixing**
F_{CR}	Amount of nitrogen in crop residues returned to soils annually	32 kg N/ha (aver. Soil), 27 kg N/ha (sandy soil), 35 kg N/ha (clay soil), calculated using the informations in in **Table 5.26**
F_{OS}	Area of organic soils cultivated annually (ha)	0%, according to **Table 5.13** this should be 5%. But since most organic soils in Denmark are bogs and meadows it is assumed that rapeseed is not cultivated here
EF_1	Emission factor for emissions from N inputs (kg N2O-N/kg N input)	1.25% (IPCC 2000, p 4.60)
EF_2	Emission factor for emissions from organic soil cultivation (kg N2O-N/ha-yr)	8 (IPCC 2000, p 4.60)

Table 5.28: Parameters in the equation calculating direct N_2O-emissions in IPCC (2000, p 4.54)

FAO and IFA (2001): According to FAO and IFA (2001, p 34) the direct N_2O emission is calculated as:

$$\ln(\text{kg } N_2O\text{-N/ha}) = -0.414 + (F \cdot \text{N-app.}) + Cr + S + C + D + pH + Cl + LM + FM \tag{4}$$

The parameter values used in **Equation (4)** are described in **Table 5.29**.

Parameter	Description	Parameter value
F	Type of fertiliser	0.0037, Fertiliser type is calcium ammonia nitrate
N-app.	Applied N, kg/ha	See **Table 5.16**
Cr	Crop type	0.000, Crop type is 'other'
S	Soil texture	-0.008 (coarse for sandy soil) and 0.000 (fine for clay soil), average soil is the average of -0.008 (coarse), -0.472 (medium) and 0.000 (fine)
C	Soil organic C content	0.140, 1-3% C in normal soil types, based on Berntsen and Petersen (2007)
D	Soil drainage	-0.420, good drainage. Good drainage is needed in order to have suitable conditions for agriculture in Denmark
pH	Soil pH	0.109, Soil pH 5.5 - 7.3
Cl	Climate	0.000, Temp. climate
LM	Length of measurement period (the model is constructed to fit with literature measurements. Thus, to model emissions obtained from literature the method of measurement in literature should also be considered since this affects the measured emission)	0.825 Length of measurement period is >300 days, i.e. the longest period available in the model (chosen as the most precise)
FM	Frequency of measurement (see comment above)	0.000 Frequency of measurement is >1measure/day, i.e. the highest frequency available in the model (chosen as the most precise)

Table 5.29: Parameters in the equation calculating direct N_2O-emissions in FAO and IFA (2001, p 34-35)

Vinther and Hansen (2004): The model calculates the direct N_2O emission for eight different soil types. The variable parameters are fertiliser application, applied manure, N input to pastures (N-deposit during grazing and N_2 fixing by clover) and N_2 fixing by legumes crops. All parameters except from fertiliser input is zero. The fertiliser input is given in **Table 5.16**.

The calculated N_2O emissions using the three models are summarised in **Table 5.30**.

Soil type	IPCC (2000), kg N2O-N/ha	FAO and IFA (2001), kg N2O-N/ha	Vinther and Hansen (2004), kg N2O-N/ha
Aver. soil	2.1	2.1	2.3
Sand soil	2.0	2.3	1. 7
Clay soil	2.2	2.5	2.8

Table 5.30: Calculated N_2O emissions (kg N_2O-N/ha) for sand, clay and average soils. The applied values are marked with a dotted line.

It appears from **Table 5.30** that the deviations between the three models are relatively small. Thus, the determination of the applied N_2O emissions is regarded as relativy certain.

Direct NO: The emission of NO is calculated using a model described in FAO and IFA (2001). According to FAO and IFA (2001, p 35) the direct NO emission is calculated as:

$$\ln (\text{kg NO-N/ha}) = -1.527 + (F \cdot \text{N-app.}) + C + D \quad (5)$$

The parameter values used in **Equation (5)** are described in **Table 5.31**.

Parameter	Description	Parameter value
F	Type of fertiliser	0.0062, Fertiliser type is calcium ammonium nitrate
N-app.	Applied N, kg/ha	See **Table 5.16**
C	Soil organic C content	0.000, <3.0% C in normal soil types, based on Berntsen and Petersen (2007)
D	Soil drainage	0.946, good drainage. Good drainage is needed in order to have suitable conditions for agriculture in Denmark

Table 5.31: Parameters in the equation calculating direct NO-emissions in FAO and IFA (2001, p 35)

The only parameters that are changed are the application of N-fertiliser.

The calculated NO emission is summarised in **Table 5.32**.

Soil type	kg NO-N/ha
Aver. soil	1.3
Sand soil	1.3
Clay soil	1.4

Table 5.32: Calculated NO emissions (kg NO-N/ha) using the model described in FAO and IFA (2001). The applied values are marked with a dotted line.

Nitrate: The nitrate emission is calculated as the residual or rest; i.e. the surplus-N from the N-balance minus the other calculated emissions described above.

Since the nitrate emission is calculated as residual of the N-surplus it may be related to some uncertainty. Therefore, the nitrate emission has also been calculated using a model described in Østergaard (2000). The variable parameters are crop, fertiliser application, manure application, soil type and net precipitation. The calculation is performed for winter rapeseed fertilised in accordance with the norms and net precipitation at

300 mm/year. An average net precipitation at 300 mm/year in Denmark is estimated from Miljøstyrelsen (2002, appendix 3, map 20). The calculation for average soil is obtained as the average of sand soil, clay mixed sand soil and sand mixed clay soil. The calculated nitrate emission using the two approaches is shown in **Table 5.33**.

Soil type	Nitrate calculated as residual	Østergaard (2000)
Aver. Soil	36.5	97
Sand soil	51.8	132
Clay soil	26.0	72

Table 5.33: Calculated nitrate emissions (kg NO_3^--N/ha) using the the two approaches described. The applied values are marked with a dotted line.

It appears from **Table 5.33** that the nitrate emissions are very sensitive to the model used for determination of that. Despite the fact that Østergaard (2000) in principle should be more precise that the residual approach, it is chosen to apply the residual approach. Firstly, this is chosen because the high figures calculated with the model described in Østergaard (2000) may be due to inclusion of changes in the soil pool (e.g. effect of high input of organic material/manue previous years) in the model. According to **Figure 5.7** the annual changes in the N soil pool may be as high as 100 kg N/ha the first years after a shift of farm type from cattle to plant. Secondly, the residual approach is chosen because the inputs and outputs of N must be in balance. And when determining the components in the N-balance models for determining nitrate emissions is regarded as the most uncertain compared to determination of the other N-related emissions. Therefore, it is chosen to determine nitrate emissions be the residual approach instead of model calculations.

N_2O, indirect from NH_3 and nitrate: Besides the direct N_2O emissions from the field which is calculated in the previous, there are indirect emissions from the emitted ammonia and nitrate. The emission of ammonia and its subsequent deposition as NO_x and NH_4 and nitrate leached from the field increase the amount of N available for denitrification and nitrification (IPCC, 2000, p 4.67). The N_2O-N emission produced from deposited NH_4-N and NO_x-N (originating from NH_3-emission) is 0.01 kg N_2O-N/kg N. In this respect it is assumed that all emitted ammonia will end as deposited NO_x or NH_4. The N_2O-N emission produced from leached nitrate is 0.025 kg N_2O-N/kg NO_3-N. The indirect N_2O emissions are not assumed to affect the calculated emissions of ammonia and nitrate since the denitrification may take place long time after the emissions took place. Therefore, the ammonia and nitrate emissions may already have had an effect on the environment.

NO, indirect: This is not included.

Summary of emissions related to N-balance: Distribution of the N-surplus is summarised in **Table 5.34**.

Emission and source	Average soil	Sand	Clay
Ammonia from crop (kg NH_3-N/ha)	2.8	2.7	2.9
Ammonia from fertiliser application (kg NH_3-N/ha)	5.0	5.0	5.0
Denitrification (kg N/ha)	14.1	6.0	19.8
- N_2O part of denitrification (kg N_2O-N/ha)	2.1	2.0	2.2
- NO part of denitrification (kg NO-N/ha)	1.3	1.3	1.4
- N_2 part of denitrification (kg N/ha)	10.6	2.7	16.2
Nitrate (kg NO_3-N/ha)	36.5	51.8	26.0
N-surplus (kg N/ha)	**58.4**	**65.4**	**53.6**
N_2O, indirect from NH_3 (kg N_2O-N/ha)	0.1	0.1	0.1
N_2O, indirect from nitrate (kg N_2O-N/ha)	0.9	1.3	0.6

Table 5.34: Distribution of the N-surplus from the field N-balance on different emissions and sources. All numbers are given in kg N/ha.

Table 5.35 summarises the emissions in **Table 5.34** and converts them into kg emission per ha instead of kg N/ha.

Emission as kg N/ha	Average soil (41% sand and 59% clay)	Sand soil	Clay soil
Ammonia to air (kg NH_3-N/ha)	7.8	7.7	7.9
N_2O to air (kg N_2O-N/ha)	3.1	3.4	2.9
NO to air (kg NO-N/ha)	1.3	1.3	1.4
Nitrate to water (kg NO_3-N/ha)	37	52	26
Emission as kg emission/ha	**Average soil (41% sand and 59% clay)**	**Sand soil**	**Clay soil**
Ammonia to air (kg NH_3/ha)	9.5	9.3	9.6
N_2O to air (kg N_2O/ha)	4.9	5.3	4.6
NO to air (kg NO/ha)	2.9	2.7	2.9
Nitrate to water (kg NO_3/ha)	162	229	115

Table 5.35: Emissions related to N-balance.

Emissions related to P-balance

The phosphorus cycle is somehow simpler than the N-cycle. It includes no emissions to air. The emission of P as phosphate is calculated from a simple field balance. The inputs include seed and P-fertiliser and the outputs are harvested rapeseed, straw and accumulation in the soil matter. Accumulation in the soil matter is more constant than for nitrogen since the phosphorous is fixed by strong bindings to the soil particles. Therefore, the leaching of phosphate can be calculated as a fraction of the P surplus in the field. Dalgaard et al. (2007) specifies phosphate leaching as 2.9% of the surplus of P. The remaining is accumulated in the soil matter.

The content of P in harvested crop is 6.2 g per kg rapeseed and 0.77 g per kg straw (fresh weight basis) (Møller et al. 2000). No data on P content in rapeseed straw have been identified. Therefore, the 0.77 g per kg straw is based on straw from barley and wheat.

Applying the yields and straw production for different soil types specified in **Table 5.26**, assuming 13% removal of straw, seed input of 5 kg/ha and application of P fertilisers for winter rapeseed as specified in **Table 5.18**, the P-surplus can be calculated. This is shown in **Table 5.36** for different soil types.

Input (kg P/ha)	Average soil	Sand	Clay
Seed	0.03	0.03	0.03
P-fertiliser	25.0	21.0	28.0
Total P input	**25.0**	**21.0**	**28.0**
Output (kg P/ha)			
Harvested rapeseed	20.0	17.2	21.9
Removed straw	0.3	0.3	0.3
Total P output	**20.3**	**17.5**	**22.2**
Balance (kg P/ha)			
P surplus	4.8	3.6	5.9
P leaching (2.9%)	**0.14**	**0.10**	**0.17**

Table 5.36: P balance for different soil types.

Emissions related to C-balance

Mass balances for carbon are not as detailed as for nitrogen. This is because emission of carbon dioxide from biotic origin is not included. Only CO_2 from net changes of carbon in the soil and from land transformation are included.

It is assumed that the C/N-ratio in soils is relatively constant. Since the change in N in the soil pool is assumed to be zero there will be no change in the soil C pool neither.

Emissions of heavy metal

Fertilisers contain contaminants of heavy metals. The emissions from this input of heavy metals are calculated on basis of a simple field balance. The inputs are heavy metals in seed and N, P and K fertilisers and the outputs are heavy metals in harvested rapeseed and in removed straw. Deposition of heavy metals from air is not taken into account in the field balance. In addition to the field balance, the final compartments (water and soil) of the outputs of heavy metals have been estimated.

It is assumed that the heavy metal is distributed on emissions to soil and emissions to water. The emission of heavy metals to soil is calculated as the total input with fertiliser and seeds minus the share that ends in water. This means that heavy metals in leaching and runoff have been assumed to be zero, i.e. inputs of heavy metals to the field minus harvested heavy metals ends as emissions to soil. It is assumed that one eighth, i.e. 12.5%, of the heavy metals harvested with crop ends as emission to water and the other 87.5% ends as emission to soil. The underlying assumptions behind these shares are associated with some uncertainty and are described in the following. The rapeseed send to oil mill is processed into oil and meal. There are no data available on how heavy metals are distributed in the oil fraction and in the meal fraction. Therefore, it is assumed that 25% of the heavy metals go with the oil and the other 75% with the meal. The oil is refined where heavy metals are almost completely separated out and end in waste water from the oil mill. It is assumed that half of the heavy metals that go with waste water to waste water treatment end in an aquatic recipient while the rest ends in sludge which is spread out on agricultural soil. The heavy metals contained in the meal will primarily end as manure from pig and cattle which is spread out on agricultural soil, and subsequently as emissions to soil. The heavy metals contained in removed straw primary end as emissions to air and as heavy metals in deposited ashes (spread out on agricultural soil) from biofuel power plants. However, it is assumed that all straw is left in the field. This assumption has little effect because a considerable share of the heavy metals from burned straw anyway would end as emissions to soil.

Heavy metal content in fertiliser: Table 5.37, **Table 5.38** and **Table 5.39** show the content of heavy metals in calcium ammonium nitrate, triple super phosphate and potassium fertiliser from different data sources.

Heavy metals in N fertiliser; mg/kg N	**Calcium ammonium nitrate**	**CAN 21+**	**CAN-17 17-0-0**	**Calcium ammonium nitrete, applied in this study**
	(Nemecek, et al. 2003)	(WSDA 2006)	(WSDA 2006)	
Arsenic (As)	-	2.4	<0.6	1.5
Cadmium (Cd)	0.2	0.5	<0.6	0.4
Chromium (Cr)	3.0	-	-	3.0
Cobalt (Co)	-	0.5	<1.2	0.8
Copper (Cu)	8.5	-	-	8.5
Mercury (Hg)	-	0.2	<0.1	0.1
Molybdenum (Mo)	-	6.7	<0.6	3.6
Nickel (Ni)	12.6	0.5	<29.4	14.2
Lead (Pb)	5.9	5.7	<0.6	4.1
Selenium (Se)	-	26.2	<0.6	13.4
Zink (Zn)	100	1.9	<58.8	53.6

Table 5.37: Heavy metal content (mg/kg N) in calcium ammonia nitrate (CAN) fertilisers from different sources. The applied data are the average of the identified data; they are marked with a black dotted frame.

The European Parliament and the Council (2003, annex III) specify a limit at 10 mg copper per kg N for ammonium nitrate fertilisers. There are no limits specified for other heavy metals. It appears that the applied copper content in N fertiliser in **Table 5.37** is not exceeding the limit specified in European Parliament and the Council (2003, annex III).

Heavy metals in P fertiliser; mg/kg P_2O_5	**Triple superphosphate**	**SSP 0-45-0**	**PHOS 0-30-0**	**Triple super phosphate, applied in this study**
	(Nemecek et al. 2003)	(WSDA 2006)	(WSDA 2006)	
Arsenic (As)	-	15.5	<1.7	8.6
Cadmium (Cd)	113	253	0.5	5.7*
Chromium (Cr)	567			567
Cobalt (Co)	-	2.7	0.2	1.5
Copper (Cu)	97.8			97.8
Mercury (Hg)	-	0.03	<0.01	0.02
Molybdenum (Mo)	-	22.1	0.3	11.2
Nickel (Ni)	95.7	331	0.2	142
Lead (Pb)	7.6	<5.6	<0.3	4.5
Selenium (Se)	-	<11.1	<0.7	5.9
Zink (Zn)	650	2333	1.0	995

Table 5.38: Heavy metal content (mg/kg P_2O_5) in triple super phosphate (TSP) fertilisers from different sources. The two P-fertilisers from WSDA (2006) are not TSP fertilisers, see text below table. The applied data are the average of the identified data; they are marked with a black dotted frame. * See explanation in text below table.

The data from WSDA (2006) are not for TSP fertilisers but for single super phosphate and for unspefified phosphate respectively. It has not been possible to obtain other data on heavy metal content in TSP.

The European Commission is planning to introduce limits for cadmium contaminants in phosphate fertilisers. According to a draft proposal (The European Commission 2006c) the following limits are suggested:

- 60 mg Cd/kg P_2O_5 (five years after entry into force)
- 40 mg Cd/kg P_2O_5 (10 years after entry into force)
- 20 mg Cd/kg P_2O_5 (15 years after entry into force)

In 1989 Denmark introduced a limit value at 110 mg Cd per kg P for phosphate fertilisers corresponding to 48 mg Cd per kg P_2O_5. (Ministeriet for Fødevarer, Landbrug og Fiskeri 2004). According to Plantedirektoratet (2004), the average cadmium content in P fertiliser applied in Denmark has been decreasing from approximately 40 mg/kg P_2O_5 in the late 80ies to 5.7 mg/kg P_2O_5 in 2004. Therefore, the cadmium content is set to 5.7 mg/kg P_2O_5 instead of the average value from the three data sets.

Heavy metals in K fertiliser; mg/kg K_2O	**Potassium chloride**	**POTASH SOLUTION 0-0-13**	**POTASH SOLUTION 0-0-15**	**Applied in this study**
	(Nemecek, et al. 2003)	(WSDA 2006)	(WSDA 2006)	
Arsenic (As)	-	5.5	4.0	4.7
Cadmium (Cd)	0.1	<0.02	<0.01	0.04
Chromium (Cr)	3.3	-	-	3.3
Cobalt (Co)	-	1.1	0.3	0.7
Copper (Cu)	8.3	-	-	8.3
Mercury (Hg)	-	<0.2	<0.1	0.1
Molybdenum (Mo)	-	<0.2	<0.1	0.1
Nickel (Ni)	3.5	20.2	5.3	9.7
Lead (Pb)	9.2	<2.3	<2.0	4.5
Selenium (Se)	-	2.1	<0.7	1.4
Zink (Zn)	76.7	296	90.7	155

Table 5.39: Heavy metal content (mg/kg K_2O) in potassium chloride fertilisers from different sources. The applied data are the average of the identified data; they are marked with a black dotted frame.

Heavy metal content in harvested rapeseed and straw: Table 5.40 show the content of heavy metals in the harvested crop; seed and straw. The applied data are based on two different sources. It has not been possible to identify data on the heavy metal content in rapeseed straw. Instead it is assumed that the heavy metal content in straw can be estimated as the average of barley and wheat straw.

Heavy metals in harvested crop; mg/kg crop	**Rapeseed**		**Straw (barley)**		**Applied in this study**	
	(Nemecek, et al. 2003, p 154)	(Møller et al. 2000)	(Nemecek, et al. 2003, p 154)	(Møller et al. 2000)	Rapeseed	Straw
Arsenic (As)	-	-	-	-	-	-
Cadmium (Cd)	1.47	-	0.16	-	1.5	0.16
Chromium (Cr)	0.46	-	0.36	-	0.46	0.36
Cobalt (Co)	-	0.11	-	0.12	0.11	0.12
Copper (Cu)	3.04	2	4.23	3	2.4	3.5
Mercury (Hg)	0.09	-	0.07	-	0.09	0.07
Molybdenum (Mo)	-	-	-	-	-	-
Nickel (Ni)	2.39	-	0.35	-	2.4	0.35
Lead (Pb)	4.83	-	2.67	-	4.8	2.7
Selenium (Se)	-	0.04	-	0.05	0.04	0.05
Zink (Zn)	44.16	31	11.50	89	38	50

Table 5.40: Heavy metal content (mg/kg crop) in harvested rapeseed and straw. The applied data are marked with a black dotted frame.

Heavy metal emissions: Applying the yields for different soil types specified in **Table 5.26**, assuming a seed input of 5 kg/ha and application of N, P and K fertilisers for winter rapeseed as specified in section 5.4, the heavy metal emissions to soil and water can be calculated. This is shown in **Table 5.41**. Since there are no data on arsenic and molybdenum content in harvested crop and straw it is assumed that the total input to the field of these heavy metals ends as emissions to soil.

Heavy metal emissions	**Average soil**		**Sand**		**Clay**	
	Soil (g/ha)	**Water (g/ha)**	**Soil (g/ha)**	**Water (g/ha)**	**Soil (g/ha)**	**Water (g/ha)**
Arsenic (As)	1.2	-	1.0	-	1.3	-
Cadmium (Cd)	-0.21	0.61	-0.18	0.52	-0.23	0.67
Chromium (Cr)	33	0.19	28	0.16	37	0.20
Cobalt (Co)	0.22	0.045	0.20	0.038	0.24	0.049
Copper (Cu)	6.7	1.0	5.7	0.84	7.4	1.1
Mercury (Hg)	-0.011	0.036	-0.0084	0.031	-0.013	0.040
Molybdenum (Mo)	1.2	-	1.0	-	1.2	-
Nickel (Ni)	10	1.0	8.7	0.8	11	1.1
Lead (Pb)	-0.64	1.9	-0.52	1.7	-0.73	2.1
Selenium (Se)	2.3	0.016	2.2	0.014	2.4	0.018
Zink (Zn)	65	15	55	13	72	17

Table 5.41: Heavy metal emissions (g/ha) to soil and water. Emissions to soil are calculated as the input of heavy metals minus 12.5% of the content in harvested rapeseed. Emissions to water are calculated as 12.5% of the heavy metal content in harvested rapeseed. The applied data in this study are marked with a dotted black frame.

A negative emission means that some substance is removed from the soil (with harvested rapeseed). However, the net emission of heavy metals is positive for all substances. The negative numbers only reflect a redistribution of the fate of the net input of heavy metals; i.e. some of the heavy metals in the harvested rapeseed are sorted out in the refinery process and are subsequently discharged to water.

It must be stressed that the numbers on heavy metal content in fertilisers and in harvested crop are taken from different sources of different ages and different regions. Therefore, the amount as well as the comparetment of heavy metal emissions given in this section is related to significant uncertainties. Therefore, the environmental significans of emissions of heavy metals is analysed in a sensitivity analysis in section 21.10.

Emissions of pesticides

The compartments that receive the applied active ingredients in the pesticides are assumed to be 33% soil, 33% water and 33% air. This is a very rough estimate which is tested in a sensitivity analysis in section 21.11.

5.7 Overhead in agricultural stage

Overhead includes electricity and heat for administration. Administration related to rapeseed cultivation is not included since it is assumed that this takes place in the farmer's home.

5.8 Capital goods in agricultural stage

Capital goods include means of production, i.e. buildings and machinery. Only one inventory of agricultural buildings and machinery has been identified; ecoinvent (2004). Since it is not possible to obtain detailed data on building materials, foundations, machinery etc. from farms in Denmark, the inventory of capital goods will be rather roughly and based on ecoinvent (2004). The data in ecoinvent are described in detail in Nemecek et al. (2003) where capital goods are divided into two categories: 1) Agricultural buildings and 2) Agricultural machinery. These are described in the following two sections.

Agricultural buildings

The relevant buildings for rapeseed cultivation are:

- Shed, for machinery (barn building for shelter)
- Buildings for drying

The inventory of shed is described in Nemecek et al. (2003) and includes construction, maintenance and disposal of the materials used. The use of shed for machinery in ecoinvent is inventoried per hectare of field work processes and it is calculated as surface occupied by the tractor and machinery multiplied with the field work time for one hectare divided with the lifetime of the shed and with the annual employment of the machine (Nemecek et al., 2003, p 55). The included different field work processes and number of operations per hectare for rapeseed cultivation are described in **Table 5.8**. However, not all included processes are included in the ecoinvent database. This involves; soil packing, seed bed harrowing and straw chopping. Therefore, the use of shed for these field work processes are assumed to be equal to harrowing, by tine harrow. **Table 5.42** shows the required shed per hectare operation and the number of different field work operations per hectare given in **Table 5.8**.

Use of shed for machinery		**Shed, m^2 per ha per operation**	**Number of field work operation per ha**		**Shed, m^2 per ha total**	
Estimate;		**-**	**High**	**Low**	**High**	**Low**
Tillage	Ploughing	0.00801	1	1	0.00801	0.00801
	Harrowing, by tine harrow/disc harrow	0.00584	2	1	0.01168	0.00584
	Packing*	0.00584	1		0.00584	0
	Rolling	0.00534	1	1	0.00584	0.00584
	Seed bed harrowing*	0.00584	2		0.01168	0
	Seed bed harrowing, heavy*	0.00584	1		0.00584	0
	Inter-row tillage/weeding	0.00349	2	2	0.00698	0.00698
	Straw chopping*	0.00584	1		0.00584	0
Sowing	Sowing	0.00546	1	1	0.00546	0.00546
Fertilising	Fertilising, by broadcaster	0.00171	2	2	0.00342	0.00342
	Fertilising, lime application	0.00171	1		0.00171	0
Pesticide	Pesticide, by field sprayer	0.00198	4	3	0.00792	0.00594
Harvesting	Combine harvesting	0.00858	1	1	0.00858	0.00858
Transport	Transport, tractor and trailer (including empty return trip)	8.13E-05 m^2/tkm	3.2 tkm	3.2 tkm	0.00026	0.00026
	Machine transport	0	40 km	24 km	0	0
Total					**0.0891**	**0.0503**
Total, average					**0.070**	

Table 5.42: Calculation of use of shed per hectare rapeseed cultivation. The calculations are based on field work operations given in **Table 5.9** and shed use per ha per operation in Nemecek et al. (2003).*Assumed to have same utilisation of shed as harrowing by spring tine harrow. The applied data are marked with a black dotted frame.

In **Table 5.42** the average use of 0.0697 m^2 shed corresponds to 3.5 m^2 shed during the assumed 50 years lifetime of a shed.

The applied inventory data for shed is; '*Shed/CH/I*' (ecoinvent 2004).

Building hall for drying is included in the inventory data applied for drying described in section 5.3: 'Drying of seed'. Administration buildings related to rapeseed cultivation is not included since it is assumed that this work is done in the farmer's home.

Agricultural machinery

The relevant machinery for rapeseed cultivation is shown below. The machinery are categorised as in ecoinvent. Ecoinvent contains an inventory for each category.

- Tractor
- Combine harvester
- Agricultural machinery, tillage: Plough, spring tine harrow, weeder, roller
- Agricultural machinery, general: Seeder, broadcaster for fertilising, trailer and field sprayer for pesticides

The inventory of agricultural machinery is described in Nemecek et al. (2003) and includes production, maintenance and disposal of the materials used. The use of machinery in ecoinvent is inventoried per hectare of field work processes and it is calculated as the weight of the machine multiplied with the operation time per hectare divided with the life time of the machine (Nemecek et al., 2003, p 49). The included different field work processes and number of operations per hectare for rapeseed cultivation are described in **Table 5.8**. However, not all included processes are included in the ecoinvent database. This involves; soil packing, seed bed harrowing and straw chopping. Therefore, these machines are assumed to be equal to a spring tine harrow. **Table 5.43** shows the required machinery per ha per operation.

Use of machinery, per ha per operation		Machinery, kg per ha per operation			
Category of machinery		**Tractor**	**Combine harvester**	**Tillage**	**General**
Tillage	Ploughing	1.55	-	2.16	-
	Harrowing, by tine harrow/disc harrow	0.41	-	1.00	-
	Packing*	0.41	-	1.00	-
	Rolling	0.41	-	1.82	
	Seed bed harrowing*	0.41	-	1.00	-
	Seed bed harrowing, heavy*	0.41	-	1.00	-
	Inter-row tillage/weeding	0.23	-	0.63	
	Straw chopping*	0.41	-	1.00	-
Sowing	Sowing	0.60	-	-	0.97
Fertilising	Fertilising, by broadcaster	0.69	-	-	0.24
	Fertilising, lime application	0.69	-	-	0.24
Pesticide	Pesticide, by field sprayer	0.32	-	-	0.53
Harvesting	Combine harvesting	-	6.30	-	-
Transport	Transport, tractor and trailer (including empty return trip)	0.0037 kg/tkm	-	-	0.024 kg/tkm
	Machine transport	Included in other field work processes			

Table 5.43: Required machinery per ha per operation distributed on the four categories of agricultural machinery in ecoinvent (2004). *Assumed to have same amount of required machinery as harrowing by spring tine harrow.

Table 5.44 shows the total required amount of machinery. This is calculated using the number of operations given in **Table 5.8**.

Use of machinery, per ha total		Machinery, kg per ha total							
Category of machinery		**Tractor**		**Combine harvester**		**Tillage**		**General**	
Estimate;		**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**
Tillage	Ploughing	1.55	1.55	0	0	2.16	2.16	0	0
	Harrowing, by tine harrow/disc harrow	0.82	0.41	0	0	2.00	1.00	0	0
	Packing	0.41	0	0	0	1.00	0	0	0
	Rolling	0.41	0.41	0	0	1.82	1.82	0	0
	Seed bed harrowing	0.82	0	0	0	2.00	0	0	0
	Seed bed harrowing, heavy	0.41	0	0	0	1.00	0	0	0
	Inter-row tillage/weeding	0.46	0.46	0	0	1.26	1.26	0	0
	Straw chopping	0.41	0	0	0	1	0	0	0
Sowing	Sowing	0.60	0.60	0	0	0	0	0.97	0.97
Fertilising	Fertilising, by broadcaster	1.38	1.38	0	0	0	0	0.48	0.48
	Fertilising, lime application	0.69	0	0	0	0	0	0.24	0
Pesticide	Pesticide, by field sprayer	1.28	0.96	0	0	0	0	2.12	1.59
Harvesting	Combine harvesting	0	0	6.3	6.3	0	0	0	0
Transport	Transport, tractor and trailer (including empty return trip)	0.01	0.01	0	0	0	0	0.08	0.08
	Machine transport	Included in other field work processes							
Total		9.25	5.78	6.30	6.30	12.24	6.24	3.89	3.12
Total, average		7.5		6.3		9.2		3.5	

Table 5.44: Required machinery in kg per ha distributed on the four categories of agricultural machinery in ecoinvent (2004). Calculations are based on Table 5.43 and number of operations given in Table 5.8. The applied data are marked with a black dotted frame.

The applied inventories for the four categories of agricultural machinery in **Table 5.44** are:

- Tractor: '*Tractor, production/CH/I*' (ecoinvent 2004)
- Combine harvester: '*Harvester, production/CH/I*' (ecoinvent 2004)
- Agricultural machinery, tillage: '*Agricultural machinery, tillage, production/CH/I*' (ecoinvent 2004)
- Agricultural machinery, general: '*Agricultural machinery, general, production/CH/I*' (ecoinvent 2004)

5.9 Transport of materials in agricultural stage

Raw materials are transported with lorry to the rapeseed cultivating farms. Inventory data per tkm transport by lorry are described in section 4.1. The transport distances are estimated in this section. Since there are several suppliers and since there is a general lack of data on the specific marginal affected supplier, all transport distances are based on rough estimates. Determination of size of lorries is based on **Table 4.3** and very rough estimates on the total amount of goods transported.

Determination of the amount of transported fertiliser product is shown in **Table 5.45**. The contents of nutrients in fertiliser products are estimated from a review of various fertilisers in WSDA (2006).

Fertiliser	Content of nutrient in fertiliser	Applied nutrient	Applied fertiliser product
Calcium ammonium nitrate	19% N	140 kg N/ha	737 kg/ha
Triple superphosphate	38% P_2O_5 (16% P)	25 kg P/ha	156 kg/ha
Potassium chloride	14% K_2O (12% K)	82 kg K/ha	683 kg/ha
Magnesium	10% Mg	8.5 kg Mg/ha	85 kg/ha
Sulphur	15% S	25 kg S/ha	167 kg/ha
Boron	10% B	2.5 kg B/ha	25 kg/ha
Total			**1,853 kg/ha**

Table 5.45: Determination of amount of transported fertiliser product. The applied nutrients are obtained from **Table 5.16**, **Table 5.18**, **Table 5.20** and **Table 5.22**.

Table 5.46 shows the transported amounts, the route and the distances.

Material	Amount per ha	From	To	Distance	Lorry size
Seed	5 kg	Seed traders, Denmark	Farms in DK	100 km	16t
Rapeseed	3,240 kg	Farms in DK	Seed traders	100 km	28t
Rapeseed straw to utilisation	381 kg	Farms in DK	Biomass plant	100 km	28t
N, P, K, Mg, S and B fertilisers	1,853 kg	Abroad chemical plant	Farms in DK	1000 km	40t
Pesticides	0.84 kg	Abroad chemical plant	Farms in DK	1000 km	28t

Table 5.46: Transport of goods related to the agricultural stage. The return trip is included in the inventory data.

The estimated transport in **Table 5.46** is summarized per type of lorry in **Table 5.47**.

Type of lorry	Transport
16t	0.5 tkm
28t	363 tkm
40t	1,853 tkm

Table 5.47: Summary of transport in the agricultural stage.

5.10 LCI of rapeseed agricultural stage, summary

Table 5.48 summarises the inventory data relating to 1 ha cultivated in 1 year with rapeseed.

Denmark: 1 ha y rapeseed field		
Interventions	**Amount**	**Applied LCI data**
Product output		
Rapeseed (8-9% DS)	3.131 t	Product of interest
Straw removed from field	381 kg	Co-product allocation between rapeseed and straw is avoided by system expansion, see below
System expansion		
Burning of straw in biomass plant	381 kg	See **Table 5.25**
Energy use		
Traction, burned diesel	3,612 MJ	See **Table 4.5**
Drying of rapeseed (evaporated water)	100 kg	Modified version of: ‘*Grain drying, low temperature/CH*’ (ecoinvent 2004), see section 5.3
Miscellaneaus transport (passenger car)	79 km	see section 4.4
Material use		
Seed	5 kg	See **Table 5.12**
N-fertiliser (as N)	140 kg	‘*Calcium ammonium nitrate, as N, at regional storehouse/RER*’, (ecoinvent 2004)
P-fertiliser (as P_2O_5)	57 kg	Modified version of: ‘*Triple superphosphate, as P_2O_5, at regional storehouse/RER*’ (ecoinvent 2004), see section 5.4
K-fertiliser (as K_2O)	99 kg	‘*Potassium chloride, as K_2O, at regional storehouse/RER*’ (ecoinvent 2004)
Herbicide (clomazone)	0.050 kg	Modified version of: ‘*Pesticide unspecified, at regional storehouse/RER*’ (ecoinvent 2004), see section 5.4
Herbicide (propyzamid)	0.18 kg	Modified version of: ‘*Pesticide unspecified, at regional storehouse/RER*’ (ecoinvent 2004), see section 5.4
Herbicide (clopyralid)	0.020 kg	Modified version of: ‘*Pesticide unspecified, at regional storehouse/RER*’ (ecoinvent 2004), see section 5.4
Insecticide (Pyrethroid, cypermethrin)	0.0070 kg	Modified version of: ‘*Pyretroid-compounds, at regional storehouse/RER*’ (ecoinvent 2004), see section 5.4
Insecticide (Pyrethroid, alpha-cypermethrin)	0.0020 kg	Modified version of: ‘*Pyretroid-compounds, at regional storehouse/RER*’ (ecoinvent 2004), see section 5.4
Insecticide (Pyrethroid, tau-fluvalinat)	0.0072 kg	Modified version of: ‘*Pyretroid-compounds, at regional storehouse/RER*’ (ecoinvent 2004), see section 5.4
Capital goods		
Agricultural buildings	0.070 m^2	‘*Shed/CH/I*’ (ecoinvent 2004)
Machinery, tractor	7.5 kg	‘*Tractor, production/CH/I*’ (ecoinvent 2004)
Machinery, combine harvester	6.3 kg	‘*Harvester, production/CH/I*’ (ecoinvent 2004)
Machinery, tillage	9.2 kg	‘*Agricultural machinery, tillage, production/CH/I*’ (ecoinvent 2004)
Machinery, general/miscellaneous	3.5 kg	‘*Agricultural machinery, general, production/CH/I*’ (ecoinvent 2004)
Transport		
16t lorry	0.5 tkm	‘*Transport, lorry 16t*’ (ecoinvent 2004)
28t lorry	363 tkm	‘*Transport, lorry 28t*’ (ecoinvent 2004)
40t lorry	1,853 tkm	‘*Transport, lorry 40t*’ (ecoinvent 2004)
… table continued on the next page…		

Table 5.48: Interventions per ha y soil cultivated with rapeseed. Table continued on the next page…

… continued from previous page…

Emissions	Air	Water	Soil
… continued from previous page…			
Ammonia (NH_3)	9.5 kg	-	-
Dinitrogen oxide (N_2O)	4.9 kg	-	-
Nitric oxide (NO)	2.9 kg		
Nitrate (NO_3)	-	162 kg	-
Phosphorus (P)	-	0.14 kg	-
Clomazone	0.017 kg	0.017 kg	0.017 kg
Propyzamid	0.060 kg	0.060 kg	0.060 kg
Clopyralid	0.0067 kg	0.0067 kg	0.0067 kg
Cypermethrin	0.0023 kg	0.0023 kg	0.0023 kg
Alpha-cypermethrin	0.0067 kg	0.0067 kg	0.0067 kg
Tau-fluvalinat	0.0024 kg	0.0024 kg	0.0024 kg
Arsenic (As)	-	-	1.2 g
Cadmium (Cd)	-	0.61 g	-0.21 g
Chromium (Cr)	-	0.19 g	33 g
Cobalt (Co)	-	0.045 g	0.22 g
Copper (Cu)	-	1.0 g	6.7 g
Mercury (Hg)	-	0.036 g	-0.011 g
Molybdenum (Mo)	-	-	1.2 g
Nickel (Ni)	-	1.0 g	10 g
Lead (Pb)	-	1.9 g	-0.64 g
Selenium (Se)	-	0.016 g	2.3 g
Zink (Zn)	-	15 g	65 g

Table 5.48: Interventions per ha y soil cultivated with rapeseed.

6 Agricultural stage: Oil palm, fresh fruit bunches (FFB)

The oil palm (Elaeis guineensis) is a perennial crop and it grows to a height of approximately 10 m before replantet after around 25 years. The oil palm fruits are attached to bunches (FFB – fresh fruit bunches) weighting around 25 kg and each carrying 1500-2000 single fruits (for oil palms 10-15 years old). The harvested FFB contain around 20% oil, 25% nuts (5% kernels, 13% fibre and 7% shell) and 23% empty fruit bunches. The kernels contain around 55% oil and 8% protein (Corley and Tinker 2003; Møller et al. 2000).

The agricultural stage for oil palm includes activities related to cultivation of oil palm. The reference for the inventory is 1 hectare oil palm plantation in Malaysia and Indonesia. The planted area includes mature and immature palms. Most data are based on collected data on cultivation practices in Malaysia. The yield of fresh fruit bunches (FFB) is applied as the average yield in Malaysia and Indonesia. Most data are from 2004 to 2006.

Since oil palm is a perennial three different stages are considered: Nursery, immature plantation and mature plantation. The interventions from oil palm cultivation are applied as a weighted average of the three stages.

In 2003 an area of 32,600 km^2 and 30,400 km^2 was planted with oil palm in Malaysia and Indonesia respectively (FAOSTAT 2006). That corresponds to 10% and 41% of the total land area and the agricultural land in Malaysia respectively and 2% and 7% of the total land area and the agricultural land in Indonesia respectively

There are different influential factors on the interventions and thereby the environmental impact related to production of oil palm fruit (FFB). Relevant factors to take into account are: 1) type of agricultural practice (estate or small holder) as well as region – both factors affect the yield, 2) type of cultivated soil (mineral soil versus peat soil). These factors will be taken into account in sensitivity analyses in section 21.

Before the oil palms are planted in the plantation they are grown in poly bags in the nursery. The nursery consists of two main stages. In the pre-nursery that last from the sowing of the seed in a small poly bags until the seedling is approximately three to four months. The seedlings in the small poly bag are kept under a cover protecting them for direct sunlight. After that in the main-nursery, the seedling is planted in a larger poly bag in which it is cultivated without a protecting cover until it is 12 to 13 months old and ready for planting in the plantation (Singh 2006 and Corley and Tinker 2003, p 271). The pre-nursery is illustrated in **Figure 6.1** and **Figure 6.2** while the main-nursery is shown in **Figure 6.3** and **Figure 6.4**.

Figure 6.1: Pre-nursery, the seeds are sown in small poly bags where the seedlings are cultivated until they are three to four month. Picture taken by Jannick H Schmidt in United Plantation Berhad 2006.

Figure 6.2: Pre-nursery, different stages. Picture taken by Jannick H Schmidt in United Plantation Berhad 2006.

Figure 6.3: Main-nursery, early stage, the seedlings are cultivated in large poly bags when they are 3-5 months until they are 12-13 months and ready for planting in the plantation. Picture taken by Jannick H Schmidt in United Plantation Berhad 2006.

Figure 6.4: Main-nursery, palms ready for planting in plantation. Picture taken Jannick H Schmidt in United Plantation Berhad 2006.

Oil palms from the nursery are planted when they are approximately 12-13 month old. The palms are planted with a density of 136 - 148 palms per ha on mineral soils (assumed average at 142 palms per ha) and approximately 160 palms on peat soils (Xavier 2006). Before the palms are planted, the soil is sprayed with pesticides, ploughed, compacted and legume cover is sown, typically pueraria. The cover crop prevents erosion and fixes nitrogen from the atmosphere especially when the palms are young (Corley and Tinker 2003, p 265). Around each palm a circle with no vegetation is established, i.e. the palm circle. The purpose of having the palm circle for young palms is to prevent competitors to the palm (Corley and Tinker 2003, p 295). Later for the mature palm, the purpose is to allow access for harvesting and to be able to see how many fruits from the ripening fresh fruit bunch which drop down. The number of loose fruits is used as a guideline for when to harvest (Arulandoo 2006). The palm circle is kept free from weeds by application of herbicides.

The oil palms are harvested first time when they are three years old, i.e. two years after planting in the plantation (Singh 2006 and Corley and Tinker 2003, p 271). The palms are mature from two years after planting to 20-30 years after planting. An average age of palms when replanting at 26, i.e. 25 years after planting, is estimated from Corley and Tinker (2003, p 318). Yusoff and Hansen (2005) estimate the age of palms when replanting at 25-30 years. **Figure 6.5** and **Figure 6.6** shows immature palms and **Figure 6.7** shows mature palms.

Figure 6.5: Immature oil palms, newly planted palms from the nursery. Shredded biomass from the old stands can be seen between the rows of new palms. The planted palms from the nursery are immature until two years after planting, i.e. they are three years old. Picture taken by Jannick H Schmidt in United Plantation Berhad 2006.

Figure 6.6: Immature oil palms, ground cover established. Picture taken by Jannick H Schmidt in United Plantation Berhad 2006.

Figure 6.7: Mature oil palms, the palms are harvested from two years to approximately 25 after planting. Picture taken by Jannick H Schmidt in United Plantation Berhad 2006.

Figure 6.8: Harvesting of fresh fruit bunches (FFB). Picture taken by Jannick H Schmidt in United Plantation Berhad 2005.

The palms are harvested approximately every second week year round, each time one FFB is harvested. Harvesting is done manually with a knife attached on a shaft, see **Figure 6.8**. Firstly, the frond beneath the fruit bunch is pruned. Hereby the FFB is accessible for being cut of. The pruned fronds are placed in the field between the palms for mulching, see **Figure 6.9**. The harvested FFB consist of two main components; the fruits and the stalks they are attached to, also referred to empty fruit bunch (EFB). The mean weight of one FFB from young palms (3 years) is less 5 kg and more than 25 kg for older palms (10-15 years) (Corley and Tinker 2003, p 47). **Figure 6.10** and **Figure 6.11** show a harvested FFB and two single fruits from the FFB respectively. The palm's requirements for nutrients are met by artificial fertilisers as well as mulching of pruned fronds, EFB from the palm oil mill and land application of anaerobically treated POME and solid sludge. Weeds are treated with application of herbicides in the palm circle and in addition insecticides, fungicides and rodenticide are applied in order to control insect, fungus and rats. Often, the use of insecticides and rodenticide is reduced by an integrated pest management programme. Usually that includes planting of beneficial flowering plants which attract parasites and predators of the common pests of the oil palm (Arulandoo 2006; Fee and Sharma 1999). Another serious pest is rats which damage the seedlings in the nursery, immature palms and eat the fruits (Fee and Sharma 1999). In a integrated pest management programme, the number of rats are reduced by barn owls. Barn owls are attracted by setting up nesting boxes. Another part of integrated pest management is setting up of rhinoceros beetle traps (Sharma 2005).

Figure 6.9: Pruned fronds left between the oil palm rows for mulching. Picture taken by Jannick H Schmidt in United Plantation Berhad 2006.

Figure 6.10: Harvested fresh fruit bunch (FFB). Picture taken by Jannick H Schmidt in United Plantation Berhad 2005.

Figure 6.11: Two oil single oil palm fruits. Picture taken by Jannick H Schmidt 2007. Samples provided by United Plantation Berhad.

When the palms are getting too unproductive, the palms are poisoned and felled and the land is totally cleared with bulldozers. The specific reason for replanting may be decreasing productivity due to difficulties of harvesting (too high), too many dead palms or the FFB yield is simply decreasing with age. Years ago the biomass after felling was burned. However, due to undesirable emissions and uncontrollable forest fires open burning was prohibited in Malaysia in 1989 (Henson 2004, p 13). Henson (2004) assumes 90% compliance in 1998. Open burning is also prohibited in Indonesia. Therefore, the common practice today is shredding of the trunks from the clearing of the field. Hereafter the trunks are placed in the field as mulch, see **Figure 6.5**.

6.1 Product flow in agricultural stage

The reference for the inventory is one hecatare in one year, i.e. the average of the life cycle of one generation of oil palms, see **Figur 6.13**. The agricultural stage of oil palm is divided into three stages. The first two stages are the immature palms and the mature palms. The immature stage is regarded as the first two years after planting the palms from the nursery. After that it is assumed that the palms are yielding FFB in 23 years. It is assumed that the age of the oil palms in Malaysia's and Indonesia's oil palm plantations are evenly distributed. Thus, one average hectare consists of 8% immature palms and 92% mature palms. The third stage is clearing and replanting. It is assumed that this stage occur instantaneously. The FFB yield is applied as the yield in 2005 calculated from linear regression of yields from 1990 to 2005, see **Figure 6.12**. The same method as for determining the yield for rapeseed has been used, see section 5.1. Yields are obtained from FAOSTAT (2006). The expected yield in 2005 can be calculated as 18.87 t/ha when using the equation in **Figure 6.12**. For comparison with yields determined when using other methods see **Table 6.1**.

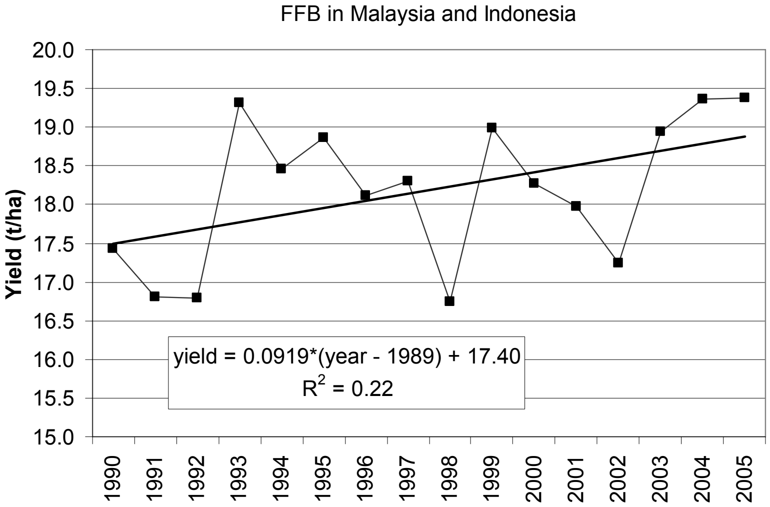
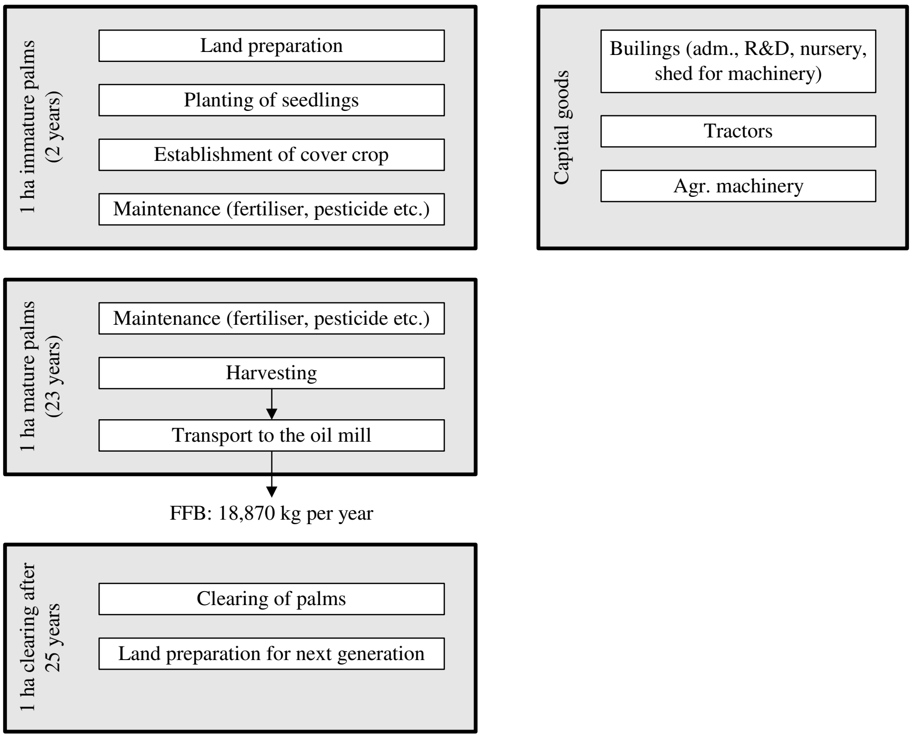


Figure 6.12: FFB yields in Malaysia and Indonesia 1990 to 2005. The linear regression line and its corresponding equation and R^2 are also shown. The yields are obtained from FAOSTAT (2006).

Region	Yield 2005 (based on regression 1990-2005)	Average yield 1990-2005	Average yield 2000-2005	Yield 2003	Yield 2004	Yield 2005
Malaysia	19.84 t/ha	18.74 t/ha	19.29 t/ha	20.48 t/ha	20.49 t/ha	20.90 t/ha
Indonesia	17.95 t/ha	17.40 t/ha	17.73 t/ha	17.30 t/ha	18.20 t/ha	17.85 t/ha
Malaysia and Indonesia	18.87 t/ha	18.19 t/ha	18.53 t/ha	18.95 t/ha	19.36 t/ha	19.38 t/ha

Table 6.1: FFB yields in Malaysia and Indonesia determined using different methods. The applied yield is marked with a dotted line.



Figur 6.13: Product flow related to cultivation of 1 ha oil palm in 25 year. The grey shaded boxes represent the unit processes in the agricultural stage.

6.2 Omitted inventory data in agricultural stage

The production of seeds has been omitted. This is not consistent with the inventory of the agricultural stage of rapeseed production. However, the life time of oil palms are 26 years compared to one year for rapeseed. Therefore, the interventions from seed production have been regarded as insignificant for oil palm cultivation.

Several pesticides are used in oil palm cultivation. However, only inventory data production of glyphosate has been identified. Therefore, production of cypermethrin, warfarin and several different fungicides has been omitted. On a mass basis glyphosate comprises 88% of the active ingredients in the used pesticides in mature oil palm plantations, see **Table 6.7**. On the emission side the EDIP97-method does not include characterisation factors for the active substances in pesticides. However, in the LCAfood database characterisation factors for glyphosate and cypermethrin have been determined within the framework of the EDIP97-method. No characterisation factors have been found for warfarin and fungicides. The active ingredients in warfarin and fungicides only comprise 0.02% of the total applied active ingredients in mature oil palm plantations, see **Table 6.7**. This share is assumed to be insignificant and therefore no characterisation factors have been calculated for warfarin and fungicides.

It has not been possible to identify any data on methane emissions from the oil palm plantation nor the nature that is converted into oil palm plantation. Therefore, this aspect is not included.

6.3 Energy use

As in the case of rapeseed cultivation in Denmark described in section 5.3 oil palm cultivation implies several field work processes using fossil fuel such as planting of new palms, sowing of crop cover, fertiliser application, pesticide application, harvesting and finally after 25 years clearing and preparing the field for replanting.

Field work operations: which and how many times?

It has not been possible to determine the specific diesel consumption per single field work process per hectare. Data has only been available as the total diesel consumption per year on the estate level. However, though not used, the number of the included field work operations has been estimated, see **Table 6.2**.

Field work process		Number of processes per year	References and comments
Replanting	Clearing of old stands	1/28	(Xavier 2006)
	Chopping of trunks	1/28	(Xavier 2006)
	Placement of chopped trunks	1/28	(Xavier 2006)
	Planting of palms	1/28	(Xavier 2006)
	Placement of chopped trunks	1/28	(Xavier 2006)
	Sowing of crop cover (Pueraria)	1/28	(Xavier 2006)
Fertilising	N-fertiliser (urea or ammonia nitrate)	3	Numbers apply to palm > 3-5 years. After 5 years fertiliser application is done by mechanical spreader attached to tractor (Xavier 2006)
	Rock phosphate	1	
	Potash	3	
	Magnesium	1	
	Boron	1	
Pesticide		?	
Harvesting		26	(Xavier 2006)
Transport	Transport of FFB to mill	~18.9 t x 5 km	Estimated per hectare from average yield in Malaysia and Indonesia and estimated distance in 50 km^2 estate

Table 6.2: Description and documentation of estimated number of field work processes. These data are only for information purposes, the data is not used as inventory data.

Diesel use

As mentioned in the previous section it has not been possible to establish a relation between field work processes and the energy consumption with the given data material. Therefore, diesel consumption in machinery in the plantation is determined as a total value including all field work processes per ha per year. Different data sources have been identified, see **Table 6.3**. The data in **Table 6.3** represent average of oil palm plantation including an area covered by immature palms.

Fuel	United Plantations (Singh 2006)	Yusoff and Hansen (2005)	Unilever (1990)	Zah and Hischier (2003)	Applied
Diesel	1,611 MJ	2,366 MJ	2,038 MJ	9,857 MJ	2,118 MJ
Petrol	340 MJ	-	-	-	-
Total	**1,951 MJ**	**2,366 MJ**	**2,038 MJ**	**9,857 MJ**	**2,118 MJ**

Table 6.3: Consumption of diesel and petrol per ha of oil palm plantation. The applied data are marked with a dotted line.

In **Table 6.3** the energy consumption in United Plantations, Yusoff and Hansen (2005) and Unilever (1990) are given in litre. This has been converted into mega joules by using calorific values for diesel at 36.4 MJ/litre given in Appendix 1: Data on fuels.

It appears from **Table 6.3** that the diesel consumption given in Zah and Hischier (2003) is 4 to 5 times higher than the figures given in the other three sources. The data in Zah and Hischier (2003) are based on Hirsinger et al. (1995). As described in section 11.3 the energy figures in Hirsinger et al. (1995) are not regarded as consistent. Therefore, the energy consumption in Zah and Hischier (2003) is not regarded as representative for Malaysian oil palm plantations. The energy use in United Plantations may be slightly lower than in average plantations because they use rail based transport of the harvested FFB to the oil mill which requires less energy than truck transportation. Not many plantations have that technology because it is only applicable in flat terrain and investments costs are high. The applied energy use is the average of United Plantations, Yusoff and Hansen (2005) and Unilever (1990). For simplification reasons all fuel used in oil palm plantations is regarded as diesel.

The uncertainty related to the difference between energy uses determined from the data sources in **Table 6.3** is assessed in a sensitivity analysis, see section 21.6

6.4 Other processes

Other processes include those processes which are not related to the field. This includes the nursery where the seeds are sown and grown for one year before the seedlings are planted in the plantation. According to section 6.2 the nursery is omitted from the inventory.

6.5 Materials

Seeds

According to section 6.2 production of oil palm seeds have been omitted from the inventory.

Fertilisers

Several data on the use of fertilisers in oil palm plantations have been identified see **Table 6.4**. Data for mature and immature oil palms have been identified. Thus, distinction between these two stages is done.

Fertiliser	N (kg N/ha)	P (kg P_2O_5/ha)	K (kg K_2O/ha)	Mg (kg MgO/ha)	S	B	Source
Applied fertiliser in oil palm plantations							
1) United Plantations 2005	136	77	297	42	-	-	(United Plantations Berhad 2006, p 110, 123, 129)
2) Malaysia, average	96	28	172	48	-	-	(Yusoff and Hansen 2005)
3) Malaysia, costal soils*	124*	128*	256*	19*	16*	-	(Subranamiam 2006a)
4) Malaysia, average 2001	100	45	205	-	-	-	(IFA et al. 2002, p 13)
5) Malaysia, average 2002	76	86	119	-	-	-	(FAO 2004)
6) Malaysia, immature	90	35	140	29			(Henson 2004, p 33)
Applied value (mature)	106	73	210	36	16	-	Average of 1, 2, 3, 4 and 5
Applied value (immature)	90	35	140	29	-	-	The value given in 6
Theoretical figures							
Recommended application (by MPOB)	128	144	200	-	-	-	(FAO 2004)
Nutrient demand, 10 year old palms	114	32	180	53	-	-	(Corley and Tinker 2003, p 332)
Nutrient demand, 15 year old palms	182	56	315	95	-	-	(Corley and Tinker 2003, p 332)

Table 6.4: Input of nutrients to the plantation. The applied fertiliser uses in this study are marked with a dotted line. * The data in Subranamiam (2006a) are provided as total fertiliser product per palm. This is converted to fertiliser component per ha be assuming 142 palms/ha (see description of oil palm cultivation in the beginning of section 6) and 35% N in ammonia nitrate, 30% P_2O_5 in china rock phosphate, 60% K_2O in muriate of potash and 27% MgO and 23% S in kieserite (Corley and Tinker 2003, p 385).

The fertiliser uses applied in this study are shown in **Table 6.4**. The adopted figures are the average of five different sources on the fertiliser use in mature oil palm plantations in Malaysia and one data source for immature oil palms in Malaysia. The nutrient demand for oil palm given in **Table 6.4** is the total demand that may be met by inputs of artificial fertilisers, biomass residuals (pruned fronds, EFB and POME), decomposition from the atmosphere and possible decrease in the soil nitrogen pool. In addition losses as leaching, run-off and evaporation appear. Therefore, the nutrient demand cannot be used as a stand alone guideline for application of artificial fertiliser.

The total amounts of applied nutrients in fertiliser in oil palm plantations are calculated as the average of 2 years immature and 23 mature palms. Thus, the average uses are 105 kg N/ha, 31 kg P/ha (70 kg P_2O_5), 170 kg K/ha (204 kg K_2O/ha), 21 kg Mg/ha (35 kg MgO/ha) and 16 kg S/ha.

According to Corley and Tinker (2003, p 385) more than half of the fertiliser use in Malaysia is used in the palm oil industry. Therefore, national statistics on types of N, P and K fertilisers used are assumed to be representative for oil palm. However, only statistical data on import and export have been identified (FAO 2004). However, according to FAO (2004) most of the artificial fertiliser used in Malaysia is imported. Therefore, the import of artificial fertilisers is assumed to represent the use of fertiliser in oil palm plantations. The distribution between different types of imported N, P and K fertilisers in Malaysia is shown in **Table 6.5**.

Nitrogen	Share	Phosphate	Share	Potash	Share
Ammonium sulphate	70%	Phosphate rock	64%	KCl	83%
Urea	26%	Ammonium phosphate	6%	K_2SO_4	4%
Other	4%	Other	30%	Other	13%

Table 6.5: Distribution between different types of N, P and K fertilisers imported in Malaysia in 2001 (FAO 2004).

Nitrogen: According to Subranamiam (2006a) urea is typically applied on costal soils while ammonium sulphate is applied on inland soils. The reason for that may be that costal soils are moister. Hereby, the urea hydrolyses faster and volatilisation of ammonia is reduced (based on discussions on United Plantations Berhad with Singh 2006). According to Corley and Tinker (2003, p 367) 27-48% of the applied N with urea volatises. However, if the urea is applied on moister costal soils volatilisation is estimated to only 10-15% (based on discussions on United Plantations Berhad with Singh 2006). It is assumed that the marginal source of N-fertiliser is 73% ammonium sulphate and 27% urea. More sophisticated assumptions could have been done, e.g. that increased production by expanding the cultivated area takes place on inland soils while increases in yields are more likely to take place in the well established plantations in the costal areas. Thus, the marginal fertiliser for increases by area should be ammonium sulphate (inland) while the marginal fertiliser for increases by yield should be urea (coastal areas). However, it has not been possible to find any data that document that. Therefore, the same fertiliser mix of 73% ammonia sulphate and 27% urea is regarded as the marginal fertiliser for increased production by area as well as yield.

Inventory data for ammonia sulphate and urea are described in section 5.4 and **Table 5.17**.

Phosphate: The marginal source of phosphate fertiliser is assumed to be phosphate rock. In Europe, the marginal phosphate fertiliser is assumed to be triple super phosphate, see section 5.4. The reason why plain phosphate rock can beneficially be applied in South East Asia is that the soils are acidic (Corley and Tinker 2003, p 387). That helps dissolving the phosphate. In addition, there is more time for the crops to absorb the phosphate because oil palms are perennials (Corley and Tinker 2003, p 387).

Two inventories of phosphate rock have been identified, one for phosphate rock from Morocco and one for phosphate rock from U.S. Analysing the data sets in Simapro and using the EDIP97 for LCIA, it appears that global warming, acidification and toxicity are the most significant impact categories. In **Table 5.17** the two inventories are compared within these categories.

LCI-data for N-fertiliser	CO_2-eq.	SO_2-eq.	ETWC, m^3 water	Description of data
'*Phosphate rock, as P2O5, beneficiated, dry, at plant/MA'* (ecoinvent 2004)	217 g	1.0 g	151 m^3	*Time:* Data from around 2000 *Geography:* Morocco *Technology:* US technology for dry rock or dried wet rock processing *Co-product allocation*: Not relevant *Capital goods:* Machinery, buildings
'*Phosphate rock, as P2O5, beneficiated, wet, at plant/US'* (ecoinvent 2004)	194 g	1.2 g	187 m^3	*Time:* Data from around 2000 *Geography:* US *Technology:* US technology for wet rock processing *Co-product allocation*: Not relevant *Capital goods:* Machinery, buildings

Table 6.6: Comparison of LCIs of phosphate rock. The comparison is shown as characterised results using the EDIP97-method for LCIA. All the life cycle inventories are for 1 kg fertiliser, as P_2O_5.

It appears from **Table 5.17** that the differences between the two data sets for phosphate rock are not significant. It is chosen to apply the average of the two. Analysing the data sets in SimaPro it appears that the use of electricity is significant regarding the impact categories shown in **Table 5.17**. Therefore, is chosen to apply a modified version of the ecoinvent data on phosphate rock where average electricity has been replaced by marginal electricity assumed to be produced from coal.

Potassium (K): The marginal source of potash is assumed to be KCl, see **Table 6.5**. Inventory data for potassium chloride are described in section section 5.4 and **Table 5.21**.

Pesticides

The use of pesticides is determined from data provided by United Plantations Research Department (Singh 2006). The use of pesticides per hectare is given in **Table 6.7**.

Pesticide	Mature		Immature		Nursery	
	kg/ha	kg a.i./ha	kg/ha	kg a.i./ha	kg/ha	kg a.i./ha
Herbicide (typically glyphosate)	4.3	2.3	11	3.6	49	8.2
Insecticide (typically cypermethrin)	0.82	0.30	5.3	0.45	5.6	0.28
Fungicide (several different fungicides)	0.00059	0.00018	0.21	0.16	12	6.8
Rodenticide (typically warfarin)	0.60	0.00022	0.19	0.000092	-	-
Total	**5.7**	**2.6**	**16.7**	**4.2**	**66.6**	**15.3**

Table 6.7: Use of pesticides per hectare per year. The amount and type of pesticides used are based on figures from United Plantations in 2005 (Singh 2006).

Inventory data for production of the pesticides in **Table 6.7** have only been identified for glyphosate: 'Glyphosate, at regional storehouse/RER' (ecoinvent 2004). The data set includes energy use, transport to regional storehouse and capital goods, i.e. machinery and buildings. Analysing the data in Simapro and using the EDIP97 method use of electricity appears to be significant within several impact categories. Therefore, European average electricity is replaced by marginal electricity based on coal technology. Production of the other pesticides has been applied as 'Pesticide unspecified, at regional storehouse/RER' (ecoinvent 2004). Also in this case, European average electricity is replaced by marginal electricity based on coal technology. The applied a.i. of pesticides are the average of 2 years immature and 23 years mature oil palm, i.e. annual application of 2.4 kg a.i. glyphosate/ha, 0.31 kg a.i. cypermethrin/ha, 0.013 kg a.i. fungicides/ha and 0.00021 kg a.i. warfarin/ha.

6.6 Co-products

There are no co-products in the agricultural stage of palm oil production. The pruned fronds and felled trunks at replanting, however, could be regarded as a co-products displacing artificial fertiliser. But since mulching of is a common practice and since the amounts of pruned fronds and trunks at replanting are proportional with the cultivated area, changes in oil palm cultivation do not affect the nutrient balances and the consequential emissions and fertiliser use per unit of area. Only if changes in the use of pruned fronds are affected, the effects should be included. The co-products EFB and POME are co-products from the oil mill stage, but they appear as inputs to the agricultural stage. Normally, application of EFB and POME is constant with the plantation area as in the case of pruned fronds. Thus, a change in demand for palm oil will not affect the application of EFB and POME per unit of area and the consequential emissions and fertiliser use per unit of area.

6.7 Emissions

Emissions from the plantation are determined from mass balances of the relevant substances, i.e. N, P and C, during the oil palms life cycle. However, since most of the net fluxes of C during the life cycle of one oil palm generation are zero (CO_2 uptake equals CO_2 release), a detailed balance has not been conducted. Mass balances are established per ha on an annual basis. Firstly all known inputs and outputs are summarised. The residuals are then distributed on various emissions calculated from different models. Oil palm is not an annual crop like rapeseed. Oil palm is a perennial. During the life cycle of one generation oil palm plantation the input and uptake of nutrients, harvesting of FFB and decomposition of biomass residues varies. Therefore, it is not desirable to establish a simple annual nutrient balance as for rapeseed described in section 5.6. The 25 years from planting to replanting is divided into several stages representing different inputs and outputs of nutrients. The following four components of the balance are considered: 1) net inputs, 2) release from decomposition of biomass, 3) uptake of nutrients from the soil in the standing biomass and 4) harvested biomass. The residual is then the field surplus of N and P from which emissions are calculated. During the life cycle of one oil palm generation 2) and 3) are equal, but within the singe stages they may differ. Comparing the nutrient balance for oil palm with rapeseed, 2) and 3) are not necessary for rapeseed because the balance is ‘reset’ each year. The principle for establishing a field balance of nutrients in each stage during the life cycle of one generation of oil palm is illustrated in **Figure 6.14**. The four components are described in the following.

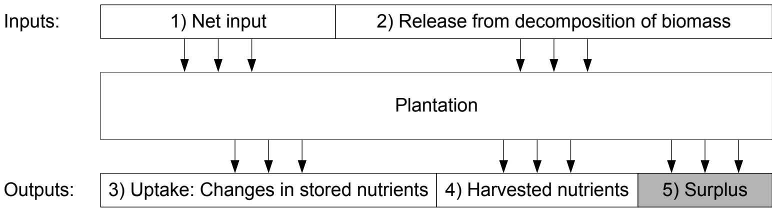


Figure 6.14: Principle for establishing a field nutrient balance. The surplus of from which different emissions are calculated is grey shaded.

All emissions are inventoried for average, peat and mineral (i.e. non-peat) soils. According to Henson (2004), an area of 1,360 km^2 was planted with oil palm on peat in Malaysia in 2003/2004. The total planted area with oil palm in Malaysia was 32,600 km^2 in 2003 and 34,100 km^2 in 2004. Thus, 4.0 - 4.2% of the area planted with oil palm in Malaysia is on peat. The same figures are assumed to be valid for oil palm in Indonesia. Data for average soil (4.1% peat) is applied in the baseline scenario while inventories for peat and mineral soils are applied as sensitivity analyses described in section 21.13. According to Corley and Tinker (2003, p 81) much of the open land remaing land for expanding the oil palm cultivation in SE-Asia is peat soils. According to Wetland International (2007), more than 50% of the planned new plantations in Malaysia and Indonesia are on peat soils.

Inputs: Net inputs of nutrients

Inputs of nutrients include artificial N- and P-fertiliser, N-deposition from the atmosphere, N-fixation from legume cover crops (typical pueraria), planting of palms and application of EFB and POME as organic fertiliser.

Artificial fertiliser: The inputs of artificial fertilisers are described in **Table 6.4**. The amount of applied P_2O_5 is converted into P by use of molar masses.

N-deposition: Three figures on atmospheric N-deposition in Malaysia have been identified; 17 kg N/ha (Corley and Tinker 2003, p 358), 21 kg N/ha (Corley and Tinker 2003, p 292) and 14.6 kg N/ha (Chew 1999, p 64). It is chosen to apply the average of these three values as representative for N-deposition in Malaysia, i.e. 17.5 kg N/ha.

N-fixation: According to Chew et al. (1999, p 64) legumes cover crop has a negligible effect on addition of nitrogen in a nitrogen balance for oil palm. However, it may be questioned if the legumes cover crop has only a negligible effect on the nitrogen balance, at least for nitrogen balances the first five years after planting. Hauser (2006) provides experimental results for pueraria and mucuna legumes grown in maize fields in Cameroon. These results show that the average annual nitrogen fixation over a period of four years are 35.3 kg N/ha for mucuna and 76.0 kg N/ha for pueraria. Swart and Diest (1987, p 145) found a higher value for pueraria at 292 kg N/ha during a growing season at 5½ month. Haque and Jutzi (1984) provides average nitrogen fixation rates for 16 forage legumes (not including pueraria and mucuna) in Sub-Sahara Africa. The means ranges from 62 to 290 kg/ha on an annual basis. Arulandoo (2006) estimates the total contribution of the leguminous cover crop in young oil palm plantations around 200 kg N/ha. It appears that very different figures exist. It is certain that fixation takes place. It is assumed that fixation the first year is 200 kg N/ha and after that it gradually decreases to zero the sixth year.

Planting of palms: No data on the weight of palm seedlings have been identified. Therefore, it assumed that each palm has a dry weight at 10 kg corresponding to 1.42 t/ha with a palm density at 142 palms/ha. Four different data sources for N and P contents in oil palms have been identified, see **Table 6.8**. Three of the data sources are cited in Henson (2004).

Nutrients content in oil palm	kg N/t biomass	kg P/t biomass
1) Henson (2004, p 33)	6.3	0.62
2) Henson (2004, p 33)	5.8	0.54
3) Henson (2004, p 33)	6.4	0.57
4) Corley and Tinker (2003, p 328)	5.4	0.78
Applied value	6.0	0.63

Table 6.8: Contents of N and P in oil palm total standing biomass (dry weight basis). The applied values are marked with a dotted line.

EFB: The production of EFB amounts 22.5% of the FFB (see **Table 10.2**). It is assumed that the EFB from the palm oil mill are distributed evenly through the plantation on immature as well as mature palms. Thus, the production of EFB is 22.5% of the FFB yield of 18.87 t/ha, i.e. 4.25 t/ha. Henson (2004, p 24) estimates the decay/decomposition time for EFB as one year. The content of N and P in EFB is given in **Table 6.9**.

Nutrients content in EFB	kg N/t EFB	kg P/t EFB
Dry weight	8.0	0.96
Fresh weight (60% water)	3.2	0.38

Table 6.9: Contents of N and P in empty fruit bunches (EFB). (Singh et al. 1999, p 172)

POME: The production of POME is 672.5 kg/t crude palm oil (see **Figure 10.1**). Applying the oil extraction rate at 19.98% (see **Figure 10.1**) and the yield at 18.87 t FFB/ha, the amount of POME can be calculated as 2.54 t POME/ha. As for EFB it is assumed that POME is applied evenly distributed in the plantation on immature as well as mature palms. This does not represent what actually happens, since only a minor part of the plantation receives POME. However, it is assumed that unequally distribution of nutrients because of POME application is equalised through differentiated application of artificial fertiliser. Henson (2004, p 24) estimates the decay/decomposition time for POME as one year. The content of N and P in POME is given in **Table 6.10**.

Nutrients content in POME	kg N/t POME	kg P/t POME
Dry weight	19	3.0
Fresh weight (95% water)	0.95	0.15

Table 6.10: Contents of N and P in palm oil mill effluent (POME). Nutrients content (Department of environment 1999) and moisture content (Singh 1999).

The net inputs of N and P are summarised in **Table 6.11**.

Input of nitrogen, kg N/ha per year	**year 1**	**year 2**	**year 3**	**year 4**	**year 5**	**year 6-25**
N-fertiliser	90	90	106	106	106	106
N-deposition from the atmosphere	17.5	17.5	17.5	17.5	17.5	17.5
N-fixation by legumes	200	160	120	80	40	0
Planted palm seedlings	8.5	0	0	0	0	0
EFB	13	13	13	13	13	13
POME	2.4	2.4	2.4	2.4	2.4	2.4
Total net input of N	**332**	**283**	**259**	**219**	**179**	**139**
Input of phosphorus, kg P/ha per year	**year 1**	**year 2**	**year 3**	**year 4**	**year 5**	**year 6-25**
P-fertiliser	15	15	32	32	32	32
Planted palm seedlings	0.9	0	0	0	0	0
EFB	1.6	1.6	1.6	1.6	1.6	1.6
POME	0.4	0.4	0.4	0.4	0.4	0.4
Total net input of P	**18**	**17**	**34**	**34**	**34**	**34**

Table 6.11: Summary of annual net inputs of N and P to the plantation.

Inputs: Release of nutrients from decomposition of biomass

Decomposition of biomass residues includes decomposition of fronds, trunks, cover crop, EFB and POME **Table 6.12** summarises the biomass residues from the agricultural stage left in the field during the life cycle of one generation of an oil palm plantation. The pruned fronds are left in the field as a biomass resource.

Biomass residues per ha	**Field source**		**At replanting**
	Immature: year 1 and 2	**Mature: year 3-25**	
Pruned fronds	0 t/ha	10.70 t/ha	0 t/ha
Biomass at felling	0 t/ha	0 t/ha	94.9 t/ha

Table 6.12: Biomass residues as annual output and from replanting as a single output in the end of the palm's economical life. Data on annual pruned fronds and biomass at felling are obtained as the average of data from two different references cited in Weng (1999, p 43)

The data for pruned fronds in **Table 6.12** are slightly higher than values identified in Henson (2004, p 10): 8-9 t/ha and in Corley and Tinker (2003, p 293): 9 t/ha. When comparing the data for biomass at felling values found in Henson (2004, p 100 t/ha) are in good accordance with the used values. However, Corley and Tinker (2003, p 92) specify biomass at felling as around 62 and 68 t/ha for 17.5 and 27.5 years old palms respectively, which seem to be underestimated compared to Weng (1999) and Henson (2004). The data in Weng (1999) seem to be more consistent and comparable than the data provided in Corley and Tinker (2003) and Henson (2004). Therefore, it is chosen to apply these data in this study.

As it appears from **Table 6.12** the output of biomass from the field varies significant in the three stages. Therefore the three different stages have to be considered when establishing nutrient balances and in addition the decomposition time of biomass residues left in the field must also be taken into account. The decomposition time is assumed to be 2 years for fronds and shredded trunks. 2 years are the same decomposition time as for unburned shells (Henson 2004, p 24). **Figure 6.15** shows production and decomposition of biomass residues during the life cycle of one ha oil palm plantation.

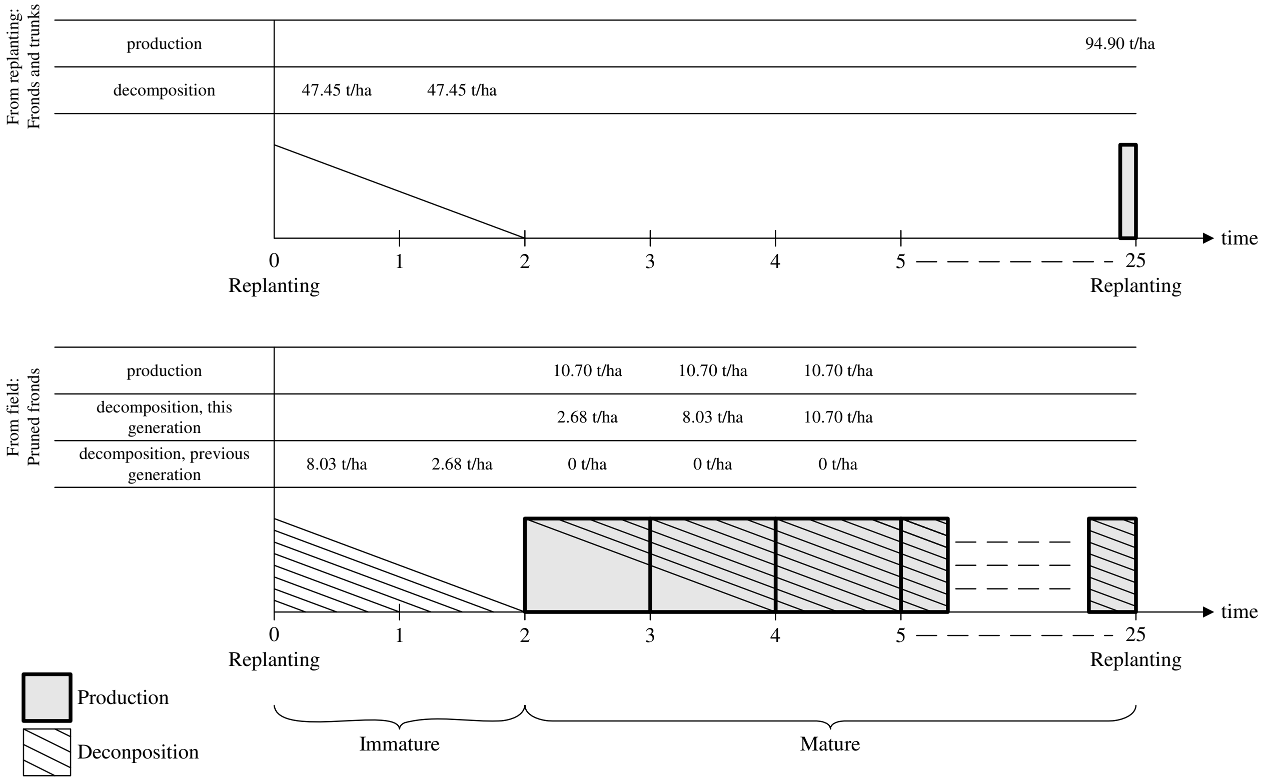


Figure 6.15: Production and decomposition of fronds and trunk during the life cycle of one ha of oil palm. The figure is divided into two parts where the one in the top refers to clearing and replanting and the one in the bottom refers to annual production and decomposition of biotic residues.

In addition to the biotic residues from the agricultural stage given in **Table 6.12** legume cover crop also constitute inputs of nutrients to the plantation. According to Chew et al. (1999, p 64) legumes play an important role in immobilising nitrogen from decomposing trunks and fronds during the immature period. The immobilised nitrogen is released as the cover crop dies back when it is shaded out at about 3-5 years after planting (Chew et al., p 72). Thus, after 12 month the N accumulated in cover crop is around 289 kg/ha, whiles this is reduced to 227 kg after 20 month (Chew et al., p 73). Based on above figures, the net N-uptake in cover crops the first five years after planting is estimated, see **Table 6.13**. It is assumed that there is no decomposition of legume cover the first year. The decomposition in year 2 to 5 is assumed to be 72.3 kg each years adding up to the 289 kg. The 289 kg N/ha is regarded as uptake and is included in that component of the nitrogen balance. Uptake in and decomposition of legume cover crops only include the part of nitrogen that is taken up from the soil. In addition the cover crop fixes nitrogen from the atmosphere. This is regarded as an input which is released the same year as it is fixed in the plant. The effect of legume cover crop is included for the nitrogen balance only. According to Corley and Tinker (2003, p 387) there are so far no data on the effect of cover crop on the phosphate balance.

Net N-decomposition in cover crop	year 1	year 2	year 3	year 4	year 5
N-decomposition (kg N/ha)	0	72.3 kg	72.3 kg	72.3 kg	72.3 kg

Table 6.13: Net uptake by cover crops under oil palm the first five years after planting. Due to shading, the presence of cover crops is assumed to insignificant after five years.

Table 6.14 summarises the amount of biomass residues that decompose in each stage.

Decomposition of biotic residues, t/ha (dry weight)	year 1	year 2	year 3	year 4	year 5	year 6-25
Pruned fronds, present generation	-	-	2.68 t/ha	8.03 t/ha	10.70 t/ha	10.70 t/ha
Fronds, previous generation	8.03 t/ha	2.68 t/ha	-	-	-	-
Biomass from replanting	47.45 t/ha	47.45 t/ha	-	-	-	-
Legume cover crop	0 kg N/ha	72.3 kg N/ha	72.3 kg N/ha	72.3 kg N/ha	72.3 kg N/ha	-

Table 6.14: Decomposition of biotic residues during different stages of the life cycle of one generation of oil palm.

In order to establish a nutrient balance it is also necessary to knowing the contents of N and P in the fronds and felled biomass at replanting, i.e. whole palms. This is given in **Table 6.15**.

Component	kg N/t dry weight	kg P/t dry weight	Reference
Fronds	12.2	0.9	Fronds consists of 65% rachis and 35% leaflet (Tinker and Smilde 1963, p 354). Nutrient contents of rachis and leaflets are obtained from Khalid et al. (2000, p 50)
Whole palm	6.0	0.63	Aver. of values in Henson (2004, p 33) and Corley and Tinker (2003, p 328)
FFB	5.5	0.8	Corley and Tinker (2003, p 331)

Table 6.15: Nutrient contents in oil palm components.

Based on **Table 6.14** and **Table 6.15** the inputs of nutrients to the soil from release of decomposing biomass are determined, see **Table 6.16**.

Release of nitrogen from decomposition, kg N/ha	year 1	year 2	year 3	year 4	year 5	year 6-25
Release from pruned fronds, present generation	0	0	33	98	131	131
Release from pruned fronds, previous generation	98	33	0	0	0	0
Release from felled biomass from replanting	285	285	0	0	0	0
Release from dying back of legume cover crop	0	72	72	72	72	0
Total input of nitrogen from decomposition of biomass	**383**	**390**	**105**	**170**	**203**	**131**
Release of phosphorus from decomposition, kg P/ha	**year 1**	**year 2**	**year 3**	**year 4**	**year 5**	**year 6-25**
Release from pruned fronds, present generation	0,0	0,0	2,3	6,8	9,1	9,1
Release from pruned fronds, previous generation	6,8	2,3	0,0	0,0	0,0	0,0
Release from felled biomass from replanting	29,9	29,9	0,0	0,0	0,0	0,0
Total input of nitrogen from decomposition of biomass	**36,7**	**32,2**	**2,3**	**6,8**	**9,1**	**9,1**

Table 6.16: Summary of release of N and P from decomposition of biomass residues.

Outputs: Uptake, stored and harvested nutrients

Uptake includes harvested nutrients and increases in nutrients in stored biomass, i.e. annual accumulated nutrients in standing biomass. Stored nutrients in the biomass are considered as an output because it immobilises nutrients until they are released when the biomass dies back. A considerable share of the nutrient inputs are accumulated in the living biomass until it dies back. The release of nutrients from decomposition of biomass is described in the previous section.

Increase in standing biomass, oil palms: It is assumed that the stored biomass in the oil palms increases linearly from estimated 1.42 t/ha (see nutrients in planted palms described previously) to 94.9 t/ha at felling (see **Figure 6.15**). Thus, during the 25 years of one oil palm generation the annual accumulation in standing biomass is 3.74 t/ha (dry weight). The content of N and P in oil palms is given in **Table 6.15**.

Increase in standing biomass, cover crops: According to section 6.7: "Inputs: Release of nutrients from decomposition of biomass" there is only a net uptake of N in cover crops the first year. The uptake is 289 kg N/ha.

Harvested FFB: The annual yield of FFB from mature and immature oil palm plantations is 18.87. Two of the 25 years of the life cycle of one generation of oil palm are immature. Thus the average yield from mature oil palms can be determined as 20.51 t/ha. The yield varies during the mature period from around 10-20 t/ha the first years after planting to 25-34 t/ha when the yield reaches its maximum (Corley and Tinker 2003, p 239, 321). Based on the yield profiles provided in Corley and Tinker (2003, p 239, 321) an average profile is estimated, see **Table 6.17**.

Year	1-2	3	4	5	6	7	8-10	11-16	17	18-19	20	21	22	23	24	25
Yield, as given	0	15	18	21	24	26	27	27	27	26	26	25	24	23	22	21
Yield, adjusted	0	13	15	17	20	22	22	23	22	22	21	21	20	19	18	18

Table 6.17: Yield profile (t FFB/year, fresh weight) as a function of palm age. The values in the top line are obtained as the average of six yield profiles given in Corley and Tinker (2003, p 293, 321). The figures in the bottom line are adjusted values of the top line so that they fit the total average yield in the mature period at 20.51 t FFB/ha.

The harvested N and P in FFB can then be determined from the adjusted yield profile in **Table 6.17** and the content of N and P in FFB given in **Table 6.15**.

Pruned fronds: According to Weng (1999, p 43) 10.70 t/ha[13] (dry weight) pruned fronds are harvested each year. However, this is only from mature oil palms. No fronds are harvested the two first, immature, years. As a comparison United Plantations has 9.56 t pruned fronds/ha (dry weight) in 2005 (United Plantations Berhad 2006, p 123 and 129). The reason for deviation from the 10.70 t/ha obtained from Weng (1999) may be due to different distribution between immature and mature areas. Since the data from Weng (1999) represents averages of a larger area, the 10.70 t/ha is applied. It is assumed that the amount of pruned fronds is constant through the entire mature period that last from 2 to 25 years after planting. This may be a simplification of the actual situation, but no data on changes with palm age have been identified. The content of N and P in fronds is given in **Table 6.15**.

The increase in stored N and P in the field are summarised in **Table 6.18**.

---

[13] This is adopted as the average of two different values given in Weng (1999).

Uptake, stored and harvested nitrogen, kg N/ha	**Year**													
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Uptake in oil palms	23	23	23	23	23	23	23	23	23	23	23	23	23	23
Uptake in cover crop	289	0	0	0	0	0	0	0	0	0	0	0	0	0
Harvested FFB	0	0	36	43	50	57	63	65	65	65	65	65	65	65
Pruned fronds	0	0	131	131	131	131	131	131	131	131	131	131	131	131
Total nitrogen	**312**	**23**	**190**	**197**	**204**	**211**	**216**	**218**	**218**	**218**	**219**	**219**	**219**	**219**

Uptake, stored and harvested phosphorus, kg P/ha	**Year**													
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Uptake in oil palms	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Uptake in cover crop	0	0	5	6	7	9	9	10	10	10	10	10	10	10
Harvested FFB	0	0	9	9	9	9	9	9	9	9	9	9	9	9
Total phosphorus	**2**	**2**	**17**	**18**	**19**	**20**	**21**	**21**	**21**	**21**	**21**	**21**	**21**	**21**

Uptake, stored and harvested nitrogen, kg N/ha	**Year**										
	15	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Uptake in oil palms	23	23	23	23	23	23	23	23	23	23	23
Uptake in cover crop	0	0	0	0	0	0	0	0	0	0	0
Harvested FFB	65	65	64	64	62	61	59	57	55	53	52
Pruned fronds	131	131	131	131	131	131	131	131	131	131	131
Total nitrogen	**219**	**219**	**218**	**217**	**216**	**215**	**213**	**211**	**209**	**207**	**205**

Uptake, stored and harvested phosphorus, kg P/ha	**Year**										
	15	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Uptake in oil palms	2	2	2	2	2	2	2	2	2	2	2
Uptake in cover crop	10	10	10	9	9	9	9	9	8	8	8
Harvested FFB	9	9	9	9	9	9	9	9	9	9	9
Total phosphorus	**21**	**21**	**21**	**21**	**21**	**21**	**20**	**20**	**20**	**19**	**19**

Table 6.18: Summary of release of N and P per ha per year from decomposition of biomass residues.

Emissions related to N-balance

Point of departure when calculating N-emissions is a N-balance on the field scale. The N-balance is shown in **Table 6.19** below.

	Year													
Inputs: Net inputs	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
N-fertiliser	90	90	106	106	106	106	106	106	106	106	106	106	106	106
N-deposition from the atmosphere	18	18	18	18	18	18	18	18	18	18	18	18	18	18
N-fixation by legumes	200	160	120	80	40	0	0	0	0	0	0	0	0	0
Planted palm seedlings	9	0	0	0	0	0	0	0	0	0	0	0	0	0
EFB	14	14	14	14	14	14	14	14	14	14	14	14	14	14
POME	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Total	**332**	**283**	**259**	**219**	**179**	**139**	**139**	**139**	**139**	**139**	**139**	**139**	**139**	**139**
Inputs: Release from decomposition of biomass														
Pruned fronds, present generation	0	0	33	98	131	131	131	131	131	131	131	131	131	131
Pruned fronds, previous generation	98	33	0	0	0	0	0	0	0	0	0	0	0	0
Felled biomass from replanting	285	285	0	0	0	0	0	0	0	0	0	0	0	0
Dying back of legume cover crop	0	72	72	72	72	0	0	0	0	0	0	0	0	0
Total	**383**	**390**	**105**	**170**	**203**	**131**	**131**	**131**	**131**	**131**	**131**	**131**	**131**	**131**
Output: Increase in standing biomass (uptake that stays in the field)														
Uptake in oil palms	23	23	23	23	23	23	23	23	23	23	23	23	23	23
Uptake in cover crop	289	0	0	0	0	0	0	0	0	0	0	0	0	0
Pruned fronds	0	0	131	131	131	131	131	131	131	131	131	131	131	131
Total	**312**	**23**	**154**	**154**	**154**	**154**	**154**	**154**	**154**	**154**	**154**	**154**	**154**	**154**
Output: Harvested FFB (uptake that is brought out of the field)														
Harvested FFB	0	0	36	43	50	57	63	65	65	65	65	65	65	65
Total	**0**	**0**	**36**	**43**	**50**	**57**	**63**	**65**	**65**	**65**	**65**	**65**	**65**	**65**
Balance														
N surplus (input – output)	**403**	**650**	**175**	**193**	**179**	**59**	**54**	**52**	**52**	**52**	**52**	**52**	**52**	**51**

	Year										
Inputs: Net inputs	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
N-fertiliser	106	106	106	106	106	106	106	106	106	106	106
N-deposition from the atmosphere	18	18	18	18	18	18	18	18	18	18	18
N-fixation by legumes	0	0	0	0	0	0	0	0	0	0	0
Planted palm seedlings	0	0	0	0	0	0	0	0	0	0	0
EFB	14	14	14	14	14	14	14	14	14	14	14
POME	2	2	2	2	2	2	2	2	2	2	2
Total	**139**	**139**	**139**	**139**	**139**	**139**	**139**	**139**	**139**	**139**	**139**
Inputs: Release from decomposition of biomass											
Pruned fronds, present generation	131	131	131	131	131	131	131	131	131	131	131
Pruned fronds, previous generation	0	0	0	0	0	0	0	0	0	0	0
Felled biomass from replanting	0	0	0	0	0	0	0	0	0	0	0
Dying back of legume cover crop	0	0	0	0	0	0	0	0	0	0	0
Total	**131**	**131**	**131**	**131**	**131**	**131**	**131**	**131**	**131**	**131**	**131**
Output: Increase in standing biomass (uptake that stays in the field)											
Uptake in oil palms	23	23	23	23	23	23	23	23	23	23	23
Uptake in cover crop	0	0	0	0	0	0	0	0	0	0	0
Pruned fronds	131	131	131	131	131	131	131	131	131	131	131
Total	154	154	154	154	154	154	154	154	154	154	154
Output: Harvested FFB (uptake that is brought out of the field)											
Harvested FFB	65	65	64	64	62	61	59	57	55	53	52
Total	65	65	64	64	62	61	59	57	55	53	52
Balance											
N surplus (input – output)	**52**	**52**	**52**	**53**	**54**	**55**	**57**	**59**	**61**	**63**	**65**

Table 6.19: N-balance for 1 hectare oil palm plantation.

The N surplus is distributed on different emissions. Determination of each emission is described in the following. The same approach as determination of emissions from rapeseed fields has been used, see section 5.6.

Ammonia from crop: No data on ammonia emission from oil palm have been identified. Therefore the same value as for rapeseed has been applied, i.e. 5 kg NH_3-N/ha.

Ammonia from fertiliser application: The ammonia emission from fertiliser depends on the type of fertiliser applied. According to Andersen et al. (2001, p 35) the ammonia emission from fertilisers based on ammonia is 2% of the N content in the fertiliser. As described in section 6.5 the ammonia volatilisation from urea is as high as 27-48% of the applied N (Corley and Tinker 2003, p 367). However, if the urea is applied on moister costal soils volatilisation is estimated to only 10-15% (based on discussions on United Plantations Berhad with Singh 2006). It is assumed that ammonia volatilisation from urea averages at 30%. According to section 6.5 the applied N-fertiliser consists of 73% ammonium sulphate and 27% urea. Thus, 9.6% of the applied N-fertiliser volatises as ammonia.

Denitrification (total): The total denitrification (gaseous N oxides and molecular N_2) is calculated using the model; SimDen (Vinther and Hansen 2004). The reason why the total denitrification is calculated is that this is the only way of estimating N-loss as N_2. N_2 is determined as the total denitrification minus N_2O and NO.

The model is developed for Danish soils. Thus, the calculated total denitrification may be related to some uncertainty. The model calculates denitrification as the sum of background denitrification, denitrification from application of artificial fertiliser, denitrification related to application of manure and denitrification from fixed nitrogen. No manure is applied in oil palm plantations. The background denitrification depends on the past history of organic matter content in the soil and the soil type (Vinther and Hansen, 2004, p 30). The model includes calculations for eight different soil types and three levels of organic content. Average organic content for mineral soil and high organic content for peat soil are assumed. Denitrification from application of artificial fertiliser depends on the amount of N applied with fertiliser, a factor describing the ratio between applied N and N_2O-emission and the N_2/N_2O-ratio (Vinther and Hansen, 2004, p 31). Because of lack of information of soil types in Malaysia, it is chosen to apply a value representing the average of all eight soil types included in the model as representative for mineral soil. The model does not include peat soil. Since denitrification increases with higher C content in the soil (IPCC 2000 and FAO and IFA 2001) and since denitrification increases with higher clay content (Vinther and Hansen 2004) it is assumed that clay soils containing >25% clay is representative for peat soil. One of the eight soil types included in the model contains >25% clay.

The two parameters; N-fertiliser and N-fixation vary during the first six years of cultivation. There are no variations in the period 6-25 years after planting. Thus, the total denitrification is calculated for the first six years after planting, see **Table 6.20**.

Parameter	**year 1**	**year 2**	**year 3**	**year 4**	**year 5**	**year 6-25**
N-fertiliser, kg N/ha	90	90	106	106	106	106
N-fixation, kg N/ha	200	160	120	80	40	0
Total calculated denitrification, kg N/ha	**year 1**	**year 2**	**year 3**	**year 4**	**year 5**	**year 6-25**
Mineral soil	21	19	18	15	13	11
Peat soil	52	49	46	42	38	35
Average soil (95.1% mineral soil and 4.1% peat soil)	22	20	19	16	14	12

Table 6.20: Total denitrification from oil palm cultivation. Calculated using the model SimDen (Vinter and Hansen 2004)

Direct N_2O: The direct N_2O emission is calculated using a model described in IPCC (2000). The calculated emissions are then compared with the results using another model described in FAO and IFA (2001). The results obtained from FAO and IFA (2001) are not applied in this study because the model does not include peat soils.

IPCC (2000): According to IPCC (2000, p 4.54) the direct N_2O emission is calculated as shown in **Equation (3)** in section 5.6. The parameter values used in **Equation (3)** are described in **Table 6.21**.

Parameter	**Description**	**Parameter value**
F_{SN}	Annual amount of synthetic fertiliser nitrogen applied to soils adjusted to account for the amount that volatilises as NH3 and NOx	Fertiliser application, see **Table 6.19**. 9.6% volatises
F_{AM}	Annual amount of animal manure nitrogen intentionally applied to soils adjusted to account for the amount that volatilises as NH3 and NOx	No manure
F_{BN}	Amount of nitrogen fixed by N-fixing crops cultivated annually	See **Table 6.19**
F_{CR}	Amount of nitrogen in crop residues returned to soils annually	EFB, POME and decomposition of biomass in **Table 6.19**
F_{OS}	Area of organic soils cultivated annually (ha)	0% for mineral soil,100% for peat soil and 4.1% of the area for average soil
EF_1	Emission factor for emissions from N inputs (kg N2O-N/kg N input)	1.25% (IPCC 2000, p 4.60)
EF_2	Emission factor for emissions from organic soil cultivation (kg N2O-N/ha-yr)	16 (IPCC 2000, p 4.60)

Table 6.21: Parameters in the equation calculating direct N2O-emissions in IPCC (2000, p 4.54)

FAO and IFA (2001): According to FAO and IFA (2001, p 34) the direct N_2O emission is calculated as shown in **Equation (4)** in section 5.6. The parameter values used in **Equation (4)** are described in **Table 6.22**.

Parameter	Description	Parameter value
F	Type of fertiliser	0.0042, Fertiliser type is a combination of organic and mineral
N-app.	Applied N, kg/ha	See **Table 6.19**
Cr	Crop type	0.000, Crop type is 'other'
S	Soil texture	-0.008, -0.472 and 0.000,The N2O emission is calculated as the average of coarse, medium and fine soil
C	Soil organic C content	0.140, 1-3% C in mineral soil, based on Corley and Tinker 2003, p 84)
D	Soil drainage	-0.420, good drainage. Good drainage is needed in order to have suitable conditions for cultivating oil palms (Corley and Tinker 2003, p 75-77)
pH	Soil pH	0.000, Soil pH <5.5 (based on Corley and Tinker 2003, p 84)
Cl	Climate	0.824, Tropical climate
LM	Length of measurement period (the model is constructed to fit with literature measurements. Thus, to model emissions obtained from literature the method of measurement in literature should also be considered since this affects the measured emission)	0.825 Length of measurement period is >300 days, i.e. the longest period available in the model (chosen as the most precise)
FM	Frequency of measurement (see comment above)	0.000 Frequency of measurement is >1measure/day, i.e. the highest frequency available in the model (chosen as the most precise)

Table 6.22: Parameters in the equation calculating direct N_2O-emissions in FAO and IFA (2001, p 34-35)

The calculated N_2O emissions using the two models are summarised in **Table 6.23**.

N_2O	Mineral soil		Peat soil	Average soil
Year	IPCC (2000), kg N2O-N/ha	FAO and IFA (2001), kg N2O-N/ha	IPCC (2000), kg N2O-N/ha	IPCC (2000), kg N2O-N/ha
1	8.5	3.7	24.5	9.2
2	8.1	3.7	24.1	8.7
3	4.2	4.0	20.2	4.9
4	4.5	4.0	20.5	5.2
5	4.4	4.0	20.4	5.1
6-25	3.0	4.0	19.0	3.7

Table 6.23: Calculated N_2O emissions (kg N_2O-N/ha) for mineral soil, peat soil and average soil. For mineral soil the calculated emission is compared with emissions calculated with the model: FAO and IFA (2001). The annual emission from the years 6-25 are equal.

It appears from **Table 6.23** that the deviation between the two models is relatively small from 6-25 years after planting. The larger deviations during the first six years are mainly due to high decomposition of biomass which is included as an influential factor in the IPCC model and not in the FAO and IFA model. Decomposition of biomass causes release of fixed nitrogen. Some of this nitrogen ends as N_2O emissions from denitrification in the soil. The IPCC model also take into account that different amounts of N are fixed in the cover crop the first six years. The reason why the emission level of N_2O from peat is significant higher than from mineral soil is that there is a frequent presence of anaerobic pockets in which denitrification takes place.

Direct NO: The emission of NO is calculated using a model described in FAO and IFA (2001). According to FAO and IFA (2001, p 35) the direct NO emission is calculated shown in **Equation (5)** in section 5.6. The parameter values used in **Equation (5)** are described in **Table 6.24**.

Parameter	Description	Parameter value
F	Type of fertiliser	0.0055, Fertiliser type is a combination of organic and mineral
N-app.	Applied N, kg/ha	See **Table 6.19**
C	Soil organic C content	0.000, <3% C in mineral soil, based on Corley and Tinker 2003, p 84) and 2.571, >3% C in peat soil
D	Soil drainage	0.946, good drainage. Good drainage is needed in order to have suitable conditions for cultivating oil palms (Corley and Tinker 2003, p 75-77)

Table 6.24: Parameters in the equation calculating direct NO-emissions in FAO and IFA (2001, p 35)

The FAO and IFA model is relatively coarse. Therefore, the emission of NO is only calculated in four different situations: Immature (year 1 and 2) and Mature (year 3-25) palms and for mineral soils (95.9% of the area) and peat soils (4.1% of the area). The only parameters that are changed are the application of N-fertiliser which varies from immature to mature and the content of soil C which varies from mineral soils to peat soils. However, the calculation for peat is done with only soil C at >3% because the model does not include organic soils.

The calculated NO emission is summarised in **Table 6.25**.

Mature/immature	Mineral soils	Peat soils	Average (95.9 mineral and 4.1% peat)
Immature (year 1 and 2)	0.9	12.0	1.4
Mature (year 3-25)	1.0	13.1	1.5

Table 6.25: Calculated NO emissions (kg NO-N/ha) using the model described in FAO and IFA (2001). The applied values are marked with a dotted line.

Nitrate: The nitrate emission is calculated as the residual or rest; i.e. the surplus-N from the N-balance minus the other calculated emissions described above. The average nitrate emission for the 25 years is 80.7 kg NO_3-N/ha. However, there are great variations with the highest values the first five years at 141-618 kg N/ha and more moderate figures the rest of the period at 25-39 kg N/ha.

Since the nitrate emission is calculated as residual of the N-surplus it may be related to some uncertainty. Corley and Tinker (2003, p 358) specify annual N losses (leaching, runoff and erosion) from mature oil palms at 21 kg N/ha. This is in relatively good accordance with the calculated nitrate emission at 25-39 kg/ha from the 6th to the 25th years after planting.

N_2O, indirect from NH_3 and nitrate: Besides the direct N_2O emissions from the field which is calculated in the previous, there are indirect emissions from the emitted ammonia and nitrate. The emission of ammonia and its subsequent deposition as NO_x and NH_4 and nitrate leached from the field increase the amount of N available for denitrification and nitrification (IPCC, 2000, p 4.67). The N_2O-N emission produced from deposited NH_4-N and NO_x-N (originating from NH_3-emission) is 0.01 kg N_2O-N/kg N (IPCC 2000, p 4.73). In this respect it is assumed that all emitted ammonia will end as deposited NO_x or NH_4. The N_2O-N emission produced from leached nitrate is 0.025 kg N_2O-N/kg NO_3-N (IPCC 2000, p 4.73). The indirect N_2O emissions are not assumed to affect the calculated emissions of ammonia and nitrate since the denitrification may take place long time after the emissions took place. Therefore, the ammonia and nitrate emissions may already have had an effect on the environment.

NO, indirect: This is not included.

N changes in soil matter: In the sub-section "Emissions related to C-balance" later here in section 6.7 it is determined that there are no changes in soil carbon - neither in relation to transformation of forest/other three crops into oil palm nor in relation to continuous cultivation of oil palm. Assuming a relatively constant C/N-ration in the soil, there are also no changes of N content in the soil matter. This corresponds to the assumtions done in the case of dtermination of emissions related to N-balance for rapeseed, see section 5.6.

Summary of emissions related to N-balance: The distribution of the N-surplus is summarised in **Table 6.26**.

	Year												
Emission and source	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Ammonia from crop (kg NH_3-N/ha)	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Ammonia from fertiliser application (kg NH_3-N/ha)	8.6	8.6	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2
Denitrification (kg N/ha)	22	20	19	16	14	12	12.0	12.0	12.0	12.0	12.0	12.0	12.0
- N_2O part of denitrification (kg N_2O-N/ha)	9.2	8.7	4.9	5.2	5.1	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7
- NO part of denitrification (kg NO-N/ha)	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
- N_2 part of denitrification (kg N/ha)	11.7	10.1	12.8	9.4	7.4	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8
Nitrate (kg NO_3-N/ha)	367	616	140	162	149	32.3	26.9	25.1	25.0	24.9	24.5	24.5	24.4
N-surplus (kg N/ha)	**403**	**650**	**175**	**193**	**179**	**59.4**	**54.0**	**52.2**	**52.1**	**52.0**	**51.6**	**51.6**	**51.5**
N_2O, indirect from NH_3 (kg N_2O-N/ha)	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
N_2O, indirect from nitrate (kg N_2O-N/ha)	9.2	15.4	3.5	4.0	3.7	0.8	0.7	0.6	0.6	0.6	0.6	0.6	0.6

	Year											
Emission and source	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Ammonia from crop (kg NH_3-N/ha)	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Ammonia from fertiliser application (kg NH_3-N/ha)	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2
Denitrification (kg N/ha)	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
- N_2O part of denitrification (kg N_2O-N/ha)	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7
- NO part of denitrification (kg NO-N/ha)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
- N_2 part of denitrification (kg N/ha)	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8
Nitrate (kg NO_3-N/ha)	24.3	24.4	24.5	25.3	26.1	27.2	28.3	30.2	32.1	34.2	36.3	38.0
N-surplus (kg N/ha)	**51.4**	**51.5**	**51.6**	**52.4**	**53.2**	**54.3**	**55.4**	**57.3**	**59.2**	**61.3**	**63.4**	**65.1**
N_2O, indirect from NH_3 (kg N_2O-N/ha)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
N_2O, indirect from nitrate (kg N_2O-N/ha)	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.8	0.8	0.9	0.9	0.9

Table 6.26: N-related emissions from 1 hectare oil palm plantation, average soil (96.9% mineral soil and 4.1% peat soil). All values are given in kg N/ha.

The summary of N-related emissions from mineral soil and peat soil are not specified each of the 25 years, only the total annual average is shown, see **Table 6.27**.

Emission as kg N/ha	**Average soil (95.9% mineral soil and 4.1% peat soil)**	**Mineral soil**	**Peat soil**
Ammonia to air (kg NH_3-N/ha)	15.1	15.1	15.1
N_2O to air (kg N_2O-N/ha)	6.4	5.8	21.2
NO to air (kg NO-N/ha)	1.5	1.0	13.0
Nitrate to water (kg NO_3-N/ha)	79.7	80.7	55.9
Emission as kg emission/ha	**Average soil (95.9% mineral soil and 4.1% peat soils)**	**Mineral soil**	**Peat soil**
Ammonia to air (kg NH_3/ha)	18.3	18.3	18.3
N_2O to air (kg N_2O/ha)	10.1	9.1	33.3
NO to air (kg NO/ha)	3.2	2.1	27.9
Nitrate to water (kg NO_3/ha)	353	358	248

Table 6.27: Emissions related to N-balance.

Emissions related to P-balance

Emissions of P are simpler to determine than emissions related to N. Only one substance is emitted, i.e. P as phosphate to water/soil. As described in the case of emissions from rapeseed cultivation (see section 5.6) accumulation of phosphorus in the soil is relatively constant due to strong binding to the soil. Therefore, the emission of P is calculated as a fraction of the field surplus. According to section 5.6: ‘Emissions related to P-balance’, 2.9% of the P surplus is emitted to water as leaching of phosphate. The remaining is accumulated in the soil matter.

The P-balance for one generation of oil palm is presented in **Table 6.28**. P-balance is based on the description of inputs to and outputs from the field previous in this section.

	Year												
Inputs: Net inputs	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
P-fertiliser	15.3	15.3	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9
Planted palm seedlings	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EFB	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
POME	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Total	**18.2**	**17.3**	**33.9**	**33.9**	**33.9**	**33.9**	**33.9**	**33.9**	**33.9**	**33.9**	**33.9**	**33.9**	**33.9**
Inputs: Release from decomposition of biomass													
Pruned fronds, present generation	0.0	0.0	2.3	6.8	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1
Pruned fronds, previous generation	6.8	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Felled biomass from replanting	29.9	29.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	**36.7**	**32.2**	**2.3**	**6.8**	**9.1**	**9.1**	9.1	9.1	9.1	9.1	9.1	9.1	9.1
Output: Increase in standing biomass (uptake that stays in the field)													
Uptake in oil palms	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
Pruned fronds	0.0	0.0	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1
Total	**2.4**	**2.4**	**11.5**	**11.5**	**11.5**	**11.5**	**11.5**	**11.5**	**11.5**	**11.5**	**11.5**	**11.5**	**11.5**
Output: Harvested FFB (uptake that is brought out of the field)													
Harvested FFB	0.0	0.0	5.4	6.4	7.5	8.5	9.3	9.6	9.6	9.6	9.7	9.7	9.7
Total	**0.0**	**0.0**	**5.4**	**6.4**	**7.5**	**8.5**	**9.3**	**9.6**	**9.6**	**9.6**	**9.7**	**9.7**	**9.7**
Balance													
P surplus (input – output)	**52.5**	**47.1**	**19.3**	**22.8**	**24.0**	**23.0**	**22.2**	**21.9**	**21.9**	**21.9**	**21.8**	**21.8**	**21.8**
P leaching (2.9%)	**1.52**	**1.37**	**0.56**	**0.66**	**0.70**	**0.67**	**0.64**	**0.63**	**0.63**	**0.63**	**0.63**	**0.63**	**0.63**

	Year											
Inputs: Net inputs	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
P-fertiliser	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9	31.9
Planted palm seedlings	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EFB	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
POME	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Total	**33.9**	**33.9**	**33.9**	**33.9**	**33.9**	**33.9**	**33.9**	**33.9**	**33.9**	**33.9**	**33.9**	**33.9**
Inputs: Release from decomposition of biomass												
Pruned fronds, present generation	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1
Pruned fronds, previous generation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Felled biomass from replanting	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1
Output: Increase in standing biomass (uptake that stays in the field)												
Uptake in oil palms	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
Pruned fronds	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1
Total	**11.5**	**11.5**	**11.5**	**11.5**	**11.5**	**11.5**	**11.5**	**11.5**	**11.5**	**11.5**	**11.5**	**11.5**
Output: Harvested FFB (uptake that is brought out of the field)												
Harvested FFB	9.7	9.7	9.7	9.6	9.4	9.3	9.1	8.8	8.6	8.2	7.9	7.7
Total	**9.7**	**9.7**	**9.7**	**9.6**	**9.4**	**9.3**	**9.1**	**8.8**	**8.6**	**8.2**	**7.9**	**7.7**
Balance												
P surplus (input – output)	**21.8**	**21.8**	**21.8**	**21.9**	**22.0**	**22.2**	**22.4**	**22.7**	**22.9**	**23.3**	**23.6**	**23.8**
P leaching (2.9%)	**0.63**	**0.63**	**0.63**	**0.64**	**0.64**	**0.64**	**0.65**	**0.66**	**0.67**	**0.67**	**0.68**	**0.69**

Table 6.28: P-balance for 1 hectare oil palm plantation.

The average annual emission of phosphate during the 25 years oil palm life is 0.71 kg PO_4-P/ha. This is in good accordance with P losses in runoff reported in Corley and Tinker (2003, p 380) at 0.7-1.1 kg P/ha per year.

Since large amounts of P are accumulated in the soil, the emission may be larger in the case of erosion. Erosion depends on the slope of the field, terracing, rainfall, vegetation cover, residue management (mulching of pruned fronds and EFB) and oil palm age (Corley and Tinker 2003, p 236, 380). Thus, it is relatively difficult to determine soil loss from erosion. However, Corley and Tinker (2003, p 381) report P lost in eroded sediments as 0.5-1.3 kg P/ha per year (measures from a plantation within normal rates of erosion). The average value at 0.9 kg P/ha per year is applied in this study. Hence, the total annual emission of P is 1.61 kg P/ha.

No data on differences between soil types have been identified. Thus, there is no distinguishing between P-related emissions from mineral and peat soils.

Emissions related to C-balance

Mass balances for carbon are not as detailed as for nitrogen. This is because emission of carbon dioxide from biotic origin is not included. Only CO_2 from net changes of carbon in the soil and from land transformation are included. Carbon emissions that arise from transformation of alang-alang and tropical rain forest into oil palm plantations are described in section 19.1.

Henson (2004, p 15-17) summarises different surveys on changes in soil carbon under oil palm. In general there is lack of good data on soil carbon changes under oil palm in the long term (Henson 2004). Henson (2004) identifies studies that show increasing, no change and decreasing carbon in soil under oil palm. Thus, Henson (2004) concludes that the best assumption is to presume that there are no changes in soil carbon from continuous cultivation of oil palm. Hence, it is chosen to apply the assumption suggested by Henson (2004): soil carbon in mineral soils, i.e. not peat soils, does not change over time under oil palm.

Peat soils which contain almost 100% organic material are a special case. When peat soils are drained aeration is increased. The subsequent oxidation causes release of carbon dioxide (Henson 2004, p 28). Henson (2004) has calculated a mean annual emission from peat soils at 7.5 t C/ha. This mean value take into account that carbon emissions gradually decreases over time as subsidence is taking place. According to Henson (2004) carbon emissions as high as 12 to 18 t C/ha have been measured. Reijnders and Huijbregts (2006) report 10-15 t C/ha from oil palm cultivated on peat and IPCC (2003, p 3.79) specify 20 t C/ha per year for cultivation on tropical peat soils (average tillage and drainage). It is chosen to apply 10 t C/ha from oil palm on peat. 10 t C/ha corresponds to ~37 t CO_2/ha. The value at 10 t C/ha is significantly smaller than the value specified by IPCC. However, oil palm plantations have a very low level of tillage (once every 25 years). Therefore, a lower value than specified by IPCC is assumed. Applying a FFB yield at 18.87 t/ha and an oil extraction rate in the oil mill at 0.2 t oil/t FFB the 37 t CO_2/ha corresponds to ~10 t CO_2/t crude palm oil. This is a significant contribution to global warming compared to contributions from other stages and processes, e.g. methane from POME treatment in the palm oil mill contributes with only ~0.2 t CO_2-eq[14]/t crude palm oil (see **Table 10.10**) and CO_2 from burning of diesel in machinery in the oil palm plantation contributes with only ~40 kg CO_2/t crude palm oil[15]. Therefore, a sensitivity analysis applying other levels of carbon emission from peat soils is presented in section 21.14. Section 21.13 presents a sensitivity analysis that compares cultivation on peat with cultivation on mineral soils.

The area planted on peat soil in Malaysia in 2003/2004 accounted for 4.1% of the total planted area. The same figures are assumed to be valid for oil palm in Indonesia. Thus, the CO_2-emission from degradation under average oil palm in Indonesia and Malaysia can be calculated as 4.1% of 37 t CO_2, i.e. 1.5 t CO_2/ha.

Emissions of heavy metal

Fertilisers contain contaminants of heavy metals. The emission from the input of heavy metals is regarded as emissions to soil. The crude palm oil and kernels are brought out of the field, but no data on the contents of heavy metals have been identified. Therefore, the entire input is regarded as emissions to soil. The heavy metal content in the crude palm oil is sorted out in the refining process. Since a considerable share of the heavy met-

---

[14] GWP at 25 g CO_2-eq/g CH_4 has been applied.

[15] The diesel consumption and inventory data for burning diesel in machinery as described in section 6.3 and an oil extraction rate in the oil mill at 0.2 t oil/t FFB have been applied.

als will be in the sludge from waste water treatment, some of the heavy metals in the CPO will end as emissions to soil from landfilling of the sludge. The same is the case for palm kernel oil. The palm kernel cake which is used as animal fodder also ends as emissions to soil with the droppings from the animals. Therefore, the assumption that the entire input of heavy metals with fertiliser ends as emissions to soil is regarded as relatively certain.

The content of heavy metals in ammonia sulphate, urea and phosphate rock are shown in **Table 6.29** to **Table 6.31**. The heavy metal content in potassium chloride is shown in **Table 5.39**.

Heavy metals in N fertiliser, Ammonia Sulphate; mg/kg N	**Ammonium sulphate**	**AMMONIUM SULFATE 21-0-0**	**AMMONIUM SULFATE 21-0-0**	**Ammonia sulphate, applied in this study**
	(Nemecek, et al. 2003)	(WSDA 2006)	(WSDA 2006)	
Arsenic (As)	-	<0.3	<0.1	0.2
Cadmium (Cd)	0.2	<0.03	<0.2	0.1
Chromium (Cr)	10.0	-	-	10.0
Cobalt (Co)	-	<0.04	<1.1	0.6
Copper (Cu)	19.0	-	-	19.0
Mercury (Hg)	-	<0.01	<0.004	0.01
Molybdenum (Mo)	-	<0.1	<0.1	0.1
Nickel (Ni)	8.6	<0.1	<0.5	3.1
Lead (Pb)	5.2	<0.3	<1.1	2.2
Selenium (Se)	-	<0.3	<0.1	0.2
Zink (Zn)	143	<0.1	<1.1	48.1

Table 6.29: Heavy metal content (mg/kg N) in ammonia sulphate fertilisers from different sources. The applied data are the average of the three data sets; they are marked with a black dotted frame.

Heavy metals in N fertiliser, UREA; mg/kg N	**Urea**	**UREA 46%**	**UREA 46-0-0**	**Urea, applied in this study**
	(Nemecek, et al. 2003)	(WSDA 2006)	(WSDA 2006)	
Arsenic (As)	-	<0.2	<0.5	0.4
Cadmium (Cd)	0.1	<0.5	<0.5	0.4
Chromium (Cr)	4.4	-	-	4.4
Cobalt (Co)	-	<2.3	<0.5	1.4
Copper (Cu)	13.0	-	-	13.0
Mercury (Hg)	-	<0.01	<0.3	0.16
Molybdenum (Mo)	-	<2.3	<0.5	1.4
Nickel (Ni)	4.4	<1.4	<0.5	2.1
Lead (Pb)	2.4	<0.05	<0.5	1.0
Selenium (Se)	-	<0.2	<0.5	0.4
Zink (Zn)	95.7	<46.0	<0.5	47.4

Table 6.30: Heavy metal content (mg/kg N) in Urea fertilisers from different sources. The applied data are the average of the three data sets; they are marked with a black dotted frame.

Heavy metals in P fertiliser, Phosphate Rock; mg/kg P_2O_5	Rock Phosphate	Pelletized rock phosphate 0-3-0	Phosphate rock, applied in this study
	(Nemecek, et al. 2003)	(WSDA 2006)	
Arsenic (As)	-	<0.6	0.6
Cadmium (Cd)	50	2.6	26.3
Chromium (Cr)	612	-	612
Cobalt (Co)	-	0.09	0.09
Copper (Cu)	115	-	115
Mercury (Hg)	-	0.01	0.01
Molybdenum (Mo)	-	0.6	0.6
Nickel (Ni)	76.9	5.1	41.0
Lead (Pb)	23.8	0.3	12.1
Selenium (Se)	-	<1.5	1.5
Zink (Zn)	915	0.04	458

Table 6.31: Heavy metal content (mg/kg P_2O_5) in Urea fertilisers from different sources. The applied data are the average of the three data sets; they are marked with a black dotted frame.

Based on the fertiliser input shown in **Table 6.4** and the contents of heavy metals in fertilisers in **Table 6.29** to **Table 6.31** and **Table Table 5.39**, the emissions of heavy metals from fertiliser can be calculated. The distribution between ammonia sulphate and urea as N fertiliser is 73% to 27%. The results are shown in **Table 6.32**.

Heavy metal emissions	Emission, g/ha
Arsenic (As)	1.0
Cadmium (Cd)	1.9
Chromium (Cr)	44.4
Cobalt (Co)	0.2
Copper (Cu)	11.6
Mercury (Hg)	0.03
Molybdenum (Mo)	0.1
Nickel (Ni)	5.1
Lead (Pb)	2.0
Selenium (Se)	0.4
Zink (Zn)	68.7

Table 6.32: Heavy metal emissions from oil palm cultivation, g/ha.

Emissions of pesticides

The compartments that receive the applied active ingredients in the pesticides are assumed to be 33% soil, 33% water and 33% air. This is a very rough estimate which is tested in a sensitivity analysis in section 21.11.

6.8 Overhead in agricultural stage

No data on electricity use in administration, research, laboratory and nursery buildings related to oil palm cultivation have been identified. Therefore it is very roughly assumed that overhead for the agricultural stage is equal to the palm oil mill at 1 MJ/t FFB, see section 10.7. Applying a yield at 18.87 t FFB/ha, this corresponds to 0.053 MJ/ha per year. Buildings are not heated in Malaysia.

6.9 Capital goods in agricultural stage

Capital goods in the agricultural stage for rapeseed are described in section 5.8. It includes means of production, i.e. buildings and machinery. Only one inventory of agricultural buildings and machinery has been identified; ecoinvent (2004). This has been used for describing capital goods in rapeseed cultivation, see section 5.8. The data in ecoinvent (2004) covers capital goods in European agriculture. Since no other data have been identified, it is chosen to use these data for production, maintenance and disposal of the relevant capital goods for oil palm cultivation in Malaysia and Indonesia.

No data on the amounts of used buildings (shed and buildings for administration, research and laboratories/nursery) and machinery (tractors, agr. machinery-tillage and agr.machinery-general) have been identified. Thus, this is determined from modified figures of the capital goods used in rapeseed cultivation. It is assumed that the amount of tractors, agricultural machinery-general and shed are equivalent with the diesel consumption per hectare. The diesel consumption in rapeseed cultivation is 3,612 MJ/ha (see section 5.3) and the diesel consumption in oil palm cultivation is 2,118 MJ/ha (see **Table 6.3**). Thus, use of tractors, shed and agricultural machinery per ha oil palm plantation is 59% of the use per ha rapeseed field. Since the oil palm field is only cleared once every 25 years, the use of agricultural machinery-tillage is determined as 1/25 of the use in rapeseed cultivation. The use of buildings for administration, research and laboratories/nursery is assumed to be equal to the use of buildings for administration in the palm oil mill at 0.0262 m^3 '*Building, multi-storey*' per t FFB, see section 10.8. Applying a yield at 18.87 t FFB/ha, this corresponds to 0.0014 m^3/ha per year.

Capital goods	Use of capital goods, kg/ha per year Rapeseed (Table 5.44)	Oil palm
Tractor	7.5 kg	4.4 kg
Agricultural machinery, general	3.5 kg	2.1 kg
Agricultural machinery, tillage	9.2 kg	0.4 kg
Shed	0.070 m^2	0.041 m^2
Administration, research and laboratories/nursery buildings	0 m3	0.0014 m^3

Table 6.33: Use of capital goods in oil palm cultivation.

6.10 Transport of materials in agricultural stage

Raw materials are transported with lorry to the oil palm plantations. Inventory data per tkm transport by lorry are described in section 4.1. Since there are several suppliers and since there is a general lack of data on the specific marginal affected supplier, all transport distances are based on rough estimates. Determination of size of lorries is based on **Table 4.3** and very rough estimates on the total amount of goods transported.

Determination of the amount of transported fertiliser is shown in **Table 6.34**. The contents of nutrients in fertilisers are estimated from a commonly used fertilisers in oil palm cultivation in Corley and Tinker (2003, p 385) and a review of various fertilisers in WSDA (2006).

Fertiliser	Content of nutrient in fertiliser	Applied nutrients (see section 6.5)	Applied fertiliser product
Ammonium sulphate	21% N	76 kg N/ha	362 kg/ha
Urea	35% N	28 kg N/ha	80 kg/ha
Phosphate rock	30% P_2O_5 (13% P)	31 kg P/ha	238 kg/ha
Potassium chloride	14% K_2O (12% K)	170 kg K/ha	1,417 kg/ha
Magnesium	27% MgO	35 kg MgO/ha	130 kg/ha
Sulphur	23% S	16 kg S/ha	70 kg/ha
Boron	10% B	- kg B/ha	- kg/ha
Total			**2,297 kg/ha**

Table 6.34: Determination of amount of transported fertiliser product. The applied nutrients are obtained from **Table 6.4**.

The amount of pesticide products used is adopted as the average of 2 years immature and 23 years mature given in **Table 6.7**, i.e. 6.6 kg pesticide product/ha per year.

Table 6.35 shows the transported amounts, the route and the distances.

Material	Amount per ha	From	To	Distance	Means of transportation
Seed	insignificant	-	-	-	-
FFB	18,870 kg	Plantation	Palm oil mill	Transport is included in energy use in the plantation	
EFB	4,150 kg	Palm oil mill	Plantation		
Fertilisers	2,297 kg	Abroad chemical plant	Port in Malaysia/Indonesia	5000 km	Transoceanic tanker
Fertilisers	2,297 kg	Port in Malaysia/Indonesia	Oil palm plantation	500 km	40t lorry
Pesticides	6.6 kg	Abroad chemical plant	Port in Malaysia/Indonesia	5000 km	Transoceanic tanker
Pesticides	6.6 kg	Port in Malaysia/Indonesia	Oil palm plantation	500 km	40t lorry

Table 6.35: Transport of goods related to the agricultural stage. The return trip is included in the inventory data.

The estimated transport in **Table 6.35** is summarized per type of lorry in **Table 6.36**.

Means of transportation	Transport
40t lorry	1,152 tkm
Oceanic tanker	11,520 tkm

Table 6.36: Summary of transport in the agricultural stage.

6.11 LCI of oil palm agricultural stage, summary

Table 6.37 summarises the inventory data relating to 1 ha soil cultivated in 1 year with oil palm.

Malaysia and Indonesia: 1 ha y oil palm plantation		
Interventions	**Amount**	**Applied LCI data**
Product output		
FFB	18.87 t	Product of interest
Energy use		
Traction, burned diesel	2,118 MJ	See section 4.3
Electricity for overhead	0.053 MJ	See **Table 3.3**
Material use		
N-fertiliser, ammonium sulphate (as N)	76 kg	'*Ammonium sulphate, as N, at regional storehouse/RER*' (ecoinvent 2004)
N-fertiliser, urea (as N)	28 kg	'*Urea, as N, at regional storehouse/RER*', (ecoinvent 2004)
P-fertiliser (as P_2O_5)	70 kg	Phosphate rock, see section 6.5: Fertilisers
K-fertiliser (as K_2O)	204 kg	*Potassium chloride, as K_2O, at regional storehouse/RER'*, ecoinvent (2004)
Herbicide, typically glyphosate	2.4 kg	'Glyphosate, at regional storehouse/RER' (ecoinvent 2004)
Insecticide, typically cypermethrin	0.31 kg	'Pesticide unspecified, at regional storehouse/RER' (ecoinvent 2004)
Fungicides, various different	0.013 kg	'Pesticide unspecified, at regional storehouse/RER' (ecoinvent 2004)
Rodenticide, typically warfarin	0.00021 kg	'Pesticide unspecified, at regional storehouse/RER' (ecoinvent 2004)
Capital goods		
Agricultural buildings, shed	0.041 m^2	'*Shed/CH/I*' (ecoinvent 2004)
Agricultural buildings, administration etc.	0.00139 m^3	'*Building, multi-storey*' (ecoinvent 2004)
Machinery, tractor	4.4 kg	'*Tractor, production/CH/I*' (ecoinvent 2004)
Machinery, tillage	0.4 kg	'*Agricultural machinery, tillage, production/CH/I*' (ecoinvent 2004)
Machinery, general/miscellaneous	2.1 kg	'*Agricultural machinery, general, production/CH/I*' (ecoinvent 2004)
Transport		
40t lorry	1,152 tkm	'*Transport, lorry 40t*' (ecoinvent 2004)
Oceanic tanker	11,520 tkm	'*Transport, transoceanic tanker/OCE*' (ecoinvent 2004)

Emissions	**Air**	**Water**	**Soil**
Carbon dioxide (CO_2)	1,500 kg		
Ammonia (NH_3)	18.3 kg	-	-
Dinitrogen oxide (N_2O)	10.1 kg	-	-
Nitric oxide (NO)	3.2 kg	-	-
Nitrate (NO_3)	-	353 kg	-
Phosphorus (P)	-	1.6 kg	-
Glyphosate	0.80 kg	0.80 kg	0.80 kg
Cypermethrin	0.10 kg	0.10 kg	0.10 kg
Fungicides, various different	Not included, no characterisation data exist in LCIA methods		
Warfarin	Not included, no characterisation data exist in LCIA methods		
Arsenic (As)	-	-	1.0 g
Cadmium (Cd)	-	-	1.9 g
Chromium (Cr)	-	-	44 g
Cobalt (Co)	-	-	0.23 g
Copper (Cu)	-	-	12 g
Mercury (Hg)	-	-	0.026 g
Molybdenum (Mo)	-	-	0.11 g
Nickel (Ni)	-	-	5.1 g
Lead (Pb)	-	-	2.0 g
Selenium (Se)	-	-	0.42 g
Zink (Zn)	-	-	69 g

Table 6.37: Interventions per ha y oil palm plantation.

7 Agricultural stage: Soybean

The soybean plant (Glycine max.) is an annual leguminous plant which grows to a height of 120-180 cm, and the soybeans contain around 35% protein and 18% oil (Dalgaard et al. 2007).

This section provides data for a change in production of soybean in Brazil. Some of the inventory data for soybean are directly applied from Dalgaard et al. (2007) and other are modified in order to maintain consistency with the methodologies for inventorying rapeseed and oil palm cultivation. The modified data are the emissions related to the N-, P- and C-balances and the inventory data for traction and fertilisers. In addition to the modifications, the inventory presented here includes more processes than included in Dalgaard et al. (2007). These are; Production and emissions of pesticides, drying of soybeans, the use of and processing of soybean seed, capital goods and transport of materials in agricultural stage.

Reference for the data in Dalgaard et al. (2007) is one crop rotation on one hectare. Since 25% of the area is double-cropped, this is not the same as one hectare in one year. This study applies a reference for the inventory in the agricultural stage of one hectare in one year. Thus, the uses of energy and materials in Dalgaard et al. (2007) have to be multiplied with (0.25·2 + 0.75) = 1.25 in order to represent cultivation of one hectare in one year.

7.1 Product flow in agricultural stage

The inventory of the agricultural stage is divided into the unit processes shown as shaded boxes in **Figure 7.1**. The product flow is determined per hectare per year, see descriptions below the figure.

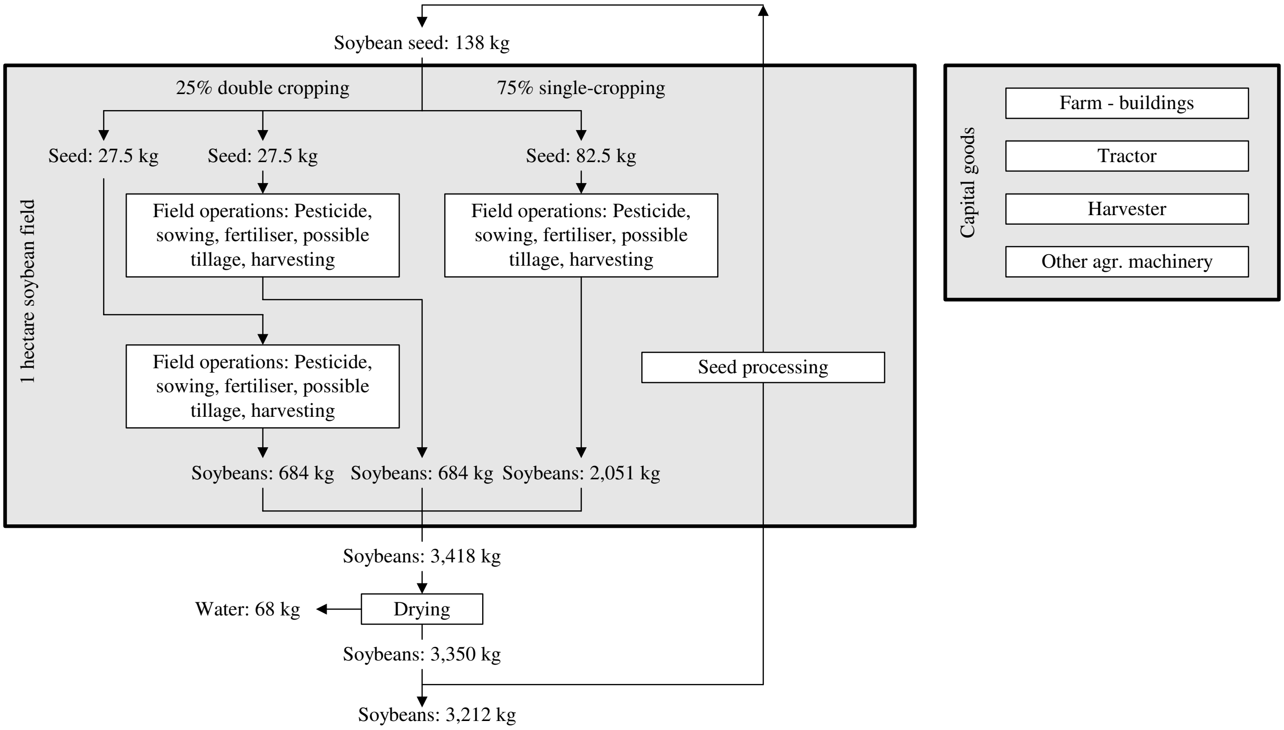


Figure 7.1: Product flow related to cultivation of 1 ha soybean field in 1 year. The grey shaded boxes represent the unit processes in the agricultural stage.

Yield: The soybean yield is applied as the yield in 2005 calculated from linear regression of yields from 1990 to 2005, see **Figure 7.2**. The same method as for determining the yield for rapeseed has been used, see section 5.1. Yields are obtained from FAOSTAT (2006). The expected yield in 2005 can be calculated as 2.68 t/ha t/ha using the equation in **Figure 7.2**. For comparison with yields determined using other methods see **Table 7.1**. However, the yield calculated from the formula in **Figure 7.2** has to be adjusted in order to take into account that 25% of the soybean cultivated area in Brazil is by double-cropping (see section 2.3). Thus, since 25% of the area has the double output, the adjusted yield is calculated by multiplying with (0.25·2 + 0.75) = 1.25. **Table 7.1** shows the adjusted as well as the non-adjusted yields.

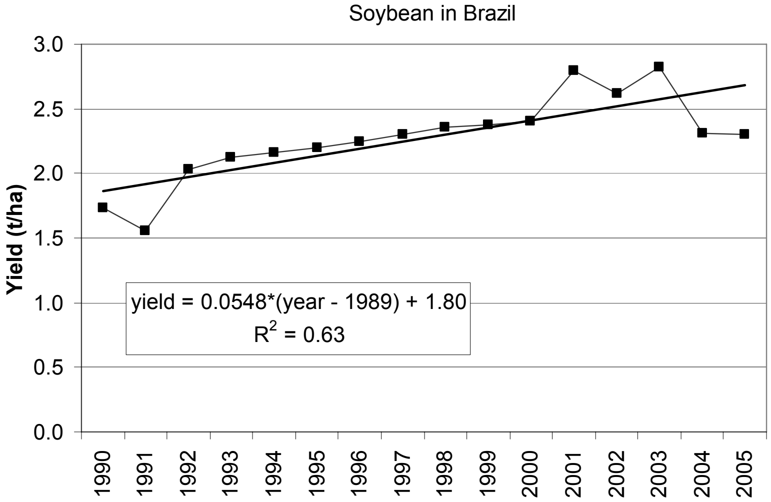


Figure 7.2: Soybean yields in Brazil 1990 to 2005. The linear regression line and its corresponding equation and R^2 are also shown. The yields are obtained from FAOSTAT (2006).

Region	Yield 2005 (based on regression 1990-2005)	Average yield 1990-2005	Average yield 2000-2005	Yield 2003	Yield 2004	Yield 2005
Brazil (not adjusted for double-cropping)	2.68 t/ha	2.27 t/ha	2.54 t/ha	2.82 t/ha	2.31 t/ha	2.30 t/ha
Brazil (adjusted for double-cropping)	3.35 t/ha	2.84 t/ha	3.18 t/ha	3.52 t/ha	2.89 t/ha	2.88 t/ha

Table 7.1: Soybean yield in Brazil determined using different methods. The applied yield is marked with a dotted line.

Seed input: According to Nemecek et al. (2003, p 125) the use of seed is 110 kg/ha. These data are for cultivation without double cropping. Thus, the use of seed when 25% of the area is double-cropped is 138 kg.

Water loos in drying: According to Nemecek et al. (2003, p 121) and Dalgaard et al. (2001) grains (unspecified grains) are typically dried 2 percent points. No specific data on drying of soybeans have been identified. Therefore, the two percent points are applied. Since the dried yield is 3,350 kg soybeans per ha, the water dried is 68 kg.

7.2 Omitted inventory data in agricultural stage

Magnesium (Mg), Sulphur (S) and Boron fertilisers and dust emissions and soil erosion have not been taken into account. These interventions are regarded as insignificant.

7.3 Energy use

Traction

According to Dalgaard et al. (2007) the energy use as burning of diesel in agricultural machinery is 42 litre/ha. Adjusting for double cropping this corresponds to 52.5 litre/ha. Applying calorific values as given in Appendix 1: Data on fuels, the energy use is 1,911 MJ/ha.

The inventory data for traction are described in section 4.3.

Drying of seed

According to **Figure 7.1**, 68 kg of water is dried out of the harvested soybeans per ha. The inventory data for drying of seed are described in section 5.3: 'Drying of seed'. However, the use of electricity in the inventory is adjusted to Brazilian marginal electricity, see **Table 3.3**.

7.4 Materials

Seed

The interventions related to the agricultural stage in production of seed are accounted for by subtracting an amount of seed from the yield. According to Nemecek et al. (2003, p 103) the yield of seed production is the same as for conventional cultivation of soybean.

No inventory data for production of soybean seed have been identified. However, in ecoinvent the data in an inventory of pea seed are used as representative for production of soybean seed. It is chosen to apply a modyfied version of these data in this study. The modifications corresponds to the modifications done for rapeseed production, see section 5.4: 'Seed'. The inventory of soybean seed production is shown in **Table 7.2**.

LCI-data for production of 1 kg seed	Amount	LCI data used in this study
Soybean from agriculture	1 kg	This is accounted for by subtracting 1 kg from the yield at 3.35 tonne/ha per kg seed used, see figure **Figure 7.1**.
Pesticide	0.0016 kg	'Pesticide unspecified, at regional storehouse/CH' (ecoinvent 2004)
Electricity	0.21 MJ	Electricity, see **Table 3.3**
Building for storage	$2.0 \cdot 10^{-5}$ m^3	Building, multi-storey/RER (ecoinvent 2004)
Transport from farm to warehouse	0.76 tkm	Transport, lorry 28t/CH (ecoinvent 2004)

Table 7.2: Inventory data for production of 1 kg soybean seed (ecoinvent 2004).

Fertiliser

No N and K fertiliser are applied in soybean cultivation (Dalgaard et al. 2007). The amount of applied P fertiliser in Dalgaard et al. (2007) is 16 kg P per hectare. Adjusting for double-cropping and transforming to P as P_2O_5 this corresponds to 46 kg P_2O_5/ha.

According to IFA (2007), the most widely used P-fertiliser in Latin America is phosphate rock. Therefore, it is assumed that this represents the marginal source of P-fertiliser in Brazil. Inventory data for phosphate rock are described in section 6.5: Fertilisers.

Pesticides

The use of pesticides in soybean cultivation is given in Dalgaard et al. (2007). However, Dalgaard et al. (2007) do not include pesticides as interventions in the LCIA and consequentially no inventory data are applied for the production of pesticides. According to Dalgaard et al. (2007) the following pesticides are used: glyphosate (herbicide), 2-4 D (herbicide), imazethapyr (herbicide), cypermethrin (insecticide), chlorpyrifos (insecticide). However, for 2-4 D and imazethapyr the application of active ingredients (a.i.) is not specified. Therefore, because of lack of data, the use and consequential emission of these pesticides has been omitted from the study. Inventory data have only been identified for glyphosate and cypermethrin (as pyretroid-compounds). These data are from the ecoinvent database (ecoinvent 2004). Inventory data for the remaining pesticides are applied as 'Pesticide unspecified', also obtained from the ecoinvent database. The use of pesticides per hectare is given in **Table 7.3**. In **Table 7.3** the data obtained from Dalgaard et al. (2007) are adjusted for double-cropping

	Dalgaard et al (2007)		**Applied in this study**	
Pesticide	**kg/ha**	**kg a.i./ha**	**kg/ha**	**kg a.i./ha**
Herbicide, glyphosate	5	1.8	6.3	2.3
Herbicide, 2-4 D	0.35	no data	0.44	no data
Herbicide, imazethapyr	1	no data	1.3	no data
Insecticide, pyrethroid, cypermethrin	0.1	0.01	0.13	0.013
Insecticide, Chlorpyrifos	0.8	0.16	1.0	0.20
Total	**7.3**	**2.0**	**9.1**	**2.5**

Table 7.3: Use of pesticides per hectare per year. The amount and type of pesticides used are based on figures from Dalgaard et al. (2007) and Dalgaard (2007).

7.5 Emissions

N- and P balances are established for soybean cultivation. The relevant data in this respect are given in **Table 7.4**.

Parameter	**Amount**	**Reference**
Annual soybean yield	3,350 kg/ha	See **Table 7.1**
Seed input	138 kg/ha	Nemecek et al (2003, p 125)
Soybean dry matter	87%	Møller et al. (2000, p 17)
Soybean straw solid matter	87%	Møller et al. (2000, p 43). Assumed to be the same as pea straw
Straw removed from field	0%	Nemecek et al (2003, p 125)
Residue to crop ratio	2.1	IPCC (2000, p 4.58)
Soybean N-content	0.065 kg N/kg DS	Møller et al. (2000, p 17), N content is protein content divided by 6.25
Residue N-content	0.012 kg N/kg DS	Møller et al. (2000, p 43). Assumed to be the same as pea straw, N content is protein content divided by 6.25
Soybean P-content	0.063 kg P/kg DS	Møller et al. (2000, p 17)
Residue P-content	0.002 kg P/kg DS	Møller et al. (2000, p 43). Assumed to be the same as pea straw
Atmospheric N-deposition	8.0 kg/ha y	Trebs et al. (2004)
N-fixing	165 kg N/ha y	Dalgaard et al. (2007) specifies 132 kg N/ha per crop rotation. Adjusting for 25% double-croppping, N-fixing is 165 kg N/ha per year.

Table 7.4: Relevant data in order to establish field balances of N and P for soybean cultivation.

The N- and P-balances are shown in **Table 7.5**.

Inputs	**N**	**P**
Deposition	8.0 kg N/ha	0 kg P/ha
Seed	9.0 kg N/ha	0.76 kg P/ha
Fertiliser	0 kg N/ha	20.0 kg P/ha
N-fixing	165 kg N/ha	-
Changes in soil matter	0 kg N/ha	-
Total	**182.0 kg N/ha**	**20.8 kg P/ha**
Outputs		
Harvested soybeans	189.4 kg N/ha	18.4 kg P/ha
Removed straw	0 kg N/ha	0 kg P/ha
Total	**189.4 kg N/ha**	**18.4 kg P/ha**
Balance		
surplus (input – output)	**-7.5 kg N/ha**	**2.4 kg P/ha**

Table 7.5: Annual N- and P-balances for 1 hectare soybean field.

It appears that there is a negative N-surplus from soybean cultivation. This means that more N is removed with the harvested soybeans than the input of N from deposition, N-fixing and soybean seed. A negative N-surplus is consistent with Dalgaard et al. (2007) and Austin et al. (2006).

Emissions related to the N-balance

Since there is a negative N-surplus in the N-balance, it is assumed that there are no emissions of NH_3 from crop and no nitrate leaching. This is in accordance with Dalgaard et al. (2007). Since there is no surplus of N, it is not necessary to calculate the total denitrification. Neither indirect emissions of N_2O from NH_3 and nitrate are relevant since there are no emissions of NH_3 and nitrate. In the following the direct emissions of N_2O and NO are determined.

Direct N_2O: The direct N_2O emission is calculated using a model described in IPCC (2000). The calculated emissions are then compared with the results using another model described in FAO and IFA (2001). The results obtained from FAO and IFA (2001) are not applied in this study because the model does not include peat soils which is relevant for palm oil – thus, it would not be consistent to apply calculated emissions from different emissions for the desired crops.

IPCC (2000): According to IPCC (2000, p 4.54) the direct N_2O emission is calculated as shown in **Equation (3)** in section 5.6. The parameter values used in **Equation (3)** are described in **Table 7.6**.

Parameter	Description	Parameter value
F_{SN}	Annual amount of synthetic fertiliser nitrogen applied to soils adjusted to account for the amount that volatilises as NH3 and NOx	No N-fertiliser application
F_{AM}	Annual amount of animal manure nitrogen intentionally applied to soils adjusted to account for the amount that volatilises as NH3 and NOx	No manure
F_{BN}	Amount of nitrogen fixed by N-fixing crops cultivated annually	151 kg N/ha, see **Table 7.5**
F_{CR}	Amount of nitrogen in crop residues returned to soils annually	67.1 kg N/ha, calculated using the informations in in **Table 7.5**
F_{OS}	Area of organic soils cultivated annually (ha)	0% The total area of peat soil in Brazil is 15,000 km^2 (Andriesse 1988). Comparing with the total area of Brazil at 8.46 mio km^2, this corresponds to 0.2% of Brazil which is regarded as insignificant.
EF_1	Emission factor for emissions from N inputs (kg N2O-N/kg N input)	1.25% (IPCC 2000, p 4.60)
EF_2	Emission factor for emissions from organic soil cultivation (kg N2O-N/ha-yr)	16 (IPCC 2000, p 4.60)

Table 7.6: Parameters in the equation calculating direct N2O-emissions in IPCC (2000, p 4.54)

FAO and IFA (2001): According to FAO and IFA (2001, p 34) the direct N_2O emission is calculated as shown in **Equation (4)** in section 5.6. The parameter values used in **Equation (4)** are described in **Table 7.7**.

Parameter	Description	Parameter value
F	Type of fertiliser	Not relevant, no N-fertiliser application
N-app.	Applied N, kg/ha	No N-fertiliser application
Cr	Crop type	-0.023, Crop type is ‘legume’
S	Soil texture	-0.008, -0.472 and 0.000,The N2O emission is calculated as the average of coarse, medium and fine soil
C	Soil organic C content	0.140, 1-3% C in mineral soil. Assumed to be the same as in Malaysia, see **Table 6.22**
D	Soil drainage	-0.420, good drainage. It is assumed that good drainage is needed in order to have suitable conditions for cultivating soybeans
pH	Soil pH	0.000, Soil pH <5.5, Assumed to be the same as in Malaysia, see **Table 6.22**
Cl	Climate	0.824, Tropical climate
LM	Length of measurement period (the model is constructed to fit with literature measurements. Thus, to model emissions obtained from literature the method of measurement in literature should also be considered since this affects the measured emission)	0.825 Length of measurement period is >300 days, i.e. the longest period available in the model (chosen as the most precise)
FM	Frequency of measurement (see comment above)	0.000 Frequency of measurement is >1measure/day, i.e. the highest frequency available in the model (chosen as the most precise)

Table 7.7: Parameters in the equation calculating direct N_2O-emissions in FAO and IFA (2001, p 34-35)

The calculated N_2O emissions using the two models are summarised in **Table 7.8**.

IPCC (2000)	FAO and IFA (2001)
3.0 kg N2O-N	2.5 kg N2O-N

Table 7.8: Calculated N_2O emissions (kg N_2O-N/ha) for soybean cultivation in Brazil using the two models. The applied N_2O-emission is marked with a dotted line.

It appears from **Table 7.8** that the deviation between the two models is relatively small, only ~17%.

Direct NO: The emission of NO is calculated using a model described in FAO and IFA (2001). According to FAO and IFA (2001, p 35) the direct NO emission is calculated shown in **Equation (5)** in section 5.6. The parameter values used in **Equation (5)** are described in **Table 7.9**.

Parameter	Description	Parameter value
F	Type of fertiliser	Not relevant, no N-fertiliser application
N-app.	Applied N, kg/ha	No N-fertiliser application
C	Soil organic C content	0.000, <3% C, see **Table 7.7**
D	Soil drainage	0.946, good drainage, see **Table 7.7**

Table 7.9: Parameters in the equation calculating direct NO-emissions in FAO and IFA (2001, p 35)

The calculated NO emission is 0.6 kg NO-N/ha.

In summary, the annual N-related emissions from soybean cultivation are 4.7 kg N_2O/ha and 1.2 kg NO/ha.

Emissions related to the P-balance

As described in the case of emissions from rapeseed cultivation (see section 5.6) accumulation of phosphorus in the soil is relatively constant due to strong binding to the soil. Therefore, the emission of P is calculated as a fraction of the field surplus. According to section 5.6: 'Emissions related to P-balance', 2.9% of the P surplus is emitted to water as leaching of phosphate. The remaining is accumulated in the soil matter. Thus the emission of P is 2.9% of the surplus at 2.4 kg P/ha given in **Table 7.5**, i.e. 0.07 kg P/ha.

Emissions related to the C-balance

As in the case for rapeseed cultivation (section 5.6) and oil palm cultivation (section 6.7) it is assumed that continuous cultivation of soybean does not affect the soil content of carbon.

Carbon emissions that arise from transformation of the Cerrado and Amazon forest into soybean fields are described in section 19.

Emissions of heavy metal

The emissions of heavy metals from input of fertiliser are calculated using the same method as for rapeseed cultivation, see section 5.6: 'Emissions of heavy metal'. Hence, it is assumed that the heavy metal input from P-fertiliser is distributed on emissions to soil and emissions to water. The emission of heavy metals to soil is calculated as the total input with fertiliser and seeds minus the share that ends in water. This means that heavy metals in leaching and runoff have been assumed to be zero, i.e. inputs of heavy metals to the field minus harvested heavy metals ends as emissions to soil. It is assumed that one eighth, i.e. 12.5%, of the heavy metals harvested with crop ends as emission to water and the other 87.5% ends as emission to soil.

The content of heavy metals in phosphate rock is shown in **Table 6.31** and the content in soybeans is shown in **Table 7.10**.

Heavy metals in harvested crop; mg/kg crop	Soybeans		Applied in this study
	(Nemecek, et al. 2003, p 154)	(Møller et al. 2000, p 17)	
Arsenic (As)	-	-	-
Cadmium (Cd)	0.052	-	0.052
Chromium (Cr)	0.45	-	0.45
Cobalt (Co)	-	0.070	0.070
Copper (Cu)	13.1	13.9	13.5
Mercury (Hg)	0	-	0
Molybdenum (Mo)	-	-	-
Nickel (Ni)	4.63	-	4.63
Lead (Pb)	0.070	-	0.070
Selenium (Se)	-	0.087	0.087
Zink (Zn)	41.5	39.2	40.4

Table 7.10: Heavy metal content (mg/kg crop) in harvested soybeans. The applied data are marked with a dotted frame.

Based on the fertiliser input at 46 kg P_2O_5, the content of heavy metals in P-fertiliser in **Table 6.31**, and the content of heavy metals in harvested crop in **Table 7.10**, the emissions of heavy metals from fertiliser can be calculated. The results are shown in **Table 7.11**.

Heavy metal emissions	Soil (g/ha	Water (g/ha)
Arsenic (As)	-	-
Cadmium (Cd)	1.2	0.0
Chromium (Cr)	27.9	0.2
Cobalt (Co)	0.0	0.0
Copper (Cu)	1.5	5.7
Mercury (Hg)	0.0	0.0
Molybdenum (Mo)	-	-
Nickel (Ni)	0.6	1.9
Lead (Pb)	0.5	0.0
Selenium (Se)	0.0	0.0
Zink (Zn)	9.6	16.9

Table 7.11: Heavy metal emissions to soil and water from soybean cultivation, g/ha.

Emissions of pesticides

The compartments that receive the applied active ingredients in the pesticides are assumed to be 33% soil, 33% water and 33% air. This is a very rough estimate which is tested in a sensitivity analysis in section 21.11.

7.6 Overhead in agricultural stage

The amount of electricity used in administration buildings etc. is assumed to be insignificant.

7.7 Capital goods in agricultural stage

Corresponding to capital goods in oil palm cultivation, see section 6.9, the use of capital goods is determined from modified figures of the capital goods used in rapeseed cultivation. It is assumed that the amount of harvesters, tractors, agricultural machinery-tillage, agricultural machinery-general and shed are equivalent with the diesel consumption per hectare. The diesel consumption in rapeseed cultivation is 3,612 MJ/ha (see section 5.3) and the diesel consumption in soybean cultivation is 1,911 MJ/ha (see section 7.2). Thus, use of capital goods per ha soybean field is 53% of the use per ha rapeseed field. The use of buildings for administration, research and laboratories is assumed to be zero corresponding to rapeseed cultivation.

Capital goods	Use of capital goods per ha per year	
	Rapeseed (Table 5.44)	Soybean
Tractor	7.5 kg	4.0 kg
Harvester	6.3 kg	3.3 kg
Agricultural machinery, tillage	9.2 kg	4.8 kg
Agricultural machinery, general	3.5 kg	1.9 kg
Shed	0.070 m^2	0.037 m^2
Administration, research and laboratories buildings	0 m^3	0 m^3

Table 7.12: Use of capital goods in soybean cultivation.

7.8 Transport of materials in agricultural stage

Raw materials are transported with lorry to the soybean farms. Inventory data per tkm transport by lorry are described in section 4.1. Since there are several suppliers and since there is a general lack of data on the specific marginal affected supplier, all transport distances are based on rough estimates. Determination of size of lorries is based on **Table 4.3** and very rough estimates on the total amount of goods transported.

The amounts of used seed, fertiliser and pesticides are described in section 7.1 and 7.4. The contents of P_2O_5 in rock phosphate is 30% (see **Table 6.34**) and the use of P_2O_5 is 46 kg/ha. Thus the use of P-fertiliser solution is 153 kg/ha.

Table 7.13 shows the transported amounts, the route and the distances.

Material	Amount per ha	From	To	Distance	Means of transportation
Seed	138 kg	Seed trader	Soybean farm	100 km	40t lorry
Soybean	3,212 kg	Soybean farm	Soybean trader	500 km	40t lorry
Fertilisers	153 kg	Abroad chemical plant	Port in Brazil	5000 km	Transoceanic tanker
Fertilisers	153 kg	Port in Brazil	Soybean farm	500 km	40t lorry
Pesticides	9.1 kg	Abroad chemical plant	Port in Brazil	5000 km	Transoceanic tanker
Pesticides	9.1 kg	Port in Brazil	Soybean farm	500 km	40t lorry

Table 7.13: Transport of goods related to the agricultural stage. The return trip is included in the inventory data.

The estimated transport in **Table 7.13** is summarized per type of lorry in **Table 7.14**.

Means of transportation	Transport
40t lorry	1,701 tkm
Oceanic tanker	811 tkm

Table 7.14: Summary of transport in the agricultural stage.

7.9 LCI of soybean agricultural stage, summary

Table 7.16 summarises the inventory data relating to 1 ha soybean field in 1 year. Since the LCI in this study are highly based on the LCI of soybean described in Dalgaard et al. (2007), the applied data are compared with these data in **Table 7.15**.

	Dalgaard et al (2007)		**This study**
Interventions	**Per crop rotation**	**Ajusted to annual values (multiplied with 1.25)**	**Per year**
Product output			
Yield	2.63 t/ha	3.29 t/ha	3.212 kg/ha
Energy use			
Traction, burned diesel	42 litre ~ 1,529 MJ	52.5 litre ~ 1,911 MJ	1,911 MJ
Drying of soybenas (evaporated water)	Not included	Not included	68 kg
Materials			
Seed	Not included	Not included	138 kg
N-fertiliser (as N)	0 kg	0 kg	0 kg
P-fertiliser (as P_2O_5)	37 kg	46 kg	46 kg
K-fertiliser (as K_2O)	0 kg	0 kg	0 kg
Pesticides	Not included	Not included	Included
Capital goods			
Agr. machines, buildings	Not included	Not included	Included
Transport			
Lorry and ship	Not included	Not included	Included
Emissions			
Ammonia (NH3), to air	0 kg/ha	0 kg/ha	0 kg/ha
Dinitrogen oxide (N2O), to air	4.7 kg/ha	5.9 kg/ha	4.7 kg/ha
Nitric oxide (NO), to air	Not included	Not included	1.2 kg/ha
Nitrate (NO3), to water	0 kg/ha	0 kg/ha	0 kg/ha
Phosphorus (P), to water	0 kg/ha	0 kg/ha	0069 kg/ha
Pesticides, to air, water and soil	Not included	Not included	Included
Heavy metals, to air, water and soil	Not included	Not included	Included

Table 7.15: Comparison of LCI data in Dalgaard et al. (2007) and this study

Brazil: 1 ha y soybean field		
Interventions	**Amount**	**Applied LCI data**
Product output		
Soybean	3.212 t	Product of interest
Energy use		
Traction, burned diesel	1,911 MJ	See **Table 4.5**
Drying of soybeans (evaporated water)	68 kg	Modified version of: ‘*Grain drying, low temperature/CH*’ (ecoinvent 2004), see section 5.3
Material use		
Seed	138 kg	See **Table 7.2**
P-fertiliser (as P_2O_5)	46 kg	Phosphate rock, see section 6.5: Fertilisers
Herbicide, glyphosate	2.3 kg	‘Glyphosate, at regional storehouse/RER’ (ecoinvent 2004)
Herbicide, 2-4 D	-	-
Herbicide, imazethapyr	-	-
Insecticide, pyrethroid, cypermethrin	0.013 kg	‘Pyretroid-compounds, at regional storehouse/RER’ (ecoinvent 2004)
Insecticide, Chlorpyrifos	0.20 kg	‘Pesticide unspecified, at regional storehouse/RER’ (ecoinvent 2004)
Capital goods		
Agricultural buildings	0.037 m^2	‘*Shed/CH/I*’ (ecoinvent 2004)
Machinery, tractor	4.0 kg	‘*Tractor, production/CH/I*’ (ecoinvent 2004)
Machinery, combine harvester	3.3 kg	‘*Harvester, production/CH/I*’ (ecoinvent 2004)
Machinery, tillage	4.8 kg	‘*Agricultural machinery, tillage, production/CH/I*’ (ecoinvent 2004)
Machinery, general/miscellaneous	1.9 kg	‘*Agricultural machinery, general, production/CH/I*’ (ecoinvent 2004)
Transport		
40t lorry	1,701 tkm	‘*Transport, lorry 40t*’ (ecoinvent 2004)
Oceanic tanker	811 tkm	‘*Transport, transoceanic tanker/OCE*’ (ecoinvent 2004)

Emissions	**Air**	**Water**	**Soil**
Ammonia (NH3)	0 kg	-	-
Dinitrogen oxide (N2O)	4.7 kg	-	-
Nitric oxide (NO)	1.2 kg	-	-
Nitrate (NO3)	-	0 kg	-
Phosphorus (P)	-	0.069 kg	-
Glyphosate	0.77 kg	0.77 kg	0.77 kg
2-4 D	No LCI data on a.i.		
Imazethapyr	No LCI data on a.i., and no characterisation data exist in LCIA methods		
Cypermethrin	0.0043 kg	0.0043 kg	0.0043 kg
Chlorpyrifos	0.067 kg	0.067 kg	0.067 kg
Arsenic (As)	-	-	-
Cadmium (Cd)	-	0.022 g	1.2 g
Chromium (Cr)	-	0.19 g	28 g
Cobalt (Co)	-	0.029 g	-0.016 g
Copper (Cu)	-	5.7 g	1.5 g
Mercury (Hg)	-	0 g	0.00046 g
Molybdenum (Mo)	-	-	-
Nickel (Ni)	-	1.9 g	0.58 g
Lead (Pb)	-	0.029 g	0.53 g
Selenium (Se)	-	0.036 g	0.044 g
Zink (Zn)	-	17 g	9.6 g

Table 7.16: Interventions per ha y soybean field.

8 Agricultural stage: Barley

The barley plant (Hordeum vulgare) is an annual crop which grows to a height of 70-100 cm (Dansk Landbrugsrådgivning 2007).

This section provides data for a change in production of Barley in Denmark and Canada. Some of the inventory data for barley are directly applied from Nielsen et al. (2005) and other are modified in order to maintain consistency with the methodologies for inventorying rapeseed, oil palm and soybean cultivation. The modified data are the same as for soybean cultivation, i.e. the emissions related to the N-, P- and C-balances and the inventory data for traction and fertilisers. In addition to the modifications, the inventory in this study includes more processes. These are; Production and emissions of pesticides, drying of barley, the use of and processing of barley seed, capital goods and transport of materials in agricultural stage.

8.1 Product flow in agricultural stage

The inventory of the agricultural stage is divided into the unit processes shown as shaded boxes in **Figure 8.1** and **Figure 8.2**. The product flows are determined per hectare per year, see descriptions below the figure.

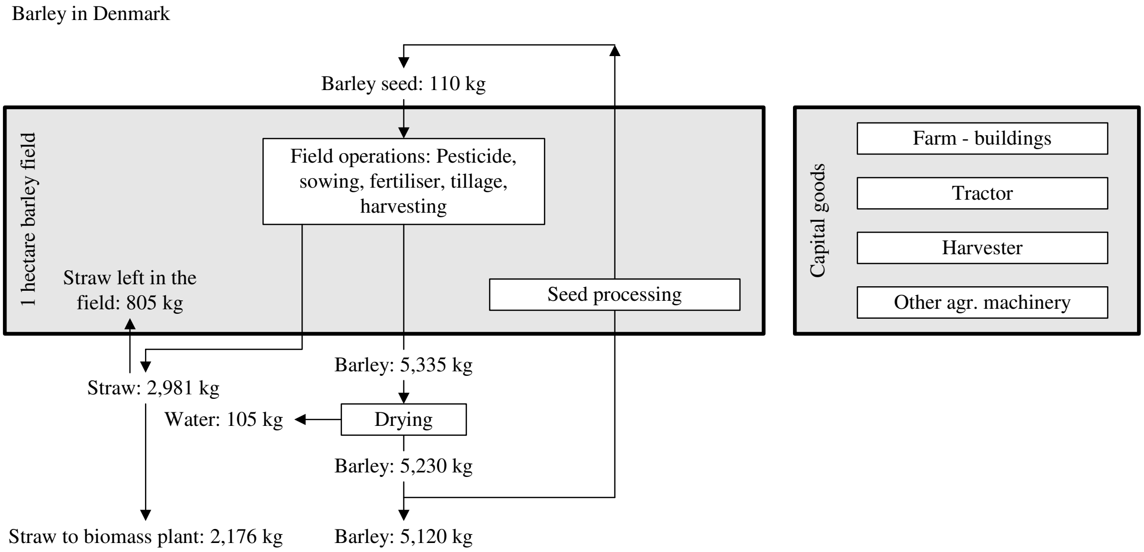


Figure 8.1: Product flow related to cultivation of 1 ha spring barley field in 1 year in Denmark. The grey shaded boxes represent the unit processes in the agricultural stage.

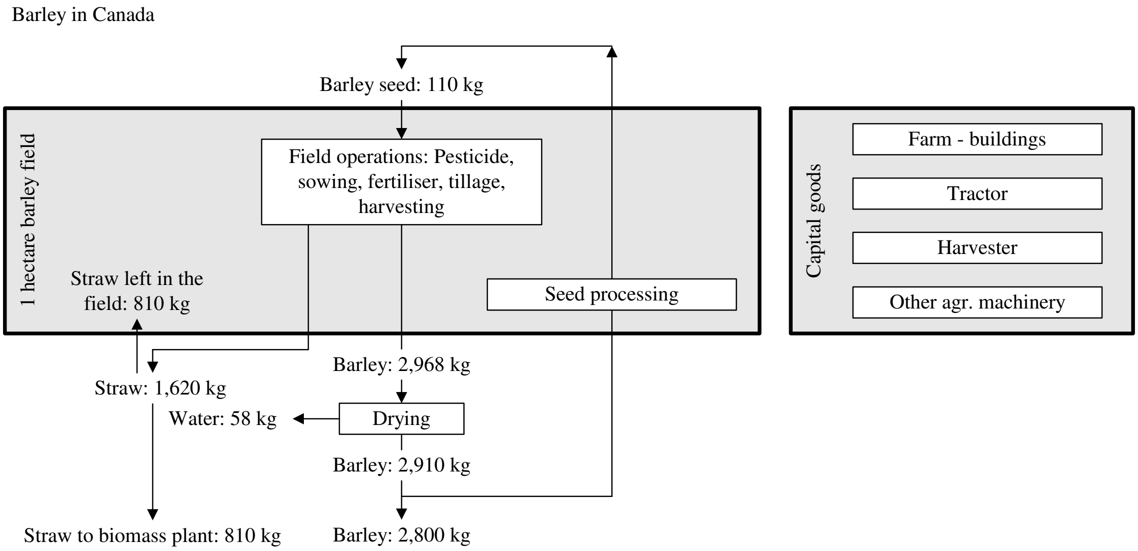


Figure 8.2: Product flow related to cultivation of 1 ha barley field in 1 year in Canada. The grey shaded boxes represent the unit processes in the agricultural stage.

Yields: The barley yields are applied as the yields in 2005 calculated from linear regression of yields from 1990 to 2005, see **Figure 8.3** and **Figure 8.4**. The same method as for determining the yield for rapeseed has been used, see section 5.1. Yields are obtained from Danmarks statistik for Denmark FAOSTAT (2006) for Canada. The expected yields in 2005 can be calculated as 5.23 t/ha and 2.91 t/ha for DEnmark and Canada respectively using the equations in **Figure 8.3** and **Figure 8.4**. For comparison with yields determined using other methods see **Table 8.1**.

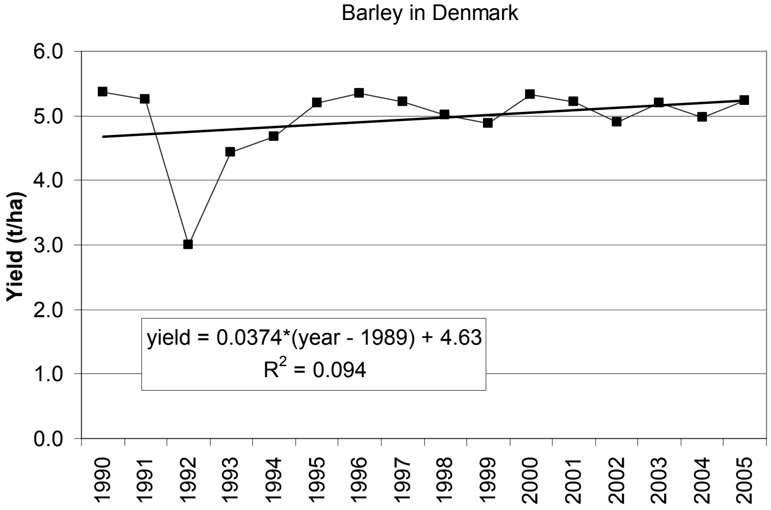


Figure 8.3: Spring barley yields in Denmark 1990 to 2005. The linear regression line and its corresponding equation and R^2 are also shown. The yields are obtained from Danmarks Statistik (2006).

Since changed production of rapeseed in Denmark in some scenarios will affect the area cultivated with spring barley, it is also necessary to know the emissions from spring barley cultivation on different soil types. Based on specified expected yields of spring barley on sand and clay soils given in Dansk Landbrugsrådgivning (2006) and the average yield at 5.23 t/ha, the yields on sand and clay have been determined as 4.23 t/ha on sand and 5.94 t/ha on clay. Due to lack of data and models to fit Canadian environments, it has not been possible to distinguish between soil types in Canada.

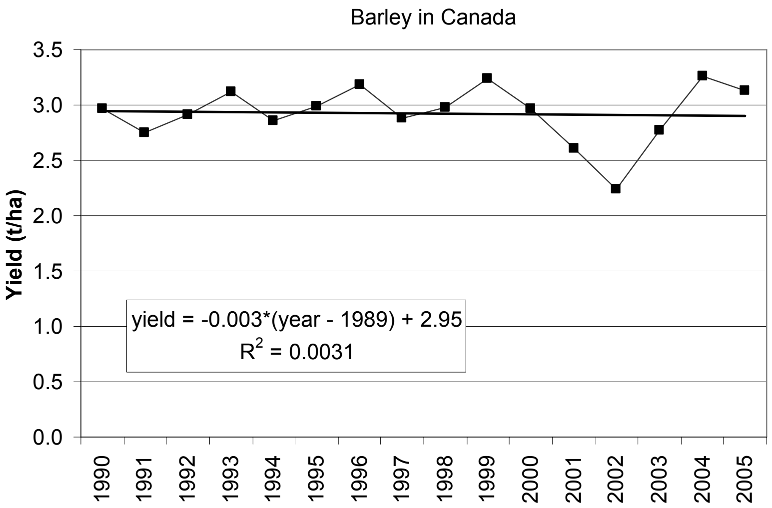


Figure 8.4: Barley yields in Canada 1990 to 2005. The linear regression line and its corresponding equation and R^2 are also shown. The yields are obtained from FAOSTAT (2006).

Region	Yield 2005 (based on regression 1990-2005)	Average yield 1990-2005	Average yield 2000-2005	Yield 2003	Yield 2004	Yield 2005
Denmark	5.23	4.95	5.14	5.19	4.97	5.23
Canada	2.91	2.93	2.83	2.77	3.26	3.13

Table 8.1: Barley yields in Denmark and Canada determined using different methods. The applied yields are marked with dotted lines.

Based on predicted yields on different soils given in Plantedirektoratet (2005a) and adjustments in accordance to the method used for rapeseed yields on sandy and clay soils in **Table 5.3**, the yeilds of spring barley on sandy and clay soils can be calculated as 4.29 t/ha and 6.02 t/ha respectively.

Seed input: According to Nemecek et al. (2003, p 125) the use of barley seed is 110 kg/ha.

Water loos in drying: According to Nemecek et al. (2003, p 121) and Dalgaard et al. (2001) grains (unspecified grains) are typically dried 2 percent points. No specific data on drying of barley have been identified. Therefore, the two percent points are applied. Since the dried yields in Denmark and Canada are 5,230 kg/ha and 2,910 kg/ha respectively, the water dried is 105 kg/ha in Denmark and 58 kg/ha for barley in Canada.

Straw: According to **Table 8.6** the straw to crop ratio is 0.57, and the removed straw from the field is 73% in Denmark and 50% in Canada.

8.2 Omitted inventory data in agricultural stage

The use of and emissions of pesticides have been omitted because of lack of data.

Magnesium (Mg), Sulphur (S) and Boron fertilisers and dust emissions and soil erosion have not been taken into account. These interventions are regarded as insignificant.

8.3 Energy use

Traction

It is assumed that there is no difference btween the energy use for traction in Denmark and Canada. According to Nielsen et al. (2005) the energy use as burning of diesel in agricultural machinery is 4,029 MJ/ha.

Based on the percentual differences for traction in rapeseed cultivation on sand, clay and average soils in section 5.3: 'Diesel consumption related to cultivation of rapeseed', the energy for traction on sand and clay for spring barley cultivation can be calculated as 3,758 MJ/ha for sand and 4,217 MJ/ha for clay.

The inventory data for traction are described in section 4.3.

Drying of seed

According to **Figure 8.1** and **Figure 8.2**, 105 kg and 58 kg of water is dried out of the harvested barley per ha in Denmark and Canada respectively. The inventory data for drying of seed are described in section 5.3: 'Drying of seed'. However, the use of electricity in the inventory is adjusted to Danish and Canadian marginal electricity, see **Table 3.3**.

8.4 Materials

Seed

The interventions related to the agricultural stage in production of seed are accounted for by subtracting an amount of seed from the yield. According to Nemecek et al. (2003, p 102) the yield of seed production is the same as for conventional cultivation of cereals.

Only one life cycle inventory of seed has been identified; '*Barley seed IP, at regional storehouse/CH*' (ecoinvent 2004). This inventory is shown in **Table 8.2** below. The inventory has been modified applying interventions for electricity as shown in **Table 3.3** instead of average Swiss electricity as in ecoinvent.

LCI-data for production of 1 kg seed	Amount	LCI data used in this study
Barley from agriculture	1 kg	This is accounted for by subtracting 1 kg from the product outputs per kg seed used, see **Figure 8.1** and **Figure 8.2**
Electricity	0.086 MJ	Electricity, see **Table 3.3**
Pesticide	0.088 g	'Cyclic N-compounds, at regional storehouse/CH' (ecoinvent 2004)
Building for storage	$2.0 \cdot 10^{-5}$ m^3	Building, multi-storey/RER (ecoinvent 2004)
Transport from farm to warehouse	0.13 tkm	Transport, lorry 28t/CH (ecoinvent 2004)

Table 8.2: Inventory data for production of 1 kg seed for barley cultivation (ecoinvent 2004).

Fertiliser

Fertiliser applications of N, P and K in Danish cultivation of spring barley are obtained from Plantedirektoratet (2005a) and Dansk Landbrugsrådgivning (2006), and fertiliser application in Canada is obtained from IFA et al. (2002). This is shown in **Table 8.3**.

Fertiliser	Spring barley in Denmark	Barley in Canada
N	121 kg N/ha	67 kg N/ha
P_2O_5	46 kg P_2O_5/ha	26 kg P_2O_5/ha
K_2O	66 kg K_2O/ha	10 kg K_2O/ha

Table 8.3: RFertiliser application on average soils in Denmark and Canada for barley cultivation.

Since changed production of rapeseed in Denmark in some scenarios will affect the area cultivated with spring barley, it is also necessary to know the emissions from spring barley cultivation on different soil types. The soil types in Denmark are described in section 5.4: ‘Fertilisers’. The fertiliser application on different soils in Danish spring barley cultivation is shown in **Table 8.4**.

Fertiliser	Spring barley in Denmark: Average soil (59% clay and 41% sand)	Spring barley in Denmark: Sand	Spring barley in Denmark: Clay
N	121 kg N/ha	117 kg N/ha	123 kg N/ha
P_2O_5	46 kg P_2O_5/ha	39 kg P_2O_5/ha	50 kg P_2O_5/ha
K_2O	66 kg K_2O/ha	55 kg K_2O/ha	74 kg K_2O/ha

Table 8.4: Fertiliser application on different soils in Danish spring barley cultivation.

The types of N, P and K fertilisers used in Denmark and corresponding LCI data are described in section 5.4: ‘Fertilisers’.

According to IFA (2007), the most widely used N-fertiliser in Northern America is ammonia. However, since no inventory data on straight ammonia have been identidied, it is assumed that the marginal source of N is ammonia nitrate which is the second most widely used N-fertiliser in Northern America. Inventory data for ammonia nitrate are specified in **Table 5.17**. The most widely used P-fertiliser in Northern America is phosphate rock (IFA 2007). Therefore, it is assumed that phosphate rock represents the marginal source of P-fertiliser in Canada. Inventory data for phosphate rock are described in section 6.5: Fertilisers. No data on the use of different types of K-fertilisers in Canada have been identified. Thus, it is assumed that potassuim chloride is the marginal source of K-fertiliser, i.e. the same marginal source of K-fertiliser as in Denmark and Malaysia/Indonesia. Inventory data for KCl are described in **Table 5.21**.

Pesticides

No good and representative data on the use of pesticides in barley cultivation in Denmark and Canada have been identified. Therefore, this is omitted from the study. In section 21.15 the significanse of this omission is analysed.

8.5 Co-products

Denmark: Barley is co-produced with straw from field. The utilisation of straw from spring barley in Denmark is given in **Table 8.5** below.

Straw uses	1997	1998	1999	2000	2001	2002	2003	2004
Straw for energy	8%	6%	8%	9%	10%	15%	17%	15%
Straw for fodder	56%	59%	52%	50%	43%	33%	33%	42%
Straw for bedding etc.	13%	14%	17%	17%	18%	29%	28%	16%
Straw left in the field	22%	21%	23%	24%	29%	24%	23%	27%
Straw, total	100%	100%	100%	100%	100%	100%	100%	100%

Table 8.5: Production and uses of spring barley straw in Denmark. (Danmarks Statistik 2006)

In average 24% of the straw is left in the field, 11% is used for energy purposes, 46% is used for fodder and 19% is used for bedding. In order to avoid co-product allocation the marginal application of straw is identified. The demand for bedding is determined by animal production. It is also assumed that the demand for straw for fodder purposes is determined by animal production, and that the use of straw for fodder does not substitude grains. Hence, bedding and fodder is not considered as the marginal use. It is assumed that the marginal use of straw is distributed on 24% left in the field and the remaining 76% is used for energy purposes. According to Energistyrelsen (2006) 29% of the potential for straw for energy purposes was utilised in 2002. This may increase in the future. In this study 24% left in the field and 76% used for energy purposes is applied. The interventions related to the straw left in the field are dealt with in section 8.6.

Inventory data for utilisation of straw for energy purposes in biomass plants are described in section 5.5.

Canada: The amount of straw left in the field in Canada is assumed to be 100%. According to Islam et al. (2004), straw is not used for energy purposes in Canada and only an insignificant fraction is used for bioethanol purposes and according to Wood and Layzell (2003) residues may be removed when yields exceeds 4.0 t/ha which is significant higher than the present 2.91 t/ha. Wood and Layzell (2003) also specify that between 750 and 1,500 kg crop residue per ha on prairie is essential to prevent wind erosion. Based on these considerations it is regarded as a good assumption that no residues are removed from barley production in Canada.

8.6 Emissions

N- and P balances are established for barley cultivation in Denmark and Canada. The relevant data in this respect are given in **Table 8.6**.

Parameter	Denmark: Spring barley	Canada: Barley	Reference
Annual barley yields	5,230 kg/ha	2,910 kg/ha	See **Table 8.1**
Seed input	110 kg/ha		Nemecek et al (2003, p 125)
Barley dry matter	85%		Møller et al. (2000, p 16)
Straw solid matter	85%		Møller et al. (2000, p 43). Assumed to be the same as pea straw
Straw removed from field	73%	0%	Straw removal in Denmark is obtained for Denmark in 2004 from Danmarks Statistik (2006).
Residue to crop ratio	1.2		IPCC (2000, p 4.58)
Straw to crop ratio	0.57		Jensen et al. (2005)
Barley N-content	0.0173 kg N/kg DS		Møller et al. (2000, p 16), N content is protein content divided by 6.25
Residue N-content	0.0064 kg N/kg DS		Møller et al. (2000, p 43)
Barley P-content	0.0035 kg P/kg DS		Møller et al. (2000, p 16)
Residue P-content	0.0009 kg P/kg DS		Møller et al. (2000, p 43)
Atmospheric N-deposition	15.0 kg/ha y	3.3 kg/ha y	Denmark: Ellermann et al. (2005) and Canada: Bergström and Jansson (2006)
N-fixing	0 kg N/ha y		-

Table 8.6: Relevant data in order to establish field balances of N and P for barley cultivation.

The N- and P-balances are shown in **Table 8.7**.

Inputs	Denmark		Canada	
	N	P	N	P
Deposition	15 kg N/ha	-	3.3 kg N/ha	-
Seed	1.9 kg N/ha	0.01 kg P/ha	1.9 kg N/ha	0.01 kg P/ha
Fertiliser	121 kg N/ha	20.0 kg P/ha	67 kg N/ha	11.4 kg P/ha
N-fixing	0 kg N/ha	-	0 kg N/ha	-
Changes in soil matter	0 kg N/ha	-	0 kg N/ha	-
Total	**137.6 kg N/ha**	**20.0 kg P/ha**	**72.2 kg N/ha**	**11.4 kg P/ha**
Outputs				
Harvested barley	76.9 kg/ha	15.6 kg P/ha	42.8 kg N/ha	8.7 kg P/ha
Removed straw	11.8 kg/ha	1.7 kg P/ha	0 kg N/ha	0 kg P/ha
Total	**88.7 kg/ha**	**17.3 kg P/ha**	**42.8 kg N/ha**	**8.7 kg P/ha**
Balance				
surplus (input – output)	**48.9 kg N/ha**	**2.7 kg P/ha**	**29.4 kg N/ha**	**2.7 kg P/ha**

Table 8.7: Annual N- and P-balances for 1 hectare barley field in Denmark and Canada.

Emissions related to the N-balance

The N-surplus in **Table 8.7** is distributed on different emissions following the same methods as for rapeseed, see section 5.6: ‘Emissions related to N-balance’.

Ammonia from crop: The ammonia emission from crops 5 kg N/ha, see section 5.6: ‘Emissions related to N-balance’.

Ammonia from fertiliser application: The ammonia emission from fertiliser depends on the fertiliser applied. According to Andersen et al. (2001, p 35) the ammonia emission from fertilisers based on ammonia is 2% of the N content in the fertiliser. Thus the ammonia emission as NH_3-N can be calculated as 2% of the applied fertiliser in **Table 8.3**.

Denitrification (total): The total denitrification (gaseous N oxides and molecular N_2) is calculated using the model; SimDen (Vinther and Hansen 2004). The reason why the total denitrification is calculated is that this is the only way of estimating N-loss as N_2. N_2 is determined as the total denitrification minus N_2O and NO. The model also calculates the N_2O-emission.

The model is described in section 5.6: ‘Emissions related to N-balance’. In Denmark the actual soil types are accounted for, while average of all soil types has been applied in Canada. The fertiliser application in Canada is given in **Table 8.3** and the fertiliser application on different soils in Denmark is given in **Table 8.4**

The total denitrification in Denmark is calculated as 13.2 kg N/ha for average soil, 5.5 kg N/ha for sand and 18.6 kg N/ha for clay. The total denitrification in Canada is calculated as 11.8 kg N/ha

Direct N_2O: The direct N_2O emission is calculated using a model described in IPCC (2000). The calculated emissions are then compared with the results using two other models described in FAO and IFA (2001) and Vinther and Hansen (2004). The results obtained using these models are due to consistency not applied in this study. The model described in Vinther and Hansen (2004) is developed for Danish conditions and may therefore not be applicable under conditions in Malaysia, Indonesia, Brazil and Canada which are affected regions in this life cycle inventory. The model in FAO and IFA (2001) does not include peat soils which is relevant in Malaysia and Indonesia.

IPCC (2000): According to IPCC (2000, p 4.54) the direct N_2O emission is calculated as shown in **Equation (3)** in section 5.6. The parameter values used in **Equation (3)** are described in **Table 8.8**.

Parameter	Description	Parameter value
F_{SN}	Annual amount of synthetic fertiliser nitrogen applied to soils adjusted to account for the amount that volatilises as NH3 and NOx	Fertiliser application, see **Table 8.3 and Table 8.4**. 2% volatises
F_{AM}	Annual amount of animal manure nitrogen intentionally applied to soils adjusted to account for the amount that volatilises as NH3 and NOx	No manure
F_{BN}	Amount of nitrogen fixed by N-fixing crops cultivated annually	**No N-fixing**
F_{CR}	Amount of nitrogen in crop residues returned to soils annually	Denmark: 22 kg N/ha (aver. Soil), 16 kg N/ha (sandy soil), 26 kg N/ha (clay soil) Canada: 19 kg N/ha (the figures are calculated using the informations in in **Table 8.6**)
F_{OS}	Area of organic soils cultivated annually (ha)	Denmark: 0% (see in **Table 5.28**) Canada: 0% (The total area of peat soil in Canada is 1,500,000 km^2 (Andriesse 1988). Comparing with the total area of Canada at 9.09 mio km^2, this corresponds to 16% of Canada. However, it is assumed that most of the peat soils are non-cultivated soils in the North)
EF_1	Emission factor for emissions from N inputs (kg N2O-N/kg N input)	1.25% (IPCC 2000, p 4.60)
EF_2	Emission factor for emissions from organic soil cultivation (kg N2O-N/ha-yr)	8 (IPCC 2000, p 4.60)

Table 8.8: Parameters in the equation calculating direct N_2O-emissions in IPCC (2000, p 4.54)

FAO and IFA (2001): According to FAO and IFA (2001, p 34) the direct N_2O emission is calculated as shown in **Equation (4)** in section 5.6. The parameter values used in **Equation (4)** are described in **Table 8.9**.

Parameter	Description	Parameter value
F	Type of fertiliser	Denmark: 0.0037, Fertiliser type is calcium ammonia nitrate Canada: 0.0061, Fertiliser type is ammonia nitrate
N-app.	Applied N, kg/ha	See **Table 8.3 and Table 8.4**
Cr	Crop type	0.000, Crop type is 'other'
S	Soil texture	-0.008 (coarse for sandy soil) and 0.000 (fine for clay soil), average soil is the average of -0.008 (coarse), -0.472 (medium) and 0.000 (fine)
C	Soil organic C content	0.140, 1-3% C in mineral soil types, based on Berntsen and Petersen (2007)
D	Soil drainage	-0.420, good drainage. Good drainage is needed in order to have suitable conditions for agriculture
pH	Soil pH	0.109, Soil pH 5.5 - 7.3
Cl	Climate	0.000, Temp. climate
LM	Length of measurement period (the model is constructed to fit with literature measurements. Thus, to model emissions obtained from literature the method of measurement in literature should also be considered since this affects the measured emission)	0.825 Length of measurement period is >300 days, i.e. the longest period available in the model (chosen as the most precise)
FM	Frequency of measurement (see comment above)	0.000 Frequency of measurement is >1measure/day, i.e. the highest frequency available in the model (chosen as the most precise)

Table 8.9: Parameters in the equation calculating direct N_2O-emissions in FAO and IFA (2001, p 34-35)

Vinther and Hansen (2004): The model calculates the direct N_2O emission for eight different soil types. The variable parameters are fertiliser application, applied manure, N input to pastures (N-deposit during grazing and N_2 fixing by clover) and N_2 fixing by legumes crops. All parameters except from fertiliser input is zero. The fertiliser input is given in **Table 8.3** and **Table 8.4**.

The calculated N_2O emissions using the three models are summarised in **Table 8.10**.

Soil type	IPCC (2000), kg N2O-N/ha	FAO and IFA (2001), kg N2O-N/ha	Vinther and Hansen (2004), kg N2O-N/ha
Denmark			
Aver. soil	2.54	1.96	2.16
Sand soil	2.95	2.21	1.53
Clay soil	2.27	2.27	2.60
Canada			
Aver. soil	1.40	1.41	1.85

Table 8.10: Calculated N_2O emissions (kg N_2O-N/ha) for sand, clay and average soils. The applied values are marked with dotted lines.

The results of the FAO and IFA model and the Vinter and Hansen model deviate from the results of the IPCC model in **Table 8.10** from around <1% to 48%.

Direct NO: The emission of NO is calculated using a model described in FAO and IFA (2001). According to FAO and IFA (2001, p 35) the direct NO emission is calculated shown in **Equation (5)** in section 5.6. The parameter values used in **Equation (5)** are described in **Table 8.11**.

Parameter	Description	Parameter value
F	Type of fertiliser	Denmark: 0.0062, Fertiliser type is calcium ammonium nitrate Canada: 0.0040, Fertiliser type is ammonium nitrate
N-app.	Applied N, kg/ha	See **Table 8.3 and Table 8.4**
C	Soil organic C content	0.000, <3.0% C in mineral soil types, based on Berntsen and Petersen (2007)
D	Soil drainage	0.946, good drainage. Good drainage is needed in order to have suitable conditions for agriculture

Table 8.11: Parameters in the equation calculating direct NO-emissions in FAO and IFA (2001, p 35)

The only parameters that are changed are the application of N-fertiliser.

The calculated NO emission is summarised in **Table 8.12**.

Soil type	kg NO-N/ha
Denmark	
Aver. soil	1.2
Sand soil	1.2
Clay soil	1.2
Canada	
Aver. soil	0.7

Table 8.12: Calculated NO emissions (kg NO-N/ha) using the model described in FAO and IFA (2001). The applied values are marked with dotted lines.

Nitrate: The nitrate emission is calculated as the residual or rest; i.e. the surplus-N from the N-balance minus the other calculated emissions described above. The calculated nitrate emission is shown in **Table 8.13**.

Soil type	kg NO3-N/ha
Denmark	
Aver. soil	28.3
Sand soil	49.1
Clay soil	14.7
Canada	
Aver. soil	11.3

Table 8.13: Calculated nitrate emissions (kg NO_3^--N/ha). The applied values are marked with dotted lines.

N_2O, indirect from NH_3 and nitrate: These calculations are described in section 5.6: ‘Emissions related to N-balance’.

NO, indirect: This is not included.

Summary of emissions related to N-balance: Distribution of the N-surplus is summarised in Table 8.14.

Emission and source	Denmark Average soil	Denmark Sand	Denmark Clay	Canada Average soil
Ammonia from crop (kg NH_3-N/ha)	2.4	2.3	2.5	1.3
Ammonia from fertiliser application (kg NH_3-N/ha)	5.0	5.0	5.0	5.0
Denitrification (kg N/ha)	13.2	5.5	18.6	11.8
- N_2O part of denitrification (kg N_2O-N/ha)	1.8	1.6	1.8	1.1
- NO part of denitrification (kg NO-N/ha)	1.2	1.2	1.2	0.7
- N_2 part of denitrification (kg N/ha)	10.2	2.7	15.5	10.0
Nitrate (kg NO_3-N/ha)	28.3	49.1	14.7	11.3
N-surplus (kg N/ha)	**48.9**	**61.9**	**40.7**	**29.4**
N_2O, indirect from NH_3 (kg N_2O-N/ha)	0.1	0.1	0.1	0.1
N_2O, indirect from nitrate (kg N_2O-N/ha)	0.7	1.2	0.4	0.3

Table 8.14: Distribution of the N-surplus from the field N-balance on different emissions and sources. All numbers are given in kg N/ha.

Table 8.15 summarises the emissions in **Table 8.14** and converts them into kg emission per ha instead of kg N/ha.

	Denmark			Canada
Emission as kg N/ha	**Average soil (41% sand and 59% clay)**	**Sand**	**Clay**	**Average soil**
Ammonia to air (kg NH_3-N/ha)	7.4	7.3	7.5	6.3
N_2O to air (kg N_2O-N/ha)	2.5	2.9	2.3	1.4
NO to air (kg NO-N/ha)	1.2	1.2	1.2	0.7
Nitrate to water (kg NO_3-N/ha)	28.3	49.1	14.7	11.3
Emission as kg emission/ha	**Average soil (41% sand and 59% clay)**	**Sand**	**Clay**	**Average soil**
Ammonia to air (kg NH_3/ha)	9.0	8.9	9.1	7.7
N_2O to air (kg N_2O/ha)	4.0	4.6	3.6	2.2
NO to air (kg NO/ha)	2.5	2.5	2.6	1.6
Nitrate to water (kg NO_3/ha)	125	217	65	50

Table 8.15: Emissions related to N-balance.

Emissions related to the P-balance

As described in the case of emissions from rapeseed cultivation (see section 5.6) accumulation of phosphorus in the soil is relatively constant due to strong binding to the soil. Therefore, the emission of P is calculated as a fraction of the field surplus. According to section 5.6: 'Emissions related to P-balance', 2.9% of the P surplus is emitted to water as leaching of phosphate. The remaining is accumulated in the soil matter. Thus the emission of P is 2.9% of the surplus in the P-balances given in **Table 8.7**. P emissions for sand and clay soils in Denmark are also calculated. This is done by first establishing P-balances as in **Table 8.7** using the data in **Table 8.4** and **Table 8.6**. The P emissions are given in **Table 8.16**.

Soil type	kg P/ha
Denmark	
Aver. soil	0.078
Sand soil	0.084
Clay soil	0.075
Canada	
Aver. soil	0.078

Table 8.16: Calculated P emissions (kg P/ha). The applied values are marked with dotted lines.

Emissions related to the C-balance

As in the case for rapeseed, oil palm and soybean cultivation it is assumed that continuous cultivation of barley does not affect the soil content of carbon.

Carbon emissions that arise from transformation of land (prairie) in Canada into barley fields are described in section 19.1.

Emissions of heavy metal

The emissions of heavy metals from input of fertiliser are calculated using the same method as for rapeseed cultivation, see section 5.6: 'Emissions of heavy metal'. Hence, it is assumed that the heavy metal input from fertilisers is distributed on emissions to soil and emissions to water. The emission of heavy metals to soil is calculated as the total input with fertiliser and seeds minus the share that ends in water. One eighth, i.e. 12.5%, of the heavy metals harvested with crop ends as emission to water and the other 87.5% ends as emission to soil.

The contents of heavy metals in fertilisers used in Denmark[16] are described in section 5.6: 'Emissions of heavy metal' and the contents of fertilisers used in Canada[17] are described in section 5.6: (N and K) and section 6.7: 'Emissions of heavy metal' (P) and the contents in barley and straw are shown in **Table 8.17**.

Heavy metals in harvested crop; mg/kg crop	**Barley**		**Applied in this study**
	(Nemecek, et al. 2003, p 154)	(Møller et al. 2000, p 17)	
Arsenic (As)	-	-	-
Cadmium (Cd)	0.068	-	0.068
Chromium (Cr)	0.31	-	0.31
Cobalt (Co)	-	0.0085	0.0085
Copper (Cu)	5.10	2.55	3.83
Mercury (Hg)	0.051	-	0.051
Molybdenum (Mo)	-	-	-
Nickel (Ni)	0.33	-	0.33
Lead (Pb)	0.35	-	0.35
Selenium (Se)	-	0.034	0.034
Zink (Zn)	37.8	26.4	32.1
Heavy metals in harvested straw; mg/kg crop	**Barley straw**		**Applied in this study**
	(Nemecek, et al. 2003, p 154)	(Møller et al. 2000, p 43)	
Arsenic (As)	-	-	-
Cadmium (Cd)	0.11	-	0.11
Chromium (Cr)	0.36	-	0.36
Cobalt (Co)	-	0.16	0.16
Copper (Cu)	4.34	2.55	3.45
Mercury (Hg)	0.085	-	0.085
Molybdenum (Mo)	-	-	-
Nickel (Ni)	0.35	-	0.35
Lead (Pb)	1.70	-	1.70
Selenium (Se)	-	0043	0043
Zink (Zn)	11.1	125.0	68.1

Table 8.17: Heavy metal content (mg/kg crop) in harvested barley and barley straw. The applied data are marked with dotted frames.

Based on the fertiliser inputs given in **Table 8.3** and **Table 8.4**, the contents of heavy metals in fertilisers, and the contents of heavy metals in harvested barley and straw in **Table 8.17**, the emissions of heavy metals from fertiliser can be calculated. The results are shown in **Table 8.18**.

---

[16] Fertilisers in Denmark; N: Calcium ammonia nitrate, P: Triple super phosphate, K: Pottasium chloride.

[17] Fertilisers in Canada; N: Ammonia nitrate, P: Rock phosphate, K: Pottasium chloride.

	Denmark						Canada	
	Aver. soil		Sand		Clay		Aver. soil	
Emission	Soil (g/ha)	Water (g/ha)	Soil (g/ha)	Water (g/ha)	Soil (g/ha)	Water (g/ha)	Soil (g/ha)	Water (g/ha)
Arsenic (As)	0.9	-	0.8	-	1.0	-	0.2	-
Cadmium (Cd)	0.3	0.0	0.2	0.0	0.3	0.1	0.7	0.03
Chromium (Cr)	26	0.2	22	0.2	29	0.2	16	0.1
Cobalt (Co)	0.2	0.01	0.2	0.00	0.2	0.01	0.06	0.003
Copper (Cu)	4.0	2.5	3.7	2.0	4.2	2.8	2.7	1.4
Mercury (Hg)	-0.01	0.03	0.00	0.03	-0.01	0.04	-0.005	0.02
Molybdenum (Mo)	1.0	-	0.9	-	1.0	-	0.3	-
Nickel (Ni)	9	0.2	7.6	0.2	9	0.2	2.0	0.1
Lead (Pb)	0.8	0.2	0.8	0.2	0.8	0.3	0.6	0.1
Selenium (Se)	2.0	0.02	1.9	0.02	2.0	0.03	1.0	0.01
Zink (Zn)	45	21	40	17	48	24	8.9	12

Table 8.18: Heavy metal emissions to soil and water from barley cultivation in Denmark and Canada.

Emissions of pesticides

As described in section 8.4 the use of pesticides in barley cultivation has been omitted from the study.

8.7 Overhead in agricultural stage

As in the case of rapeseed cultivation, the amount of electricity used in administration buildings etc. is assumed to be insignificant.

8.8 Capital goods in agricultural stage

Corresponding to capital goods in oil palm and soybean cultivation, (e.g. see section 7.7), the use of capital goods is determined from modified figures of the capital goods used in rapeseed cultivation. It is assumed that the amount of harvesters, tractors, agricultural machinery-tillage, agricultural machinery-general and shed are equivalent with the diesel consumption per hectare. The diesel consumption in rapeseed cultivation is 3,612 MJ/ha (see section 5.3) and the diesel consumption in barley cultivation is 4,029 MJ/ha (see section 8.2). Thus, use of capital goods per ha barley field is 112% of the use per ha rapeseed field. The use of buildings for administration, research and laboratories is assumed to be zero corresponding to rapeseed cultivation.

	Use of capital goods per ha per year	
Capital goods	Rapeseed (Table 5.44)	Barley in Denmark and Canada
Tractor	7.5 kg	8.4 kg
Harvester	6.3 kg	7.0 kg
Agricultural machinery, tillage	9.2 kg	10.3 kg
Agricultural machinery, general	3.5 kg	3.9 kg
Shed	0.070 m^2	0.078 m^2
Administration, research and laboratories	0 m^3	0 m^3

Table 8.19: Use of capital goods in barley cultivation.

8.9 Transport of materials in agricultural stage

Raw materials are transported with lorry to the cereal farms. Inventory data per tkm transport by lorry are described in section 4.1. Since there are several suppliers and since there is a general lack of data on the specific marginal affected supplier, all transport distances are based on rough estimates. Determination of size of lorries is based on **Table 4.3** and very rough estimates on the total amount of goods transported.

The amounts of used seed, fertiliser and pesticides are described in section 8.1 and 8.4. The contents of N, P_2O_5 and K_2O in the used fertilisers are described in **Table 5.45** and **Table 6.34** (however, the content of N in ammonia nitrate is found in WSDA (2006)) and the use of fertilisers is descibed in **Table 8.3**.

Fertiliser	**Content of nutrient in fertiliser**	**Applied nutrients (see Table 8.3)**	**Applied fertiliser product**
Denmark			
Calcium ammonium nitrate	19% N	121 kg N/ha	637 kg/ha
Triple superphosphate	38% P_2O_5 (16% P)	46 kg P_2O_5/ha	121 kg/ha
Potassium chloride	14% K_2O (12% K)	66 kg K_2O/ha	471 kg/ha
Total			**1,229 kg/ha**
Canada			
Ammonia nitrate	20% N	67 kg N/ha	335 kg/ha
Phosphate rock	30% P_2O_5 (13% P)	26 kg P_2O_5/ha	87 kg/ha
Potassium chloride	14% K_2O (12% K)	10 kg K_2O /ha	71 kg/ha
Total			**493 kg/ha**

Table 8.20: Determination of amount of transported fertiliser product.

Table 8.21 shows the transported amounts, the route and the distances.

Denmark					
Material	**Amount per ha**	**From**	**To**	**Distance**	**Means of transportation**
Seed	110 kg	Seed trader, DK	Barley farm, DK	100 km	40t lorry
Barley	5,230 kg	Barley farm, DK	Cereal trader, DK	100 km	40t lorry
Straw to utilisation	2,176 kg	Barley farm, DK	Biomass plant, DK	100 km	40t lorry
Fertilisers, N, P and K	1,229 kg	Abroad chemical plant	Barley farm, DK	1000 km	40t lorry
Pesticides	Not included	Abroad chemical plant	Barley farm, DK	1000 km	40t lorry
Canada					
Material	**Amount per ha**	**From**	**To**	**Distance**	**Means of transportation**
Seed	110 kg	Seed trader, CAN	Barley farm, CAN	250 km	40t lorry
Barley	2,910 kg	Barley farm, CAN	Cereal trader, CAN	250 km	40t lorry
Straw to utilisation	810 kg	Barley farm, CAN	Biomass plant, CAN	250 km	40t lorry
Fertilisers, N, P and K	493 kg	Abroad chemical plant	Barley farm, CAN	1000 km	40t lorry
Pesticides	Not included	Abroad chemical plant	Barley farm, CAN	1000 km	40t lorry

Table 8.21: Transport of goods related to the agricultural stage. The return trip is included in the inventory data.

The estimated transport in **Table 8.21** is summarized in **Table 8.22**.

Means of transportation	**Transport, 40t lorry**
Barley in Denmark	1,981 tkm
Barley in Canada	1,451 tkm

Table 8.22: Summary of transport in the agricultural stage.

8.10 LCI of barley agricultural stage, summary

Table 8.23 summarises the inventory data relating to 1 ha spring barley cultivated in 1 year in Denmark and **Table 8.24** summrises the inventory for barley in Canada.

Denmark: 1 ha y spring barley field			
Interventions	**Amount**	**Applied LCI data**	
Product output			
Spring barley (Denmark)	5.120 t	Product of interest	
Straw removed from field	2,176 kg	Co-product allocation between barley and straw is avoided by system expansion, see below	
System expansion			
Burning of straw in biomass plant	2,176 kg	See **Table 5.25**	
Energy use			
Traction, burned diesel	4,029 MJ	See **Table 4.5**	
Drying of barley (evaporated water)	105 kg	Modified version of: ‘*Grain drying, low temperature/CH*’ (ecoinvent 2004), see section 5.3	
Material use			
Seed	110 kg	See **Table 8.2**	
N-fertiliser (as N)	121 kg	*‘Calcium ammonium nitrate, as N, at regional storehouse/RER’*, (ecoinvent 2004)	
P-fertiliser (as P_2O_5)	46 kg	Modified version of: ‘*Triple superphosphate, as P_2O_5, at regional storehouse/RER’* (ecoinvent 2004), see section 5.4	
K-fertiliser (as K_2O)	66 kg	‘*Potassium chloride, as K_2O, at regional storehouse/RER’* (ecoinvent 2004)	
Capital goods			
Agricultural buildings	0.078 m^2	‘*Shed/CH/I*’ (ecoinvent 2004)	
Machinery, tractor	8.4 kg	‘*Tractor, production/CH/I*’ (ecoinvent 2004)	
Machinery, combine harvester	7.0 kg	‘*Harvester, production/CH/I*’ (ecoinvent 2004)	
Machinery, tillage	10.3 kg	‘*Agricultural machinery, tillage, production/CH/I*’ (ecoinvent 2004)	
Machinery, general/miscellaneous	3.9 kg	‘*Agricultural machinery, general, production/CH/I*’ (ecoinvent 2004)	
Transport			
40t lorry	1,981 tkm	‘*Transport, lorry 40t*’ (ecoinvent 2004)	
Emissions	**Air**	**Water**	**Soil**
Ammonia (NH3)	9.0 kg	-	-
Dinitrogen oxide (N2O)	4.4 kg	-	-
Nitric oxide (NO)	2.5 kg	-	-
Nitrate (NO3)	-	125 kg	-
Phosphorus (P)	-	0.078 kg	-
Arsenic (As)	-	-	0.88 g
Cadmium (Cd)	-	0.044 g	0.27 g
Chromium (Cr)	-	0.20 g	26 g
Cobalt (Co)	-	0.0056 g	0.21 g
Copper (Cu)	-	2.5 g	4.0 g
Mercury (Hg)	-	0.033 g	-0.0081 g
Molybdenum (Mo)	-	-	1.0 g
Nickel (Ni)	-	0.22 g	8.7 g
Lead (Pb)	-	0.23 g	0.81 g
Selenium (Se)	-	0.022 g	2.0 g
Zink (Zn)	-	21 g	45 g

Table 8.23: Interventions per ha y spring barley field in Denmark.

Canada: 1 ha y barley field		
Interventions	**Amount**	**Applied LCI data**
Product output		
Barley (Canada)	2.800 t	Product of interest
Straw removed from field	0 kg	-
System expansion		
Burning of straw in biomass plant	0 kg	-
Energy use		
Traction, burned diesel	4,029 MJ	See **Table 4.5**
Drying of barley (evaporated water)	58 kg	Modified version of: ‘*Grain drying, low temperature/CH*’ (ecoinvent 2004), see section 5.3
Material use		
Seed	110 kg	See **Table 8.2**
N-fertiliser (as N)	67 kg	‘*Ammonium nitrate, as N, at regional storehouse/RER*’, (ecoinvent 2004)
P-fertiliser (as P_2O_5)	26 kg	Phosphate rock, see section 6.5: Fertilisers
K-fertiliser (as K_2O)	10 kg	‘*Potassium chloride, as K_2O, at regional storehouse/RER*’ (ecoinvent 2004)
Capital goods		
Agricultural buildings	0.078 m^2	‘*Shed/CH/I*’ (ecoinvent 2004)
Machinery, tractor	8.4 kg	‘*Tractor, production/CH/I*’ (ecoinvent 2004)
Machinery, combine harvester	7.0 kg	‘*Harvester, production/CH/I*’ (ecoinvent 2004)
Machinery, tillage	10.3 kg	‘*Agricultural machinery, tillage, production/CH/I*’ (ecoinvent 2004)
Machinery, general/miscellaneous	3.9 kg	‘*Agricultural machinery, general, production/CH/I*’ (ecoinvent 2004)
Transport		
40t lorry	1,451 tkm	‘*Transport, lorry 40t*’ (ecoinvent 2004)

Emissions	**Air**	**Water**	**Soil**
Ammonia (NH3)	7.7 kg	-	-
Dinitrogen oxide (N2O)	2.2 kg	-	-
Nitric oxide (NO)	1.6 kg	-	-
Nitrate (NO3)	-	50 kg	-
Phosphorus (P)	-	0.078 kg	-
Arsenic (As)	-	-	0.16 g
Cadmium (Cd)	-	0.025 g	0.69 g
Chromium (Cr)	-	0.11 g	16 g
Cobalt (Co)	-	0.0031 g	0.061 g
Copper (Cu)	-	1.4 g	2.7 g
Mercury (Hg)	-	0.019 g	-0.0050 g
Molybdenum (Mo)	-	-	0.26 g
Nickel (Ni)	-	0.12 g	2.0 g
Lead (Pb)	-	0.13 g	0.55 g
Selenium (Se)	-	0.012 g	0.94 g
Zink (Zn)	-	12 g	8.9 g

Table 8.24: Interventions per ha y barley field in Canada.

9 Oil mill stage: Rapeseed oil

The LCI for the oil mill stage takes its point of departure in production of rapeseed oil at AarhusKarlshamn in Aarhus, Denmark. In order to have a representative set of data, data from both 2003 and 2004 are used where possible.

Two different types of oil mill technologies exist; solvent extraction and full press. The difference between the two technolies is that the solvent extraction technology uses hexane as a solvent in order to achieve a higher oil extraction rate. The solvent extraction which is used at AarhusKarlshamn is the most dominant technology in the rapeseed oil industry (Kronborg 2006). As sensitivity analysis, data are also collected for a full press mill; Scanola in Aarhus, Denmark, see section 21.16.

The inventory of the oil mill stage is mainly based AarhusKarlshamn's energy report (2005b) and environmental report (Aarhus United, 2005a). Since AarhusKarlshamn produces other products than rapeseed oil and since their activities include milling and refining as well as modification of oils such as interestification, fractionation and hardening, overall environmental data from environmental accounts and energy accounts are not directly applicable. Therefore use of energy, use of ancillary materials, emissions and waste have to be based on more detailed investigations – mainly based on personal communication with Korning (2006), Kronborg (2006) and Hansen (2006). However, there are interventions which are not directly connected to any of the production lines. In these cases allocation has been carried out. This has been necessary in the case of heat and power supply for buildings (administration and research and development). Allocation is carried out between products and between process stages for rapeseed oil (milling, refining and modifying).

Figure 9.1 shows the output of rapeseed meal from the oil mill.

Figure 9.1: Rapeseed meal. Picture taken by Jannick H Schmidt 2007. Samples provided by Nordic Folkecenter for Renewable Energy..

9.1 Rapeseed oil mill product flow

The inventory of the oil mill stage is divided into the unit processes shown in **Figure 9.2**. **Figure 9.2** also shows the product flows through the oil mill. The product flow is determined from data on production of crude rapeseed oil at AarhusKarlshamn in 2004 (Aarhus United 2005b; Kronborg 2006 and Hansen 2006).

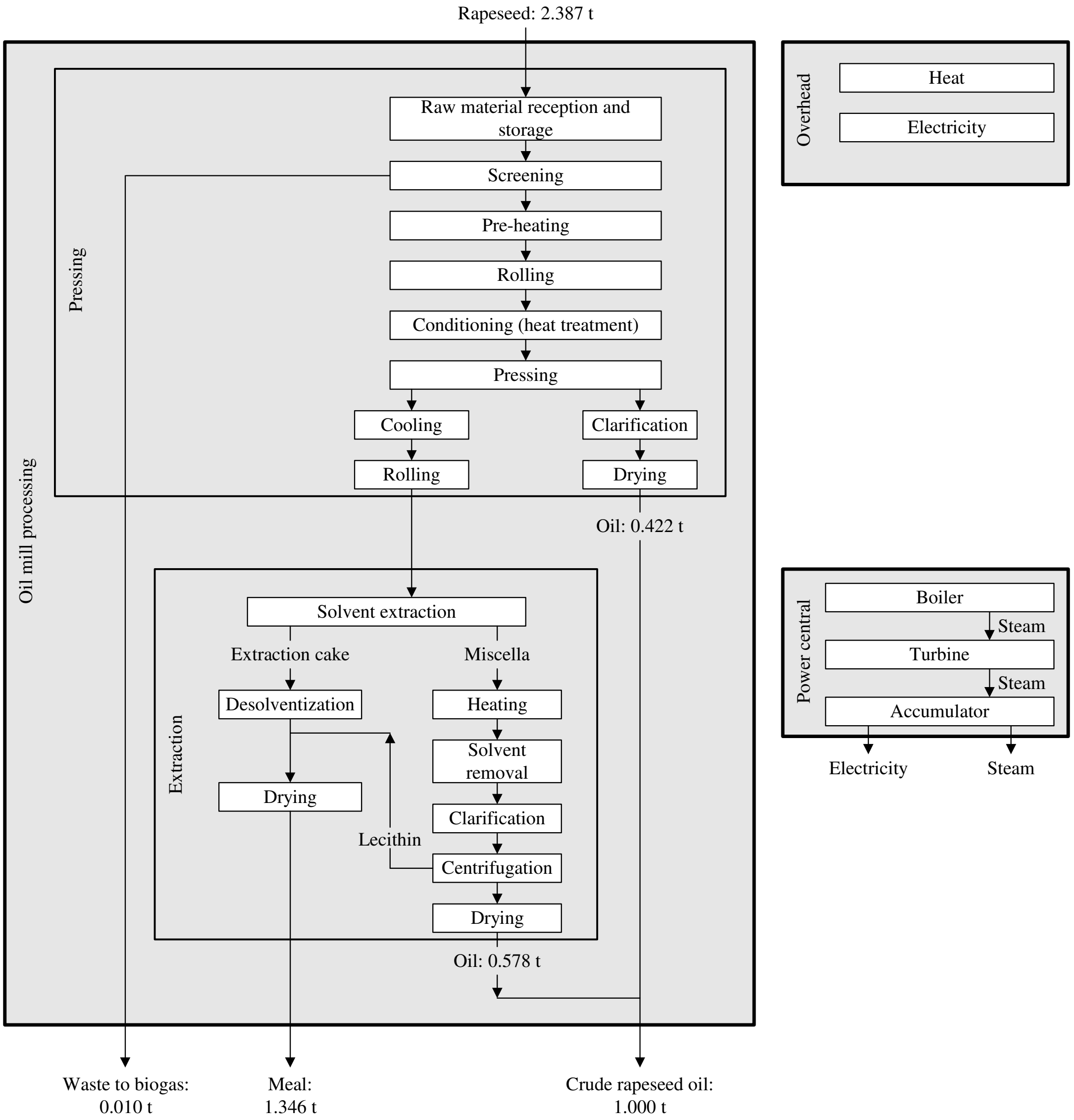


Figure 9.2: Product flow related to production of 1 t crude rapeseed oil in the rapeseed oil mill. The numbers are obtained from Aarhus United in 2004. The grey shaded boxes represent the unit processes in the rapeseed oil mill stage.

Milling and extraction	2003		2004	
	Rape	Shea	Rape	Shea
Inputs				
Seed and nuts	**75,481**	**50,006**	**61,841**	**86,533**
Outputs				
Oil from pressing	13,587	11,001	11,131	19.037
Oil from extraction	17,314	13,437	15,231	23,401
Meal	44,581	25,568	35,479	44,094
Total	**75,482**	**50,006**	**61,841**	**86,532**

Table 9.1: Mass balance for milling and extraction at AarhusKarlshamn 2003 and 2004. All numbers are given in tonne. (Aarhus United, 2004b and 2005b)

The numbers shown in **Table 9.1** from AarhusKarlshamn only cover production of crude oils at AarhusKarlshamn and they do not take into account that there is a minor loss of water and residuals from screening of the incoming rapeseed. It is the numbers on amount of produced crude oils that are the correct ones. The loss of residual and water per kg crude oil is given in **Figure 9.3**.

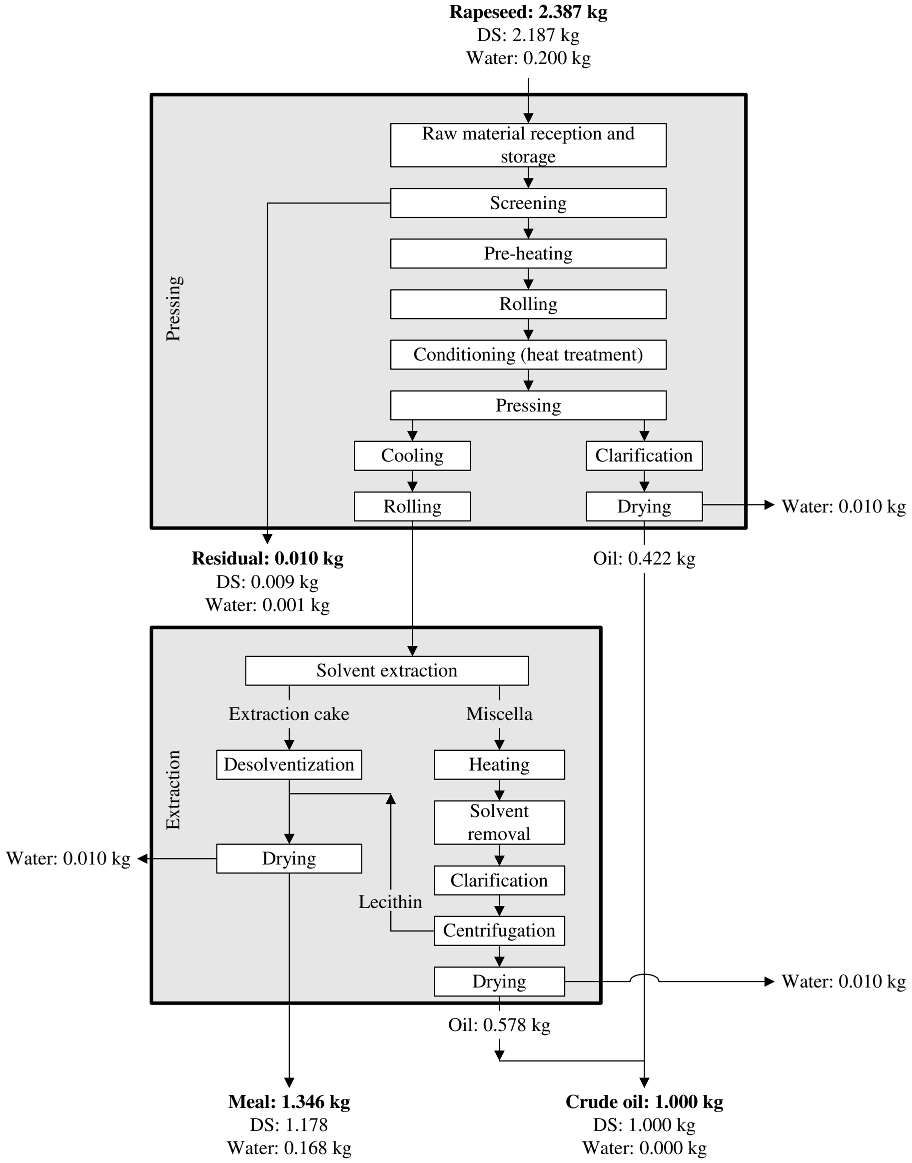


Figure 9.3: Losses of water and residual in the screening process related to pressing and extraction of 1 kg crude rapeseed oil. The calculation of losses is described in the following.

Loss; residual from screening: According to Kronborg (2006) the amount of residual from screening of the incoming rapeseed is approximately 0.4%. The water content in residual is assumed to be the same as in rapeseed which is 8-9%, see **Table 5.1**.

Loss; water: It has not been possible to obtain data on loss of water in the rapeseed through the processes at AarhusKarlshamn. Therefore, point of departure is taken in the overall loss in rapeseed oil mills in the EU which was 1.7% in 2003 and 2004 (Based on Oil World 2005). Applying the overall loss of incoming rapeseed at 1.7% in the EU and the ratio between oil and meal as in **Figure 9.2**, the total input of rapeseed per tonne crude oil is 2.387 tonne.

The water content of the meal is estimated as 12.5%. This based on rapeseed meal containing 4% fat in Møller et al. (2000). Møller et al. (2000) provide data on different types of rapeseed meals; meals containing 4%, 10% and 13% fat. Meals containing 10% and 13% fat are meals from oil mills without solvent extraction. Based on the numbers given in **Figure 9.2** and a content of 199 g protein and 442 g fat per kilo rapeseed (Møller et al. 2000) and an overall loss of inputs to oil to rapeseed oil mills in the EU at 1.7%, it can be calculated that the meal produced at AarhusKarlshamn contains approximately 4.1% fat and 35.3% protein. A standard rapeseed meal containing 4% fat in Møller et al. (2000) contains 34% protein, which relatively close to the numbers calculated.

The overall loss at 1.7% of the input of rapeseed is distributed on 0.4% residual from screening of rapeseed; ~0.0095 t, and the remaining 1.3% is water; 0.031 tonne. Since the content of water in the meal is 12.5%, the amount of water in the meal is 0.168 tonne. The water content of the residual is assumed to be the same as in rapeseed ~8-9%; ~0.001 tonne. The water content in the incoming rapeseed is calculated from the dry matter content in the outputs; the meal (1.178 t), the crude oil (1.000 t) and the residual (~0.009 t) totalling 2.187 tonne dry solid matter. The total input of rapeseed was determined to be 2.387 tonne. Comparing the dry solid matter and the total input, the water content can be calculated as 8.4% (0.200 t). This is consistent with **Table 5.1** which specify water content at 8-9%. Thus, the loss of water in the different drying processes can be calculated as the residual water in excess; water input (0.200 t) minus water output (0.168 t + 0.001 t) = 0.031 t. It is assumed that this water loss is equally distributed on the three drying processes given in **Figure 9.2**. Thus, the water loss is 0.010 t in each drying process.

9.2 Omitted inventory data in rapeseed oil mill stage

There are some interventions related to the oil mill stage that are not included. The reason for omitting these interventions is: i) the interventions account for an insignificant share of the interventions related to the oil mill stage, ii) inclusion would involve great uncertainties, iii) data collection would be quite time consuming. Relating to ii) one reason for uncertainties is that there is no known direct relationship between production of refined rapeseed oil at AarhusKarlshamn and the interventions. Therefore, the added value to the inventory is estimated to be very low compared to the work load needed. All omitted interventions accounts for less than 0.6 g per kg produced oil at AarhusKarlshamn. The omitted interventions are shown in **Table 9.2**.

Material flows	**Total at AarhusKarlshamn in 2004**	**Amount per kg product at AarhusKarlshamn**
Products	312,000 tonne	1 kg
Omitted material use		
Lubricating oil	3 tonne	0.01 g
Cleaning agents	13.4 tonne	0.04 g
Omitted waste		
Paper and card board to recycling	42 tonne	0.1 g
Plastic to recycling	8 tonne	0.03 g
Lubricating oil to recycling	3 tonne	0.01 g
Metals to recycling	180 tonne	0.6 g
Waste to landfill	80 tonne	0.3 g

Table 9.2: Omitted inventory data. Data from Aarhus United (2005a).

In addition to the omitted material uses and waste streams in **Table 9.2** also consumption of varies minor products such as tools, paper, computers, pencils, miscellaneous equipment etc. for process management and administration are omitted.

9.3 Power central

The energy supply to the oil mill includes electricity and steam. At AarhusKarlshamn steam is co-produced with electricity on the company's own combined heat and power plant (CHP) and deficiency of electricity is purchased from the grid. The determining product is steam and the dependent product is electricity.

The energy efficiency in term of steam and electricity production for AarhusKarlshamn's CHP is shown in **Table 9.3**. The numbers are based on the total input of fuel oil and the net output of steam and electricity.

Energy distribution	2003	2004	Average
Heat	90.1%	84.6%	87.3%
Electricity	4.9%	5.2%	5.0%
Loss	5.1%	10.1%	7.6%
Total	**100.1%**	**99.9%**	**99.9**

Table 9.3: Energy efficiency at AarhusKarlshamn's CHP. The small differences in total are due to rounding. (Aarhus United, 2004b and 2005b)

It can be seen from **Table 9.3** that the CHP has an overall average efficiency of 92.3 percent. This is consistent with Energistyrelsen (1995) where efficiency of oil boilers in Denmark is assessed to be 90-92%. According to Aarhus United (2005a) the use of fuel in 2004 was distributed on 98.3% fuel oil and 1.7% oil waste from AarhusKarlshamn. 20% of the oil waste comes from degumming of shea nut oil and 80% comes from different oil waste of vegetable oils. In 2004 29% of the crude oil production was rapeseed oil and 71% was shea nut oil (Aarhus United, 2005b). Thus, 29% of 80% of the 1.7% oil waste, i.e. 0.4% ~ 0% of the oil waste can be ascribed to the production of rapeseed oil. Hence, the amount of oil waste from rapeseed oil can be neglected. Comparing the water use for energy production in Aarhus United (2005a) the production of steam in Aarhus United (2005b) the use of water can be found as 0.12 litres per MJ heat produced.

Interventions related to production, transportation and burning of fuel oil are found using data from ecoinvent (2004): *Light fuel oil, burned in boiler 100kW, non-modulating*. The data set includes infrastructure and machinery for production and transportation of the oil.

The produced electricity is sold to the grid, where marginal supply of electricity is displaced. **Table 9.4** gives an overview of the interventions related to production of 1 MJ at the power central at AarhusKarlshamn.

1 MJ heat (steam)	Amount	Applied LCI data
Fuel oil burned in boiler	1.145 MJ	'Light fuel oil, burned in boiler 100kW, non-modulating', ecoinvent (2004)
Electricity (sold to the grid)	-0.057 MJ	See **Table 3.3**
Water, tap	0.12 litre	See **Table 13.5**

Table 9.4: Inventory data for 1 MJ heat produced at AarhusKarlshamn's power central.

9.4 Rapeseed oil mill processing: Pressing and extraction

This process includes raw material reception, storage, screening, pre-heating, rolling and conditioning. After rolling the flakes from the press process are sent to solvent extraction. There are two outputs from the solvent extraction; extraction cake and miscella. The solvent is removed from the cake and after drying the meal is finished. Miscella is a mix of oil approximately 10-30% oil and 70-90% solvent. The solvent is removed and reused and the oil is clarified and centrifuged. The residual from the centrifugation is lecithin which at AarhusKarlshamn is fed into the meal fraction. Some mills sell the lecithin which can be used as emulsifier. The segregated lecithin comprises around 2% of the desolventized miscella (Korning 2006). It is presumed that the lecithin in general at modern European oil mills is fed into the meal. Thus, it is not treated as a co-product. Interventions in the pressing and extraction stage are calculated per kg extracted rapeseed oil. The product flow per kilo pressed and extracted oil is shown in **Figure 9.2**.

Material use

There is no material use besides the input of rapeseed to the pressing process. The interventions related to rapeseed production are described in section 0. In the extraction process solvent is used. The solvent used at AarhusKarlshamn is hexane. According to Bockisch (1998) hexane is the most dominant solvent used. Other minor solvents are benzenes, carbon disulphide and trichloroethylene.

According to Kronborg (2006) consumption of hexane per tonne pressed and extracted rapeseed oil is 1.188 kg.

It has not been possible to identify any inventory data on production of hexane. However, two inventories of solvents representing hexane have been identified. The first one is an inventory used to describe hexane for extraction of rapeseed oil in an LCA of rapeseed oil (Nielsen et al. 2005). The data used is an inventory of 'Chemicals inorganic' from the ETH-database (Frischknecht et al., 1996). The second data set is data used to describe hexane for soybean oil extraction in an LCA of soybean oil (Althaus et al. 2003). The data set is an inventory of production of pentane in the ecoinvent database (Hischier 2003). In Althaus et al. (2003, p 695) it is argued that the use of data for pentane should not affect the result of the LCA of soybean oil because the manufacturing processes of hexane and pentane are similar. Analysing the two data sets in Simapro and using the EDIP97 for LCIA, it appears that global warming, acidification and toxicity are the most significant impact categories. In **Table 9.5** the two data sets are compared within these categories.

Representative LCI-data for hexane	CO_2-eq.	SO_2-eq.	ETWC, m^3 water	Description of data
'Chemicals, inorganic', ETH-ESU database (Frischknecht et al., 1996)	0.65 kg	8.8 g	530 m^3	*Time:* Data from 1990-94 *Geography:* Western Europe *Technology:* Average *Co-product allocation*: Not relevant *Capital goods:* Included for sub processes but not for the production of chemicals.
'Pentane, at plant', ecoinvent database (Hischier 2003)	1,2 kg	9.7 g	32 m^3	*Time:* Data from 1990 and 1996 *Geography:* France, Germany and UK *Technology:* Average *Co-product allocation*: Mass-allocation between co-products in the steps before pentane production (refining of oil etc) *Capital goods:* Machinery, buildings.

Table 9.5: Comparison of two LCIs representing production of 1 kg hexane. The comparison is shown as characterised results using the EDIP97-method for LCIA. The applied data are marked with a black dotted frame.

It appears from **Table 9.5** that the two data sets are significantly different within the compared impact categories. The difference in terms of global warming varies with a factor 2 and ecotoxicity with a factor 17. The main reason for the differences is probably that the two LCIs have different scopes; 'chemicals, inorganic' and 'pentane, at plant'. The validity of this argument is underpinned in the following. Besides pentane, there are inventories of 15 other different solvents in Hischier (2003). In comparison to **Table 9.5** these data varies from 0.62 kg CO_2-eq to 3.3 kg CO_2-eq and 36 m^3 to 1,000 m^3 water ecotoxicity. It can be seen that the span of contributions from different solvents in Hischier (2003) embrace the data from Frischknecht et al. (1996). Since the data from Hischier (2003) are the newest, the most precise concerning scope and the most documented of the two data sets, it is chosen to apply these in the LCA of rapeseed oil.

Energy use

According to Kronborg (2006) energy consumption related to both pressing and extraction is 1,586 MJ heat and 419 MJ electricity per tonne of rapeseed oil. Based on Kronborg (2006) and Aarhus United (2005b) it is determined that pressing comprises 22% of the heat consumption and 64% of the electricity use. These energy uses are per tonne of produced oil, see **Table 9.6**.

Energy use per kg pressed rapeseed oil	Pressing	Solvent extraction	Total
Electricity	268 MJ	151 MJ	419 MJ
Heat (steam)	349 MJ	1,237 MJ	1,586 MJ

Table 9.6: Energy consumption per t rapeseed oil produced in 2004 at AarhusKarlshamn. (Kronborg, 2006 and Aarhus United 2005b)

The interventions from production of electricity and heat are described in section 3.1 and 9.3.

Emissions

There are no emissions from the press except from dust. This originates from the handling of rapeseed and meal. However, according to Kronborg (2006) the dust emission related to rapeseed is insignificant.

From the solvent extraction process there is emission of hexane. There are three sources of hexane emission related to production of crude rapeseed oil; extraction, processing of rapeseed meal and from storage tanks.

Hexane emission from extraction: At AarhusKarlshamn the exhaust gas from the extraction is sent to the power central where it is used as input air to the burning of fuel oil. Hereby, the hexane is converted into water and carbon dioxide. Since the amount of hexane sent to the power central is insignificant compared to the amount of fuel oil used per kg extracted rapeseed oil, it is presumed that there are no emissions related to hexane sent through the power central. According to Aarhus United (2005a) the emission of hexane from extraction was 10.9 tonne. And according to Kronborg (2006) the emission of hexane can be estimated to be constant with operating hours. Since rapeseed oil was extracted 25% of the time in the extractor, the emission related to the production of 26,362 tonne crude rapeseed oil in 2004 (see **Table 9.1**) can be calculated as 0.10 kg per tonne rapeseed oil. However, the emission in Aarhus United (2005a) is given as the output from the extractor. Thus, it is not taken into account that approximately 95% of the time the exhaust gas from the extractor is sent to the power central. Hence, the emission of hexane is 0.0052 kg per tonne crude rapeseed oil.

Hexane emission from processing of rapeseed meal: A considerable share of the input of hexane goes with the meal to final processing. The total emission of hexane from meal processing is 37.1 tonne. This has to be allocated between 35,479 tonne rapeseed meal and 44,094 tonne shea meal (see **Table 9.1**). Thus, the emission of hexane from meal processing is 16.5 tonne in 2004.

The hexane emission related to the production of 26,362 tonne crude rapeseed oil in 2004 (see **Table 9.1**) can then be calculated as 0.63 kg per tonne rapeseed oil.

Hexane emission from storage tanks: This emission comes from the storage of hexane. The emission related to rapeseed oil can be calculated as the use of hexane used for extracting rapeseed oil multiplied with the emission of hexane from storage tanks per kg total used hexane. From Aarhus United (2005a) it can be derived that there is a hexane emission from storage tanks at 46 g per kg hexane used. The consumption of hexane per tonne rapeseed oil is 1.188 kg (see Material use, p 147). Thus, the emission from storage tanks can be found as 0.055 kg per tonne rapeseed oil.

The total emission of hexane from extraction is 0.69 kg per tonne crude rapeseed oil.

9.5 Waste to treatment

There are two waste streams that are sent to treatment. According to Kronborg (2006) the amount of residual from screening of the incoming rapeseed is approximately 0.4% equalling ~10 kg residual per tonne rapeseed oil, also see **Figure 9.2**. The residual is sent to biogas. For inventory data for residual sent to biogas, see section 13.4, where inventory data for bleaching earth sent to biogas are described as well.

According to Kronborg (2006) there were 1,500 m^3 waste water from the extraction process in 2004. Relating to the 26,362 tonne crude rapeseed oil in 2004 (see **Table 9.1**) this corresponds to 57 litres per tonne rapeseed oil. According to Aarhus United (2005a) the content of COD in the waste water is 3,578 mg/l. Hence, 57 litres corresponds to 0.204 kg COD per tonne rapeseed oil.

When waste water is sent to a waste water treatment plant it is treated in order to meet a certain emission limit value defined by environmental legislation. Different properties of the waste water, i.e. quantity and contaminants, affect the interventions at the plant in different ways. Kromann (1996, p 112) has investigated how different properties of the waste water affects the energy use, material use and waste generation (sludge). The findings of that are described in **Table 9.7** and **Table 9.8**.

Waste water	Amount
Waste water	6,850 m3/day
COD	7,800 kg/day
N	650 kg/day
P	190 kg/day

Table 9.7: Overview of composition of waste water to a Danish waste water treatment plant. (Kromann, 1996, p 112)

Waste/co-product	Amount	Determining property
Electricity for pumping	1,094 kWh/day	Determined by the amount of waste water
Electricity for stirring	1,328 kWh/day	Independent
Electricity for air mixing	6,561 kWh/day	Determined by amount of organic compounds, i.e. COD (and N)
Electricity for sludge dewatering	234 kWh/day	Determined by amount of organic compounds, i.e. COD (and P)
Other	156 kWh/day	Independent
Iron sulphate for removal of P	3.6 – 5.4 g/g P	Determined by the amount of P (It is presumed that removal of phosphorus is done by combined biological removal and precipitation with iron sulphate)
Polymers for sludge dewatering	1.5 g/kg COD	Determined by amount of organic compounds, i.e. COD (and P)

Table 9.8: Overview of energy use, material use and waste generation from different properties of waste water. (Kromann, 1996, p 112).

Based on **Table 9.7** and **Table 9.8** and the assumption that air mixing and amount of sludge is dependant on the amount of COD, the interventions per m^3 waste water, per kg P and per kg COD can be found, see **Table 9.9**. It is assumed that N in waste water is equivalent with COD. Thus, the interventions related to removal of N in waste water are included in removal of COD. Since the discharge of P is dependant on emission limit values and not the input of P to the sewage purifying plant, a change in P to the plant will not affect the emission of P. Thus, the marginal emission is 0. The same is the case for COD. Furthermore, the independent interventions at the plant are not affected by the quantity or contaminants of the waste water.

Interventions per m^3 waste water	Amount	Applied LCI-data
Electricity, pumping	0.57 MJ	See **Table 3.3**
Interventions per kg P content	**Amount**	**Applied LCI-data**
Iron sulphate	4.5 kg	‘Iron sulphate, at plant/RER’, ecoinvent (2004)
Interventions per kg COD	**Amount**	**Applied LCI-data**
Electricity for air mixing	3.0 MJ	See section 3.1
Electricity for sludge dewatering	0.1 MJ	See section 3.1
Polymers for sludge dewatering	1.5 g	No inventory data have been identified

Table 9.9: Life cycle inventories for the quantity and contaminants of waste water.

9.6 Overhead

Overhead includes electricity and heat for administration and research and development. It is not possible to establish a direct relationship between interventions from overhead and the production of refined rapeseed oil and rapeseed meal. This is because there are no direct linkages between production processes and overhead activities and because intermediate products are both purchased at and delivered from different stages in the oil mill, see **Figure 9.4** below.

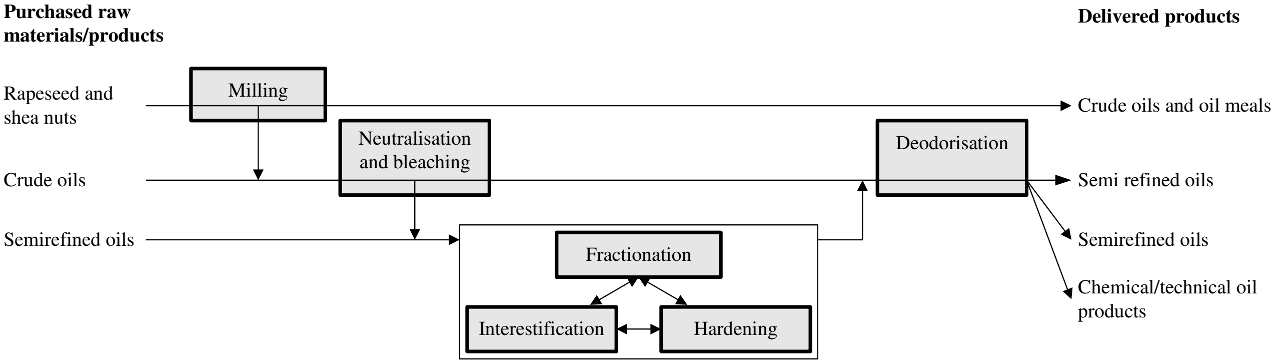


Figure 9.4: Simplified overview of processes and flow of products at AarhusKarlshamn.

Production of refined rapeseed oil includes milling, neutralisation, bleaching and deodorisation in **Figure 9.4**. Since it is not possible to establish a direct relationship between interventions from overhead and the production of refined rapeseed oil a presumed proportion of the interventions from overhead activities is used. This proportion could be estimated based on turnover, mass or other properties. It has not been possible to obtain data on turnover distributed on all AarhusKarlshamn's products. Thus, allocation could be based on mass of delivered products. For milling, rapeseed oil and meal constitute approximately 40% of the product flow. For the other processing stages it is difficult to find these numbers because the input of crude oils and semi refined oils in some cases are mixtures of different oils. However, mass allocation do reflect a causal in a wrong way; most work in laboratories, administration, marketing etc. is related to highly modified speciality oils. Therefore instead it is chosen to derive allocation factors based on the number of processing stages and products produced at AarhusKarlshamn. It is very roughly estimated that 10% of the interventions from administration, marketing, laboratories etc. can be ascribed to milling, 10% to refining and 80% to modification of oils. Three oils constitute the main oils used at AarhusKarlshamn; rapeseed oil, shea oil and palm oil. However, only two oil seeds are milled, i.e. rapeseed and shea. The outputs are then two different oils and two different meals. Thus, crude rapeseed oil's proportion of the overhead activities is determined as 25% of the 10%. Hence, the proportion related to rapeseed activities can be estimated as 2.5%.

According to Aarhus United (2005b) electricity consumption for administration and laboratories was approximately 1220 MWh in 2004. Using above determined allocation factor, the electricity consumption for overhead related to rapeseed oil can be estimated as 60 MWh in 2004. Relating abovementioned electricity use to the annual production of rapeseed oil in 2004 at 26,362 tonne shown in **Table 9.1**, the specific electricity use can be found as 4 MJ/t oil. This amounts approximately 1% of the total electricity consumption for production of crude rapeseed oil at AarhusKarlshamn, see **Table 9.13**.

Heat consumption for administration and laboratories was approximately 550 MWh in 2004 (Aarhus United, 2005b). Using abovementioned allocation factor and values in **Table 9.1** the heat consumption can be found as 2 MJ/kg rapeseed oil. Administration buildings and laboratories are heated with municipal district heat. Interventions from district heating in Aarhus are described in section 3.6.

9.7 Capital goods

Capital goods include means of production, i.e. buildings and machinery. According to Althaus et al. (2003) the environmental burden from capital goods for production of chemicals are of minor importance compared to other processes. Analysing capital goods' share of the total burden from different oil mills inventoried in ecoinvent (2004), the contributions from capital goods do not seem to be insignificant, see **Table 9.10**.

Chemical plant's share of environmental burden from oil mill	Soybean oil mill	Palm oil mill	Palm kernel oil mill	Coconut oil mill
Global warming	7%	5%	3%	8%
Acidification	13%	13%	6%	20%
ETWC, m^3 water	19%	31%	13%	49%

Table 9.10: The environmental burden from capital goods compared to the total environmental burden from activities at different oil mills. Production of oil seeds, fruits and nuts is not included. The results are found analysing the inventory in Simapro and using the EDIP97 method for LCIA. LCI databases from ecoinvent (2004) are used.

However, the great contributions to toxicity are infected with significant uncertainties and errors. A major part of the contributions originates from long term emissions of especially copper from disposal of electronics used in control units in the plant. These emissions are calculated in a time frame of several thousands years. There is no consensus in the LCA community on the time frame to be used for long term emissions. Hansen et al (2004) suggest that effects from long term emissions should be dealt with as separate impact categories.
Another important contribution to toxicity is emission of iron to air. This originates from production of hard coal coke used as fuel for production of machinery and buildings. However, the emission of iron is approximately 10 kg per 1 kg coal. According to personal communication with Bauer (2005) this is due to an error in ecoinvent by six orders of magnitude.

Not many life cycle inventories of buildings and machinery exist, only one has been identified; ecoinvent (2004). Since it is not possible to obtain detailed data on building materials, foundations, machinery etc. from oil mills in Denmark, the inventory of capital goods will be rather roughly and based on ecoinvent (2004). The data in ecoinvent are described in detail in Althaus et al. (2003) where capital goods are divided into three categories: 1) Building, hall, 2) Building, multi story and 3) Facilities, chemical production. The inventories of buildings are described in Kellenberger et al. (2003) and facilities in Althaus et al. (2003). The amount of building, hall used is measured in m^2. Building, multi story is measured in m^3 and facilities are measured as average composition of chemical production facilities per kg of the facility. In Althaus et al (2003) facilities mainly consist of distillation units and minor amounts of pipes and control units (electronic equipment). Disposal of buildings and facilities is included in the used inventories.

Using the life cycle inventories for capital goods from ecoinvent (2004) it is only necessary to collect data on the area and volume for building halls and multi story buildings respectively and weight of the facilities used for pressing, extraction and refining. The used data sets in ecoinvent are: '*Building, hall, steel construction*', '*Building, multi-storey*' and '*Facilities, chemical production*'.

Oil mill buildings

The area covered by buildings is estimated from the municipal district plan for the current district (Århus Kommune 2004).

Pressing and extraction: The buildings for pressing and extraction cover approximately 2000 m^2 and silos for storage of nuts and seeds cover approximately 300 m^2. Thus, the buildings for storage of raw material and pressing and extraction are estimated as 2,300 m^2 building hall. An average life time of building halls is estimated to 50 years. The annual amount of extracted oil at AarhusKarlshamn is approximately 50,000 tonne. Hence the building hall required per kg of pressed and extracted oil can be determined as approximately $9.2 \cdot 10^{-4}$ m^2 building hall/t oil.

Overhead: Administration buildings cover an area of approximately 2,500 m^2. In average these buildings are four storey buildings with an estimated height of 15 m. Thus, administration buildings are estimated to be at 37,500 m^3 multi story building. Applying the allocation factor at 0.22 for overhead described in section 9.6 the buildings for overhead related to rapeseed oil can be estimated as 8,300 m^3 multi story building. As the other buildings the life time is estimated to be 50 years. Relating the 8,300 m^3 multi story building to the annual production of rapeseed oil at approximately 50,000 tonne, the specific requirement of buildings for overhead can be found as $3.3 \cdot 10^{-3}$ m^3 multi story building/t oil. However, since all rapeseed oil produced is also refined the $3.3 \cdot 10^{-3}$ m^3 multi story building/t oil is related to the oil mill as well as the refinery. Therefore, half of this is ascribed to the oil mill and the other half to the refinery. Thus, the area of administration buildings related to the oil mill process for rapeseed oil at AarhusKarlshamn has been estimated as $3.3 \cdot 10^{-3}$ m^3 multi story building/t oil divided by 2, i.e. $1.7 \cdot 10^{-3}$ m^3 multi story building/t oil.

Oil mill machinery (facilities)

The weight of machinery is very roughly estimated from personal communication with Kronborg (2006). The relevant numbers are given in **Table 9.11**.

Process	Weight of machinery incl. pipes	Estimated life time	Annual production	Machinery (kg) per kg oil
Press and extraction	100 tonne	10 years	50,000 tonne	0.20 kg/t oil

Table 9.11: Required machinery (kg) per t oil produced at AarhusKarlshamn. Numbers are based on very rough estimates.

Determination of capital goods is regarded as very uncertain. Therefore a sensitivity analysis is carried out in section 21.17.

9.8 Transport of raw materials and ancillaries to rapeseed oil mill

Rapeseed and ancillary materials are transported with lorry to AarhusKarlshamn. Inventory data per tkm transport by lorry is described in section 4.1. The transport distances are estimated in this section. Since there are several suppliers and since there is a general lack of data on the specific marginal affected supplier, all transport distances are based on rough estimates. Determination of size of lorries is based on **Table 4.3**.

Material	Amount to AarhusKarlshamn	Amount per t crude rapeseed oil	From	To	Distance	Lorry size
Rapeseed	~60,000 t/year	2.387 t	Seed traders, Denmark	Aarhus	100 km	40t
Light fuel oil	~36,000 t/year	44.7 kg	Fuel oil supplier, Denmark	Aarhus	10 km	28t
Hexane	~158 t/year	1.19 kg	Abroad chemical plant	Aarhus	1000 km	40t
Rapeseed residual	~260 t/year	10 kg	Aarhus	Biogas plant	30 km	28t
Rapeseed meal	~34,000 t/year	1.346 t	Aarhus	Meal trader	10 km	28t

Table 9.12: Transport distances of the used raw materials and ancillaries in the oil mill stage. The return trip is included in the inventory data.

Transport of the rapeseed oil to the refinery is included in the refinery stage in section 13.

The amount of rapeseed in the column ‘Amount to AarhusKarlshamn’ in **Table 9.12** is based on **Table 9.1**. The amount of light fuel oil is estimated from a fuel use at 409,748 MWh at AarhusKarlshamn in 2004 (Aauhus United 2005b). With a calorific value at 40.6 MJ/kg (Appendix 1: Data on fuels) this corresponds to 36,000 tonne fuel oil. The amount of hexane is given in Aarhus United (2005a) and the amount of rapeseed residual is calculated from **Table 9.1** and **Table 9.13**. The amounts given in the column ‘Amount per t crude rapeseed oil’ are calculated from **Table 9.13**.

9.9 LCI of rapeseed oil mill, summary

Table 9.13 summarises the inventory data relating to 1 kg crude rapeseed oil produced at AarhusKarlshamn.

Denmark: 1.000 t crude rapeseed oil from oil mill					
Interventions	**Power central**	**Pressing and extraction**	**Overhead**	**Total**	**Applied LCI data**
Product output					
Crude rapeseed oil	-	1.000 t	-	**1.000 t**	**Product of interest**
Rapeseed meal	-	1.346 t	-	**1.346 t**	Co-product allocation is avoided by system expansion, see **Table 2.3**
Material use					
Rapeseed	-	2.387 t	-	**2.387 t**	See **Table 5.48**
Hexane	-	1.188 kg	-	**1.188 kg**	‘Pentane, at plant’ (ecoinvent 2004)
Energy use					
Electricity	-	419 MJ	4 MJ	**423 MJ**	See **Table 3.3**
Heat (steam)	-	1,586 MJ	-	**1,586 MJ**	See **Table 9.4**
Heat (district heat)	-	-	2 MJ	**2 MJ**	See section 3.6
Emissions to air					
Hexane	-	0.69 kg	-	**0.69 kg**	Emission to air
Waste to treatment					
Waste water, quantity	-	57 ltr.	-	**57 ltr.**	See **Table 9.9**
Waste water, COD	-	0.204 kg	-	**0.204 kg**	See **Table 9.9**
Rapeseed residual to biogas	10 kg	-	-	**10 kg**	See **Table 13.8**
Capital goods					
Building halls	-	$9.2\cdot10^{-4}$ m^2	-	**$9.2\cdot10^{-4}$ m^2**	*‘Building, hall, steel construction’* (ecoinvent 2004)
Building, multi story	-	-	$1.7\cdot10^{-3}$ m^3	**$1.7\cdot10^{-3}$ m^3**	’*Building, multi-storey’* (ecoinvent 2004)
Machinery	-	0.20 kg	-	**0.20 kg**	‘*Facilities, chemical production*’, (ecoinvent 2004)
Transport of raw materials and ancillaries to oil mill					
Rapeseed, 40t lorry	-	238.7 tkm	-	**238.7 tkm**	‘*Transport, lorry 40t*’ (ecoinvent 2004)
Fuel oil	0.45 tkm	-	-	**0.45 tkm**	‘*Transport, lorry 28t*’ (ecoinvent 2004)
Hexane	-	1.19 tkm	-	**1.19 tkm**	‘*Transport, lorry 40t*’ (ecoinvent 2004)
Rapeseed residual	-	0.3 tkm	-	**0.3 tkm**	‘*Transport, lorry 28t*’ (ecoinvent 2004)
Rapeseed meal	-	13.5 tkm	-	**13.5 tkm**	‘*Transport, lorry 28t*’ (ecoinvent 2004)

Table 9.13: Interventions per t crude rapeseed oil.

10 Oil mill stage: Palm oil

The LCI for the palm oil mill stage represents palm oil milling in Malaysia 2003 to 2005. For some processes alternative technologies and practices exist.

There are different influential factors on the interventions and thereby the environmental impact related to the production of palm oil in the palm oil mill. Some of these factors are related to uncertainties in data and some are related to improvement options. The considered factors are: 1) technology for treating palm oil mill effluent (POME), 2) required steam consumption in the palm oil mill and 3) the utilisation/waste treatment of empty fruit bunches (EFB). Regarding 1) the most common technology for treating POME is open anearobic and aerobic ponds. Therefore this is applied as the technology in the baseline scenario. The alternative technology which is installing of digester tanks for biogas capturing and subsequent utilisation of biogas is considered as an improvement option (see section 21.18). Relating to 2) different studies show different amounts of required steam in the palm oil mill process. Steam consumption at 0.65 tonne is applied in the baseline scenario in this study while 0.5 tonne is applied in a sensitivity analysis in order to analyse the effect of uncertainty in data (see section 21.19). Concerning 3) the three main treatments of EFB are: application as mulch in the plantation, landfilling near the palm oil mill and utilisation as biofuel for electricity production (UNFCCC 2007). In the past open burning was applied as treatment of EFB, but this management option is now banned (UNFCCC 2007). Appilcation as mulch is the most likely management option and is therefore used in the baseline scenario (Corley and Tinker 2003, p 376). The effects of the two other options are analysed in a sensitivity analysis (see section 21.20). The alternative treatments of EFB are regarded as potential improvement options.

The inventory of the oil mill stage is mainly based on data collected with United Plantation Berhad's Research Department (Singh 2006), data provided by MPOB (Subranamiam 2006a) and general literature on oil palm processing; Singh et al. (1999) and Department of Environment (1999).

10.1 Palm oil mill product flow

Figure 10.1 shows the product flows through the oil mill. The oil mill stage is divided into the four unit processes shown as grey shaded boxes in **Figure 10.1**.

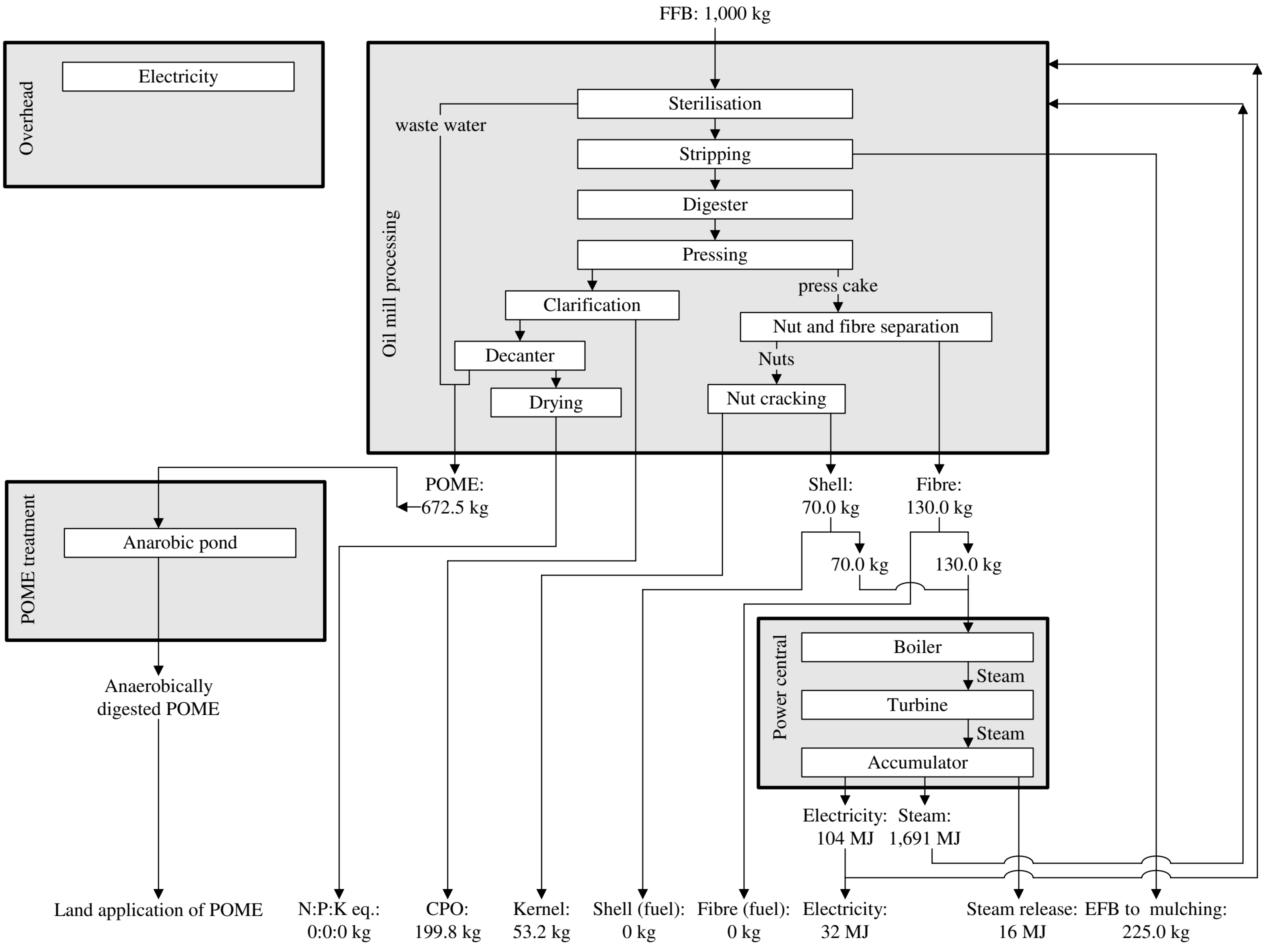


Figure 10.1: Product flow related to processing of 1 tonne FFB in the palm oil mill. The grey shaded boxes represent the unit processes in the palm oil mill stage.

It appears from **Figure 10.1** that the palm oil mill has several product outputs. The production of crude palm oil (CPO) and kernel per tonne of FFB is determined as the Malaysian average in 2003 to 2005 given in MPOB (2005) and MPOB (2006), see **Table 10.1**. Malaysian national figures on the product flows of mesocarp fibre, shell, EFB and POME per tonne of processed FFB in 1996 and 2002 are shown in **Table 10.2**, where the applied numbers are the average of 1996 and 2002 figures.

Oil mill products	2003	2004	2005	Applied
CPO	197.5 kg/t FFB	200.3 kg/t FFB	201.5 kg/t FFB	199.8 kg/t FFB
Kernel	53.6 kg/t FFB	52.5 kg/t FFB	53.4 kg/t FFB	53.2 kg/t FFB

Table 10.1: Crude palm oil (CPO) and kernel production per tonne of processed FFB in 2003 and 2004 (MPOB 2005) and 2005 (MPOB 2006). The numbers represent Malaysian national figures.

Oil mill co-product	1996	2002	Applied
Fibre	120.0 kg/t FFB	140.0 kg/t FFB	130.0 kg/t FFB
Shell	70.0 kg/t FFB	70.0 kg/t FFB	70.0 kg/t FFB
EFB	220.0 kg/t FFB	230.0 kg/t FFB	225.0 kg/t FFB
POME	670.0 kg/t FFB	675.0 kg/t FFB	672.5 kg/t FFB

Table 10.2: Mesocarp fibre, shell, EFB and POME per t FFB in 1996 (Singh 1999) and in 2002 (Ma et al. 2004). The numbers represent Malaysian national figures.

The oil mill has its own power and steam supply. The power central is fuelled with some of the fibre and shell from the processing. Subranamiam et al. (2005) present the amount of fibre and shell used as fuel in the mill's power central for six palm oil mills per tonne of FFB. According to Subranamiam et al. (2005) an average 82%

of the fibre and 55% of the shells are fed into the boiler, while Weng (1999) suggests that 90% of the fibre and 80% of the shells are used as boiler fuel. According to Subranamiam et al. (2005) excess of fibre and shell are sold out as fuel. The energy production and related emissions from burning of fibre and shell in the power central is described in section 10.3.

According to Singh and Thorairaj (2006) and Subranamiam et al. (2005) the steam requirement for processing of 1 tonne FFB is 0.65 tonne at 3 bar equalling 1,691 MJ.

The figures provided in Subranamiam et al. (2005) seem to be too low since the burning of 82% of the fibre and 55% of the shell only amount to an energy input of 1,919 MJ/t FFB[18]. This would require steam to fuel input ratio (efficiency) at 88%, which exceeds likely levels: Husain et al. (2003) specifies steam to fuel input ratio for co-generating heat and power plants in palm oil mills ranging from 50.7% to 72.7%, averaging 61.8%. Also, the boiler fuel input provided by Weng (1999) seems to be too low. Applying the boiler fuel input given by Weng (1999) the energy input is 2,359 MJ. This would require steam to fuel input ratio at 72% which is also slightly higher than a likely level. The reason why the fuel inputs suggested by Subranamiam et al. (2005) and Weng (1999) are too low is probably that the steam requirement at 0.65 t per t FFB is high compared to average palm oil mills. Hence, Chavalparit et al. (2006) report steam consumption at 0.4 t/t FFB and according to Singh and Thorairaj (2006) the steam consumption in some mills may be as low as 0.45 – 0.50 t steam/t FFB. The 0.65 tonne provided by Singh and Thorairaj (2006) includes steam for drying of nuts/kernels and less steam demanding drying decanted effluent (processed into organic fertiliser), which are not done in most mills. Still, the steam requirement of 0.65 t per t FFB is applied in this study. This is because nut/kernel drying has to be done elsewhere if not done in the oil mill. The overall result is then the same no matter if drying is done in the oil mill using more fibre and shell for fuel, or elsewhere using other fuel for drying while the excess fibre and shell also displace other fuels. In order to assess uncertainties relating the the steam reqiremet, a sensitivity analysis with steam requirement at 0.5 t steam (1,301 MJ) has been carried out, see section 21.19.

With available fuel energy of fibre and shell at 2,763 MJ and a steam to fuel input ratio at 61.8%, the produced steam amounts to 1,708 MJ (0.66 t steam at 3 bar). This is very close to the required 0.65 t steam. Therefore it is assumed that all of the fibre and shell is used as boiler fuel.

10.2 Omitted inventory data in palm oil mill stage

Minor amounts of chemicals are used in POME treatment. No information has been identified on these chemicals. Therefore they are not included. Since lubricating oil is not included in the inventory of the rapeseed oil mill, it has also been excluded from the inventory of the palm oil mill. Also consumption of varies minor products such as tools, paper, computers, pencils, miscellaneous equipment etc. for process management and administration are omitted.

10.3 Power central

The energy supply to the oil mill includes electricity and steam. Most, if not all, palm oil mills are self sufficient of electricity and heat (Henson 2004, p 30). Normally, fibre and shells are burned for energy purposes (Henson 2004; Department of Environment 1999; Subranamiam 2005). According to section 10.1 the utilisation of fibre and shell for boiler fuel are assumed to be 100%. Thus, 130.0 kg fibre and 70.0 kg shell are burned per tonne of FFB processed. Fibre and shell have calorific values 19.1 MJ/kg DS and 20.1 MJ/kg (dry matter basis) respectively (Subranamiam et al. 2004). The moisture content of fibre and shell are 40% and 10% respectively (average of values given in Singh 1999, Yosoff 2006, Ma et al. 2004 and Yosof and Weng 2004).

---

[18] The applied calorific values (dry matter basis) and moisture contents are given in section 10.3.

The calorific value of the fuel composition of 65% fibre and 35% shell can be determined as 13.8 MJ/kg. Hence, the total energy input per tonne of FFB processed is 2,763 MJ.

Husain et al. (2003) have surveyed seven palm oil mills where utilisation factors[19] range between 55.0% and 76.6%, averaging at 65.6%. The average heat to power ratio of the seven palm oil mills is 17.9. Thus, the total heat and power production per t FFB is 1,811 MJ or 0.70 t steam at 3 bars[20] (65.6% of 2.763 MJ) distributed on 1,708 MJ steam and 104 MJ electricity. Above calculated production of 0.70 t steam per t FFB and 104 MJ electricity per t FFB are in good accordance with figures on steam and electricity production per t FFB at United Plantation Berhad. These figures show 0.72 t steam/t FFB and 97 MJ electricity (Singh and Thorairaj 2006). At United Plantations Berhad all fibre and shell are burned corresponding to the assumptions in this study.

It is common that excess steam is released to the atmosphere (Subranamiam 2006a; Kandiah et al. 1992). Therefore, the difference between the required steam (1,691 MJ) and the produced steam (1,708 MJ) is assumed to be released to the atmosphere, i.e. 16 MJ per t FFB.

The electricity recovered from the turbine, i.e. 104 MJ/t FFB or 28.9 kWh/t FFB, exceeds the requirement for processing the FFB. The required electricity for processing 1 tonne of FFB varies between 14.5 kWh (Chavalparit et al. 2006) through 17.7 KWh (Yusoff and Hansen 2005) to 18-22 kWh (Singh and Thorairaj 2006) and 20 kWh (Ma et al. 2004). The average requirement is assumed to be 20 kWh per t FFB. Thus, there is approximately 30% electricity in excess, i.e. 32 MJ/t FFB. In addition to that additionally 1 MJ/t FFB is assumed to be used in administration, research, laboratories etc. buildings, see section 10.7. Since palm oil mills are not connected to the national grid, the excess electricity is normally used locally on the estate in administration buildings, residence buildings for the workers and sometimes in a refinery if the estate has its own refinery plant. But since these buildings are connected to the national grid or to local generators, the excess electricity is assumed to displace electricity delivered from the grid. Interventions related to electricity production in Malaysia are described in section 3.2.

In addition to the input of 130 kg fibre and 70 kg shell per t FFB the power central uses fossil fuel for start-ups of the boiler. According to Subranamiam et al. (2005) oil mills uses 0.37 litre of diesel per t FFB (average of six palm oil mills). It is assumed that this is used in the power central. According to ‘Appendix 1: Data on fuels’, 0.37 litres of diesel per t FFB corresponds to 14 MJ/t FFB. The emissions from burning of 14 MJ diesel per t FFB are obtained from ecoinvent: ‘*Diesel, burned in building machine*’, documented in Kellenberger et al. (2003). Since production, maintenance and disposal of the power central is included in section 10.8, the data set ‘*Diesel, burned in building machine*’ is modified so that it only includes the production of diesel and related emissions from burning it and thereby not the building machine itself and its maintenance. It is assumed that the steam produced during start-up is insignificant because of low boiler efficiency at low temperatures and because the energy input of diesel is negligible compared to energy from fibre and shell. Therefore, the produced steam from burning of diesel for start-up is not accounted for.

The water consumption for steam production is assumed to be equivalent to the steam produced, i.e. 0.65 t/t FFB. For water, it is assumed that the interventions related to water in Malaysia are the same as in Denmark.

---

[19] Utilisation factor of co-generating system is the total output of power en delivered heat divided by the total fuel energy input.

[20] Ma et al. (2004) specify energy content at 2.604 MJ/kg steam at 3 bars.

The energy and material use pr. m^3 water are very low; 1.3 MJ electricity/m^3 and 4.5 g chemicals/m^3 (see **Table 13.5**). Thus, this assumption may only cause insignificant impacts on the result.

Emissions related to the burning of fibre and shell

There exist only few inventory data on the burning of fibre and shell. Subranamiam et al. (2005) is the only existing inventory on boiler emissions from palm oil mills identified. Yusoff and Hansen (2005) regard emissions from the burning of wood in small boilers as representative for the burning of fibre and shell. In addition to the two existing data sets on stack emissions from palm oil mills emissions are calculated from figures given in an environmental audit report from United Plantations Berhad (2005).

The emissions in United Plantations Berhad (2005) are all given as concentrations in the flue gas, see **Table 10.3**. The desired data format is emissions per kg fuel (fibre and shell). This conversion is done based on the carbon content in the boiler fuel and the carbon in CO_2 concentration in the stack flue gas. The carbon content of the boiler fuel on dry matter basis is 41% and 52% of fibre and shell respectively (Henson 2004, p 22). The moisture content of fibre and shell are given previously in this section; 40% for fibre and 10% for shell. The distribution between fibre and shell used as boiler fuel is given in **Figure 10.1** as 65% fibre and 35% shell. From these figures it can be calculated that 1 kg boiler fuel (fibre and shell) contains 0.325 kg C. Relating to the CO_2 concentration of the flue gas given in **Table 10.3**, assuming that all the carbon in the fuel is converted to CO_2 and applying the ratio 3.67 kg CO_2 per kg C burned (based on molar masses and chemical reaction of carbon with oxygen), it can be calculated that 1 kg boiler fuel gives 33.1 kg flue gas. Then it is easy to convert the concentration of substances in the stack flue gas into absolute numbers per kg boiler fuel. The values are given for the relevant substances in the right column in **Table 10.3**.

Emissions	Concentration (w/w%)	Emission (g/kg boiler fuel)
CO_2	3.6%	1,190.000 g
SO_2	0.00005%	0.017 g
NO_2	0.00005%	0.017 g
NO	0.0101%	3.339 g
CO	0.0154%	5.092 g
N_2	80.2%	-
O_2	16.2%	-
Total	**100%**	**-**

Table 10.3: Stack flue gas emissions from Ulu Bernam Palm Oil Mill. The measures of concentration of substances are converted into emissions per kg boiler fuel (fibre and shell). Concentrations of substances in stack flue gas are obtained from United Plantations Berhad (2005, p 10).

The calculated emissions based on measured stack flue gas emissions in Ulu Bernam Palm Oil Mill, United Plantations Berhad are compared with stack emissions obtained from Subranamiam et al. (2005) and Yusoff and Hansen (2005) in **Table 10.4**. Since the identified inventories of palm oil mill stack emissions only include NO_x, SO_2 and CO, the remaining emissions are estimated from an inventory of burning of wood chips burned in 50 kW furnaces in Europe. Data for burning of wood chips are obtained from the ecoinvent database (Bauer 2003) and the data are treated in SimaPro 7.0.

Emissions	Emissions from burning of 1 kg boiler fuel (g/kg fuel)				
	Based burning of fibre and shell		Based on burning of wood		Applied
	Calculated (Table 10.3)	Subranamiam et al. (2005)	Yusoff and Hansen (2005)	Burning of wood chips (Bauer 2003)	
NO_x	3.356	0.175	0.552	1.050	1.361
SO_2	0.017	0.002	0.017	0.024	0.012
CO	5.092	0.104	4.862	1.120	3.353
Particulates < 2.5 um	-	-	1.190	0.324	0.757
Acetaldehyde	-	-	-	5.810E-04	5.810E-04
Ammonia	-	-	-	0.017	0.017
Arsenic	-	-	-	9.520E-06	9.520E-06
Benzene	-	-	-	8.670E-03	8.670E-03
Benzene, ethyl-	-	-	-	2.860E-04	2.860E-04
Benzene, hexachloro-	-	-	-	6.860E-11	6.860E-11
Benzo(a)pyrene	-	-	-	4.760E-06	4.760E-06
Cadmium	-	-	-	6.670E-06	6.670E-06
Chlorine	-	-	-	1.710E-03	1.710E-03
Chromium	-	-	-	3.770E-05	3.770E-05
Chromium VI	-	-	-	3.810E-07	3.810E-07
Copper	-	-	-	2.100E-04	2.100E-04
Dinitrogen monoxide	-	-	-	0.029	0.029
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	-	-	-	2.950E-10	2.950E-10
Formaldehyde	-	-	-	1.240E-03	1.240E-03
Hydrocarbons, aliphatic, alkanes	-	-	-	8.670E-03	8.670E-03
Hydrocarbons, aliphatic	-	-	-	0.030	0.030
Lead	-	-	-	2.380E-04	2.380E-04
m-Xylene	-	-	-	1.140E-03	1.140E-03
Manganese	-	-	-	1.620E-03	1.620E-03
Mercury	-	-	-	2.860E-06	2.860E-06
Methane	-	-	-	6.670E-03	6.670E-03
Nickel	-	-	-	5.710E-05	5.710E-05
NMVOC	-	-	-	8.570E-03	8.570E-03
PAH	-	-	-	1.060E-04	1.060E-04
Phenol, pentachloro-	-	-	-	7.710E-08	7.710E-08
Phosphorus	-	-	-	2.860E-03	2.860E-03
Toluene	-	-	-	2.860E-03	2.860E-03
Zinc	-	-	-	2.860E-03	2.860E-03

Table 10.4: Comparison of stack flue gas emissions from palm oil mills from different sources. The first two columns are based on measurements in palm oil mills, while the figures obtained from Yusoff and Hansen (2005) and Bauer (2003) are based on burning of wood chips. The applied data are marked with a black dotted frame.

The applied data in **Table 10.4** are the average of the three inventories on palm oil mill stack emissions while the remaining emissions are obtained from the inventory of burning of wood chips.

Waste to treatment/co-products from power central

Ash from burning of fibre and shell in the boiler is normally used as road material in the plantation. The ash contents of fibre and shell are 6.1% and 3.0% dry matter basis respectively (Ma et al. 2004). Applying the moisture contents at 40% for fibre and 10% for shell, the ash contents on fresh weight basis are 3.7% for fibre and 2.7% for shell. Thus, based on the product flows given in **Figure 10.1**, each kg fibre and shell burned generates 0.34 kg ash. It is assumed that the ash used for road material displaces a corresponding alternative road material, i.e. sand. The interventions from sand and gravel production are obtained from ecoinvent: '*Sand, at mine*', documented in Kellenberger et al. (2003).

10.4 Palm oil mill processing: Pressing, drying etc.

The main processes in the oil mill process (see **Figure 10.1**) include sterilisation, stripping, digestion, pressing, clarification of the oil and water mix, decantering of the waste water, nut treatment and drying processes. The inputs to and outputs from the system from the oil mill process include steam and electricity from the power central, diesel for vehicles, lubricating oil and electricity from the grid. The interventions related to treatment of POME are described in section 10.5. In addition to the desired product from the palm oil process, crude palm oil, there are various co-products, see **Figure 10.1**. The product substitutions from these co-products are described in section 10.6.

Material use

According to Chavalparit (2006) and UPRD (2004) the total water consumption per t FFB is 1.26 t and 1.47 t[21] respectively. The average at 1.37 t/t FFB is assumed to be representative. The water consumption in the oil mill processing stage is then 1.37 t/t FFB minus the water consumption in the power central at 0.65 t, i.e. 0.72 t/t FFB. As described in section 10.3 it is assumed that the interventions related to water in Malaysia are the same as in Denmark, see **Table 13.5**.

According to section 10.2 lubricating oil is excluded from the inventory of the palm oil mill. According to Singh, the use of lubricating oil at United Plantations six palm oil mills in 2005 were 0.053 litre/t FFB. Assuming a density at 0.9 kg/litre this corresponds to 0.048 kg/t FFB. Applying an oil extraction rate of 19.98% the use of lubricant oil amounts 10 g/t CPO which is regarded as insignificant.

Energy use

The energy uses in the palm oil mill are shown in **Table 10.5**.

---

[21] Applying OER at 21% for 2004 in accordance with United Plantation Berhad (2006).

Energy	Amount/t FFB	Source	Applied inventory data
Steam from power central	1,691 MJ	(Singh and Thorairaj; Subranamiam et al. 2005)	Emissions are included in the unit process: 'Power central', see section 10.3
Electricity from power central	72 MJ	See section 10.3	Emissions are included in the unit process: 'Power central', see section 10.3
Diesel for vehicles	7.6 MJ	Average of six palm oil mills (Subranamiam et al. 2005)	'*Diesel, burned in building machine* (ecoinvent 2004)'
Electricity from the grid	0.8 MJ	Average of six palm oil mills (Subranamiam et al. 2005)	See section 3.2

Table 10.5: Energy use per t FFB in the unit process: Oil mill processing.

10.5 POME treatment

There are great differences of how palm oil mill effluent (POME) is treated in different palm oil mills. Before 1978 palm oil mills in Malaysia discharged their effluent untreated directly into nearby water courses. After introduction of the Environmental Quality Act (EQA 2005) in 1975 and the related specific regulations on palm oil mill effluent (EQ crude palm-oil regulations 2005) the emission limit value of BOD has gradually been reduced from 25,000 mg/litre in the 70ies to 100 mg/litre after 1984 (Chun and Jaafar 2005; EQ crude palm-oil regulations 2005, p 59). Because of the high content of nutrients in POME, focus on utilisation as land application has been increasing (Lim et al. 1999). But also high emission levels of the green house gas methane from the anaerobic treatment have been in focus. Several CDM projects within the Kyoto framework have been carried out implementing a digester tank with subsequent utilisation of the captured biogas instead of anaerobic lagoons. The effect of this technology is assessed in a sensitivity analysis presented in section 21.18.

There are three main sources of POME in the palm oil mill: steriliser condensate (36% of total POME), clarification waste water (60% of total POME) and hydro cyclone waste water from nut and fibre separation (4% of total POME) (Department of Environment 1999). Some oil mills extract a considerable share of the solids of POME with a decanter prior to POME treatment, see **Figure 10.1**. This decanter cake can be mixed with inorganic fertilisers and sold or it can be used as animal feed (Singh and San 2002). However, it is not common practice to derive sludge solids with a decanter.

The composition of POME is given in **Table 10.6**.

Component	Steriliser condensate	Clarification waste water	Hydro cyclone waste water	Mixed POME
Dissolved solids (g/kg)	34	22	100	40.5
N (g/kg)	0.500	1.200	0.100	0.950
P (g/kg)	-	-	-	0.150
K (g/kg)	-	-	-	1.960
BOD (3 day, 30°C), (g/kg)	23.000	29.000	5.000	25.000
Cu (g/kg)	-	-	-	0.0009
Zn (g/kg)	-	-	-	0.0023

Table 10.6: Composition of POME from the three most important sources in the oil mill (Department of Environment 1999, p 26-28). The given numbers in Department of Environment (1999) are in units of mg/litre. Since the moisture content of POME is 95% (Singh 1999) it is assumed that the density of POME is 1 kg/litre.

After recovering residual oil in the waste water using oil traps etc., the POME is treated in an anaerobic pond, see **Figure 10.2**. After that, the treated POME meets the regulatory requirements of a maximum BOD at 5,000 mg/litre[22] for land application (EQ crude palm-oil regulations 2005, p 55). **Figure 10.3** shows a land application system.

Figure 10.2: Pond for anaerobic treatment of POME (Picture taken in United Plantation Berhad 2006).

Figure 10.3: Land application of treated POME (Picture taken in United Plantation Berhad 2006).

Table 10.7 shows POME characteristics before and after anaerobic digestion and the table is used for estimating the removal of nitrogen during treatment. However, a minor part of the removed nitrogen is fixed in the sludge solids from digested POME. Sludge solids are removed in the desludging operation to avoid sludge to build-up in the ponds and are used locally as fertiliser. No figures on the amount of sludge solids per kg of POME have been identified. However, the amount of N in the sludge is regarded as insignificant because a great share will removed by denitrification due to long storage time on the bottom of the pond under anaerobic conditions. Therefore, it is assumed that the amount of nitrogen fixed in the accumulative build-up of slurry in the bottom of the pond is negligible. Since content of phosphorus and potassium is not changed chemically during the process, the remaining P and K is assumed to be in the bottom slurry, see **Table 10.7**.

Component	Raw POME	Anaerobically digested POME	Assumed figures for bottom slurry
BOD (3 day, 30°C), (kg/t POME)	25.000	1.300	-
N (kg/t POME)	0.950	0.900	0
P (kg/t POME)	0.150	0.120	0.030
K (kg/t POME)	1.960	1.800	0.160

Table 10.7: POME characteristics before and after anaerobic digestion (Department of Environment 1999, p 28).

It appears from **Table 10.7** that 0.05 kg N per t POME is removed. The removed N should be distributed on NH_3 and denitrified N: N_2O and N_2. No inventories on N-related emissions from POME treatment have been identified. Thus, the removed N is estimated from figures on storage of manure.

According to IPCC (2000, p 4.43) 0.1% of the N in manure stored in anaerobic lagoons denitrifies as N_2O. This corresponds to 0.1% of 0.950 kg N/t POME = 0.00095 kg N_2O-N/t POME. 0.00095 kg N_2O-N/t POME corresponds to 0.0015 kg N2O/t POME. It appears that 0.00095 kg N_2O-N/t POME is insignificant (1.9%) compared to the total removed N at 0.05 kg N/t POME. Based on that, the amount of denitrified N_2 is also assumed to be insignificant and therefore, the total amount of N removed by denitrification is assumed to be 3.8% with equal shares of N_2O-N and N_2-N.

---

[22] BOD (3 day, 30°C)

According to Mikkelsen et al. (2005, p 36) 9% of stored N from pigs and 6% of stored N from cattle volatizes as NH_3 during storage in open uncovered manure tanks. Applying these figures to the N content of POME at 0.95 kg N/t POME gives volatilization of 0.057 – 0.086 kg N/t POME. This is more than the removed N at 0.05 kh N per t POME (according to **Table 10.7**). Therefore, N removed as NH_3 volatilization is assumed to be the total removed of N at 0.05 kg N/t POME minus the 3.8% that is moved by denitrification, i.e. 0.048 kg NH_3-N/t POME. 0.048 kg NH_3-N/t POME corresponds to 0.058 kg NH_3/t POME.

The emissions of N-related substances are given in **Table 10.8**.

The decomposition of organic matter in the POME causes biogas. The generation of biogas in the ponds is 28 m^3 per t POME (Ma et al. 2004). With methane content of biogas at 60-70% averaging 65% of the biogas (Ma et al. 2004) the methane emission is 18.2 m^3 per t POME. With a density of methane at 0.717 g/litre (Andersen et al. 1981, p 119), the CH_4 emission is 13.0 kg per t POME. Yacob et al. (2006) have measured the methane emission from a pond system over a period of 12 months. The average methane emission reported from that study is 13.1 kg CH_4/t POME, which is in good accordance with the figures provided in Ma et al. (2004).

Ma (1999a, p 120) reports a hydrogen sulphide content of biogas at less than 2%. Assuming a content of H_2S at 0.2% and applying the density of H_2S at 1.539 g/litre (Andersen et al. 1981, p 119), the H_2S emission is 86.2 g/t POME.

Emissions from anaerobic POME treatment	**Compartment**	**Amount**
CH_4 (kg/t POME)	Air	13.0
H_2S (kg/t POME)	Air	0.0862
NH_3 (kg/t POME)	Air	0.058
N_2O (kg/t POME)	Air	0.0015
Nitrate	Water	

Table 10.8: Emissions from anaerobic digestion of 1 t POME.

The anaerobically digested POME and the sludge obtained from desludging are applied as fertiliser in the plantation. The emissions associated with that are dealt with in section 6.7. Since there is no discharge of waste water, there are no emissions to water from POME treatment.

10.6 Co-products/waste to treatment

According to **Figure 10.1** there are several co-products from the palm oil mills stage. **Table 10.9** provides an overview of how the co-products are dealt with in the life cycle inventory.

Co-products	Description of how the co-product is dealt with in the LCI
CPO (Crude Palm Oil)	Together with processed kernels (palm kernel oil), CPO is the product of interest
Kernel	Together with CPO, the processed kernels (palm kernel oil) is the product of interest. The LCI of the palm kernel oil mill is described in section 11
Land application of POME	This is dealt with as inputs to nutrient balances in the agricultural stage of oil palm, section 6.7
N:P:K eq.	This co-product is processed decanter cake sold as organic fertiliser. However, it is not normal to have a decanter attached to the clarification process in the palm oil mill. Therefore, there is no output of this co-product in **Figure 10.1**
Shell (fuel)	According to **Figure 10.1** fibre and shell sold as fuel is zero. However, this is based on steam consumption at 0.65 t/t FFB which may be too high. Therefore, a sensitivity analysis where the steam consumption is 0.5 t/t FFB is described in 21.19. In the sensitivity analysis with steam consumption at 0.5 t/t FFB there is excess of fibre and shell and therefore some of it is sold as fuel
Fibre (fuel)	
Electricity	According to section 10.3 there is 30% excess of electricity from the power central. This displaces electricity from the grid in Malaysia which is described in section 3.2
Steam	The produced steam is either used internally in the palm oil mill or released to the atmosphere. Thus, steam as a co-product does not displace anything
Steam release	
EFB to mulching	This is dealt with as inputs to nutrient balances in the agricultural stage of oil palm, section 6.7. A sensitivity analysis presented in section 21.20 analyses two alternative management options, i.e. utilisation for energy purposes in a biomass plant and disposal at landfill site

Table 10.9: Co-products from the palm oil mill stage and implications for LCI.

10.7 Overhead

No data on electricity use in administration, research and laboratory buildings have been identified. Therefore it is assumed that electricity use from rapeseed oil milling is representative for the palm oil mill. These numbers are very uncertain. However, the electricity consumption for overhead from rapeseed oil milling at AarhusKarlshamn only accounts for 1% of the total electricity use. Therefore, the uncertainties in the assumption that electricity use for overhead is the same for rapeseed oil milling and palm oil milling will only affect the results insignificantly. The electricity consumption for overhead is then assumed to be 4 MJ/t CPO corresponding to 1 MJ/t FFB. Buildings are not heated in Malaysia.

10.8 Capital goods

The interventions related to capital goods in the vegetable oil industry are described in section 9.7. There are three types of capital goods considered in the vegetable oil industry: '*Building, hall, steel construction*', '*Building, multi-storey*' and '*Facilities, chemical production*'.

It is assumed that the capital goods estimated per tonne rapeseed oil for the rapeseed oil mill are representative for the palm oil mill per tonne of palm oil. Thus, the capital goods can be calculated as:

- $1.8 \cdot 10^{-4}$ m^2 '*Building, hall, steel construction*' per t FFB
- $0.34 \cdot 10^{-3}$ m^3 '*Building, multi-storey*' per t FFB
- 0.040 kg '*Facilities, chemical production*' per t FFB

In the ecoinvent database capital goods for the palm oil mill is also estimated, in the data set: '*Crude palm oil, at plant/MY*' (ecoinvent 2004). However, that data set is per kg crude palm oil, and mass based co-product allocation between CPO, kernels and shell has been done. Weidema and Wesnæs (2006) have 'translated' the ecoinvent data set on palm oil into consequential modelling. Therefore, according to Weidema and Wesnæs (2006) the data set '*Crude palm oil, at plant/MY*' should be multiplied with 1.186 in order to include the FFB needed for generation of kernel and shell. Thus, the use of buildings and machinery per tonne FFB can be calculated as:

- $10 \cdot 10^{-4}$ m^2 '*Building, hall, steel construction*' per t FFB
- $15 \cdot 10^{-3}$ m^3 '*Building, multi-storey*' per t FFB
- 1.2 kg '*Facilities, chemical production*' per t FFB

It appears from a comparison between the applied data on capital goods and the figures determined from the ecoinvent data set, that there are significant differences. None of the data on capital goods are regarded as certain. Therefore a sensitivity analysis is carried out in section 21.17.

10.9 Transport of raw materials and ancillaries to palm oil mill

Transport of FFB to the oil mill is included in the agricultural stage of oil palm since the oil mill is situated in or very near to the plantation. Thus, all transport of FFB is taking place in the plantation. The only material transported to the palm oil mill is then diesel to the power central and diesel for vehicles. According to section 10.3 diesel to the power central is 0.37 litre of diesel per t FFB corresponding to 0.32 kg per t FFB. Diesel used for vehicles is 7.6 MJ diesel/t FFB (see **Table 10.5**) corresponding to 0.18 kg diesel. Thus, the total use of diesel is 0.50 kg/t FFB. It is very roughly estimated that the diesel is transported in a 28 t lorry 200 km from a regional store house. Interventions related to transport with lorry are described in section 4.1.

10.10 LCI of palm oil mill, summary

Table 10.10 summarises the inventory data relating to 1 tonne FFB.

Malaysia and Indonesia: processing of 1.000 t FFB in oil mill						
Interventions	**Power central**	**Oil mill**	**POME treatment**	**Overhead**	**Total**	**Applied LCI data**
Product output						
Crude palm oil	-	199.8 kg	-	-	**199.8 kg**	Together with processed kernels (palm kernel oil), CPO is the product of interest
Kernels	-	53.2 kg	-	-	**53.2 kg**	Together with CPO, the processed kernels (palm kernel oil) is the product of interest. The LCI of the palm kernel oil mill is described in section 11.
Fibre (fuel)	-	0 kg	-	-	**0 kg**	Co-product
Shell (fuel)	-	0 kg	-	-	**0 kg**	Co-product
Electricity	104 MJ	-72 MJ	-	-1 MJ	**31 MJ**	Co-product, see displaced products below
N:P:K eq.	-	0 kg	-	-	**0 kg**	Co-product
Displaced products						
Electricity from the grid	31 MJ	-	-	-	**31 MJ**	See section 3.2
Sand	68 kg	-	-	-	**68 kg**	'*Sand, at mine*' (ecoinvent 2004)
Material use						
FFB	-	1000 kg	**-**	-	**1000 kg**	The interventions related to production of FFB are included in the plantation stage
Water	0.65 t	0.72 t	-	-	**1.37 t**	See **Table 13.5**
Energy use						
Steam from power central	-	1,691 MJ	-	-	**1,691 MJ**	The emissions to air from burning of 130 kg fibre and 70 kg shell are given in this table
Electricity from power central	-	72 MJ	-	1 MJ	**73 MJ**	The emissions to air from burning of 130 kg fibre and 70 kg shell are given in this table
Electricity from the grid	-	0.8 MJ	-	-	**0.8 MJ**	See **Table 3.3**
Diesel for startups in power central	14 MJ		-	-	**14 MJ**	Modified version of '*Diesel, burned in building machine*' (ecoinvent 2004), see section 10.3
Diesel for vehicles		7.6 MJ			**7.6 MJ**	'*Diesel, burned in building machine*' (ecoinvent 2004)
Waste to treatment						
Anaerobically digested POME and sludge from desludging of POME	-	-	672.5 kg	-	**672.5 kg**	POME is applied in the plantation. Interventions related to that are described in section 6.7
EFB	-	225 kg	-	-	**225 kg**	EFB are applied as mulch in the plantation. Interventions related to that are described in section 6.7
Capital goods						
Building halls	-	$4.6 \cdot 10^{-3}$ m^2	-	-	**$4.6 \cdot 10^{-3}$ m^2**	'*Building, hall, steel construction*', (ecoinvent 2004)
Building, multi story	-	-	-	$8.5 \cdot 10^{-3}$ m^3	**$8.5 \cdot 10^{-3}$ m^3**	'*Building, multi-storey*' (ecoinvent 2004)
Machinery	-	1.0 kg	-	-	**1.0 kg**	'*Facilities, chemical production*', (ecoinvent 2004)
Transport of raw materials and ancillaries to the oil mill						
Diesel	0.064 tkm	0.036 tkm	**-**	**-**	**0.10 tkm**	'*Transport, lorry 28t*' (ecoinvent 2004)

Table 10.10: Interventions per t FFB processed. Table continued on the next page…

Interventions	Power central	Oil mill	POME treatment	Overhead	Total	Applied LCI data
Emissions to air						
Methane	1.33 g	-	8,743 g	-	**8,744 g**	Emission to air
NO$_x$	272 g	-	-	-	**272 g**	Emission to air
SO$_2$	2.40 g	-	-	-	**2.40 g**	Emission to air
CO	671 g	-	-	-	**671 g**	Emission to air
Particulates < 2.5 um	151 g	-	-	-	**151 g**	Emission to air
Acetaldehyde	1.16E-01 g	-	-	-	**1.16E-01 g**	Emission to air
Ammonia	3.40 g	-	39.0 g	-	**42.4 g**	Emission to air
Arsenic	1.90E-03 g	-	-	-	**1.90E-03 g**	Emission to air
Benzene	1.734 g	-	-	-	**1.734 g**	Emission to air
Benzene, ethyl-	5.72E-02 g	-	-	-	**5.72E-02 g**	Emission to air
Benzene, hexachloro-	1.37E-08 g	-	-	-	**1.37E-08 g**	Emission to air
Benzo(a)pyrene	9.52E-04 g	-	-	-	**9.52E-04 g**	Emission to air
Cadmium	1.33E-03 g	-	-	-	**1.33E-03 g**	Emission to air
Chlorine	3.42E-01 g	-	-	-	**3.42E-01 g**	Emission to air
Chromium	7.54E-03 g	-	-	-	**7.54E-03 g**	Emission to air
Chromium VI	7.62E-05 g	-	-	-	**7.62E-05 g**	Emission to air
Copper	4.20E-02 g	-	-	-	**4.20E-02 g**	Emission to air
Dinitrogen monoxide	5.80 g	-	1.01 g	-	**6.81 g**	Emission to air
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	5.90E-08 g	-	-	-	**5.90E-08 g**	Emission to air
Formaldehyde	2.48E-01 g	-	-	-	**2.48E-01 g**	Emission to air
Hydrocarbons, aliphatic, alkanes	1.73 g	-	-	-	**1.73 g**	Emission to air
Hydrocarbons, aliphatic	6.00 g	-	-	-	**6.00 g**	Emission to air
Hydrogen sulphide	-	-	58.0 g	-	**58.0 g**	Emission to air
Lead	4.76E-02 g	-	-	-	**4.76E-02 g**	Emission to air
m-Xylene	2.28E-01 g	-	-	-	**2.28E-01 g**	Emission to air
Manganese	3.24E-01 g	-	-	-	**3.24E-01 g**	Emission to air
Mercury	5.72E-04 g	-	-	-	**5.72E-04 g**	Emission to air
Nickel	1.14E-02 g	-	-	-	**1.14E-02 g**	Emission to air
NMVOC	1.71 g	-	-	-	**1.71 g**	Emission to air
PAH	2.12E-02 g	-	-	-	**2.12E-02 g**	Emission to air
Phenol, pentachloro-	1.54E-05 g	-	-	-	**1.54E-05 g**	Emission to air
Phosphorus	5.72E-01 g	-	-	-	**5.72E-01 g**	Emission to air
Toluene	5.72E-01 g	-	-	-	**5.72E-01 g**	Emission to air
Zinc	5.72E-01 g	-	-	-	**5.72E-01 g**	Emission to air

Table 10.10: … Continued from previous page. Interventions per t FFB processed.

11 Oil mill stage: Palm kernel oil

The LCI for the palm kernel oil mill stage represents average palm kernel oil mills in Malaysia in 2005 and 2006. Palm kernel oil and palm kernel cake are extracted from the kernels in a mechanical pressing process. It is also possible to extract the oil using solvent extraction. However, only one out of Malaysia's 41 palm kernel oil mills were using that technology in 2005 (Singh 2006 and MPOB 2006). Therefore, the inventory in this study assumes that all palm kernel oil extraction takes place using mechanical extraction. According to Subranamiam (2006a) mechanical pressing in Malaysia is typically done using a double pressing method without pre-heating.

The inventory is mainly based on a survey of five palm kernel oil mills in Malaysia provided by MPOB (Subranamiam 2006a and Subranamiam 2006b). The palm kernel oil mill processes the kernels from the palm oil mill into palm kernel oil (PKO) and palm kernel meal. Not many data on interventions related to palm kernel oil milling exist. Therefore some figures are determined as estimates based on data for palm oil mills described in section 10.

11.1 Oil mill product flow

The product flow in the palm kernel oil mills is shown in **Figure 11.1**. The product flow of palm kernel oil (PKO), palm kernel cake (PKC) and processed kernels is based on figures from 2002/03 and 2003/04 given in Oil World (2005), see **Table 11.1**. The flow chart is based on Bockisch (1998).

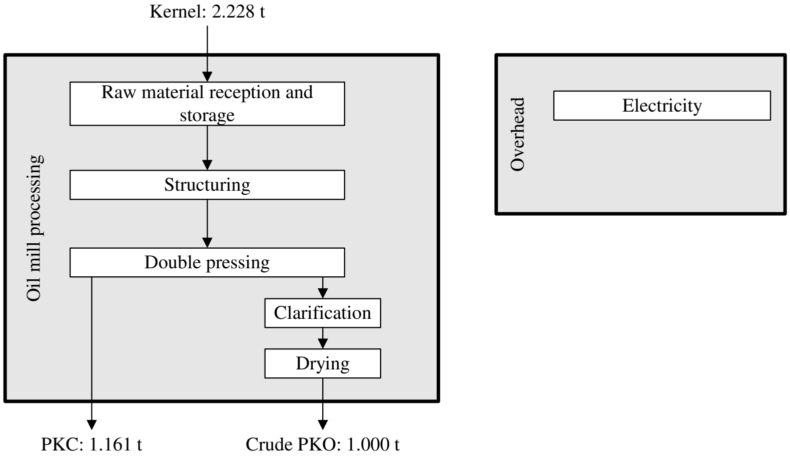


Figure 11.1: Product flow related to production of 1 t crude PKO in the palm kernel oil mill. The grey shaded boxes represent the unit processes in the palm kernel oil mill stage.

Product	2002/03	2003/04	Average per t PKO
Kernels processed	3,634,000 t	3,544,000 t	2.228 t
Palm kernel oil (PKO)	1,628,000 t	1,594,000 t	1.000 t
Palm kernel cake (PKC)	1,896,000 t	1,844,000 t	1.161 t
Loss (difference between input and output)	110,000 t	106,000 t	0.067 t

Table 11.1: Processing of kernels and production of PKO and PKC in Malaysia 2002/03 and 2003/04. (Oil World 2005)

11.2 Omitted inventory data in palm kernel oil mill stage

As in the LCI of the rapeseed oil mill and the palm oil mill lubricating oil is omitted. Also consumption of varies minor products such as tools, paper, computers, pencils, miscellaneous equipment etc. for process management and administration are omitted. Because of no data on water consumption and that it is regarded as insignificant, the use of water has been omitted.

11.3 Energy use

Several sources on energy use in the palm kernel oil milling process have been identified, see **Table 11.2**. **Table 11.2** shows the energy use associated with production of 1 tonne PKO and 1.161 tonne PKC, i.e. processing of 2.228 tonne kernels.

Energy	Energy use MJ per t PKO				
	5 PKO mills in Malaysia (Subranamiam 2006b)	PKO mills >500 t/year in Nigeria (Bamgboye and Jekayinfa 2006)	PKO mills in Malaysia (Zah and Hischier 2003) and corrected in accordance with (Weidema and Wesnæs 2006)	PKO mills in Malaysia (Schmidt 2004) based on (Unilever 1990) and (Shonfield 2004)	Applied data
Electricity from the grid	962 MJ	91 MJ	228 MJ	540 MJ	962 MJ
Fuel burned for steam production	-	252 MJ	6,217 MJ	740 MJ	0 MJ
Diesel for machinery/transportation	-	-	-	72 MJ	0 MJ

Table 11.2: Energy use per t PKO and attendant PKC, i.e. 1 t PKO and 1.161 t PKC. The applied data are marked with a dotted line.

It appears from **Table 11.2** that the different sources on energy use per tonne PKO vary significant. According to Subranamiam (2006a) the main difference is whether the oil mills use a 100% mechanical pressing or if it is combined with heating with steam. Bamgboye and Jekayinfa (2006) applies to rather small PKO mills in Nigeria (500 t/year and above) which may operate under different circumstances that in Malaysia and the electricity use seems to be unrealistic low. Zah and Hischier (2003) are based in figures in Hirsinger et al. (1995) which do not provide consistent energy figures. One example is that no reference for energy uses is given, i.e. it is not specified if the energy uses are per kg PKO or kernels or per kg or tonne product (Hirsinger et al. 1995, table 3). It is also difficult to see if energy for production of material inputs is included for the different figures provided. The use of fuel oil for steam in Zah and Hischier (2003) seems to be too high compared to steam consumption at 1,586 MJ/t rapeseed oil, see **Table 9.6**. Schmidt (2004) applies to oil mills that are using preheating before pressing which is not the most common technology in Malaysia. Therefore, the energy use given in Subranamiam (2006b) is regarded as the most representative for present energy use in Malaysian palm kernel oil mills.

Inventory data for electricity from the grid in Malaysia are described in **Table 3.3**.

11.4 Material use

Water is the only material used in the palm kernel oil mill. However, no data on water consumption in palm kernel oil mills have been identified. Since no water is needed for steam production or other processing, the water consumption is regarded as insignificant and is omitted.

11.5 Emissions

The only emissions from the palm kernel oil mill are emissions to air from the power central and contaminants in the discharged effluent. These emissions are described in section 11.3 and 11.6 respectively.

11.6 Waste to treatment

No data on the amount of waste water from the PKO mill as well as the applied technology for waste water treatment have been identified. However, as described in section 11.4 the consumption of water is regarded as insignificant. Therefore, the amount of waste water is also regarded as low. It is assumed that the waste water is treated in an aerobic pond. The COD content can be estimated to be of the same magnitude as for the effluent from the rapeseed oil mill, i.e. 3,578 mg/l, see section 9.5. This is not enough for anaerobically digestion. In an aerobic pond the content of COD (organic matter) reacts with oxygen and forms CO_2. However, this is of biotic origin and therefore, it has no impacts on global warming. There may be minor emissions of methane from small anaerobic pockets in the aerobic ponds. However, this is regarded as insignificant. The content of nitrogen in the effluent is assumed to be same per kg oil as for rapeseed oil mill effluent, i.e. 0.7 kg N (based on the amount of effluent per kg rapeseed oil, i.e. 57 kg and Aarhus United 2005a). The amount of phosphorus and other contaminants in the effluent is assumed to be insignificant. Further it is assumed that all of the content of N in the effluent sent to treatment ends as emissions of nitrate to water, i.e. 3 g NO_3^- to water per tonne PKO.

11.7 Overhead

As in the case for palm oil mills no data on electricity use in administration, research and laboratory buildings have been identified. Therefore it is assumed, as for the palm oil mill, that electricity use in rapeseed oil milling is representative for the palm kernel oil mill, i.e. 4 MJ/t PKO.

11.8 Capital goods

The interventions related to capital goods in the vegetable oil industry are described in section 9.7. There are three types of capital goods considered in the vegetable oil industry: '*Building, hall, steel construction*', '*Building, multi-storey*' and '*Facilities, chemical production*'.

It is assumed that the capital goods estimated per tonne input of rapeseed for the rapeseed oil mill are representative for the palm kernel oil mill per tonne of input of kernels. Thus, the capital goods can be calculated as:

- $8.6 \cdot 10^{-4}$ m^2 '*Building, hall, steel construction*' per t PKO
- $1.6 \cdot 10^{-3}$ m^3 '*Building, multi-storey*' per t PKO
- 0.19 kg '*Facilities, chemical production*' per t PKO

Determination of capital goods is regarded as very uncertain. Therefore a sensitivity analysis is carried out in section 21.17.

11.9 Transport of raw materials and ancillaries to palm kernel oil mill

According to Subranamiam (2006b) the average distance from palm oil mills, where the kernels are produced, to the palm kernel oil mill is 79 km. It is assumed that the 2,228 kg kernels per tonne PKO are transported in a 28 t lorry.

The distance from the palm kernel oil mill to a meal trader is assumed to be 200 km. The palm kernel cake is assumed to be transported in a 28 t lorry.

Transportation of the palm kernel oil to the refinery is included in the refinery stage in section 15.

11.10 LCI of palm kernel oil mill, summary

Table 11.3 summarises the inventory data relating to 1 tonne crude palm kernel oil.

Malaysia and Indonesia: 1.000 t crude palm kernel oil from oil mill				
Interventions	**Palm kernel oil mill**	**Overhead**	**Total**	**Applied LCI data**
Palm kernel oil	1000 kg	-	**1000 kg**	Together with CPO from the palm oil mill PKO is the product of interest
Palm kernel cake	1,161 kg	-	**1,161 kg**	Co-product allocation is avoided by system expansion, see **Table 2.3**
Material use				
Kernels	2,228 kg	-	**2,228 kg**	The interventions related to production of kernels are included in the plantation stage and the palm oil mill stage
Water	400 kg	-	**400 kg**	See **Table 13.5**
Energy use				
Electricity from the grid	751 MJ	4 MJ	**755 MJ**	See **Table 3.3**
Emissions				
Nitrate to water	3 g	-	**3 g**	Emission to water
Waste to treatment				
No interventions	**-**	-	**-**	-
Capital goods				
Building halls	$8.6\cdot10^{-4}$ m^2	-	**$8.6\cdot10^{-4}$ m^2**	*‘Building, hall, steel construction*’, (ecoinvent 2004)
Building, multi story	-	$1.6\cdot10^{-3}$ m^3	**$1.6\cdot10^{-3}$ m^3**	’*Building, multi-storey’* (ecoinvent 2004)
Machinery	0.19 kg	-	**0.19 kg**	‘*Facilities, chemical production*’, (ecoinvent 2004)
Transport of raw materials and ancillaries to the oil mill				
Kernels	176 tkm	-	**176 tkm**	‘*Transport, lorry 28t*’ (ecoinvent 2004)
Palm kernel cake	46 tkm	-	**46 tkm**	‘*Transport, lorry 28t*’ (ecoinvent 2004)

Table 11.3: Interventions per t palm kernel oil

12 Oil mill stage: Soybean meal

The LCI for the soybean mill stage represents average soybean mills in around 2000-2005. Soybean oil and soybean meal are extracted from the soybeans in a solvent extraction process similar to rapeseed milling. The inventory data for soybean meal milling are mainly obtained from Dalgaard et al. (2007). Since the LCI of soybean mills in Dalgaard et al (2007) is not as detailed as in this study, the missing data are represented with the inventory data for rapeseed milling. These data include; electricity for overhead, capital goods and transport of raw materials to the soybean mill.

12.1 Oil mill product flow

The product flow in the soybean oil mill is shown in **Figure 12.1**. The figure is based on Bockisch (1998). The product flow of soybean oil (SO), soybean meal (SM) and processed soybeans is based on figures from 2002/03 and 2003/04 given in Oil World (2005), see **Table 12.1**.

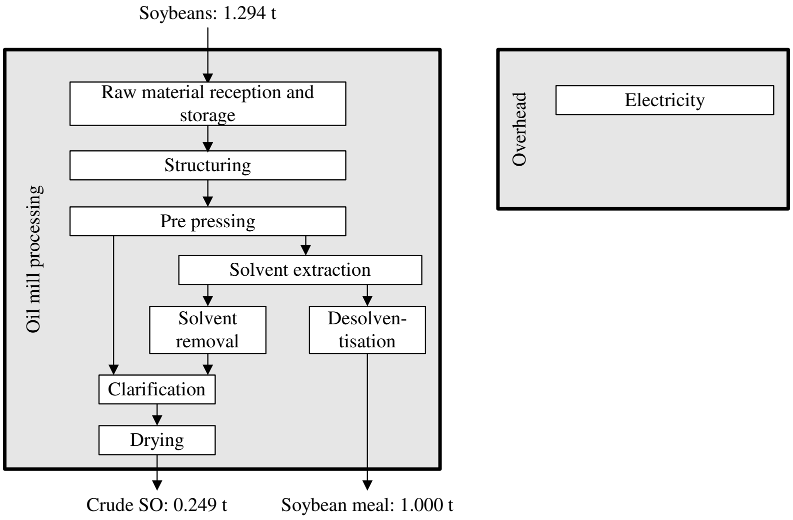


Figure 12.1: Product flow related to processing of 1 t soybeans in the soybean mill. The grey shaded boxes represent the unit processes in the palm kernel oil mill stage.

Product	2002/03	2003/04	Average per t soybean meal
Soybeans crushed	27,718,000 t	29,298,000 t	1.294 t
Soybeanl oil	5,325,000 t	5,629,000 t	0.249 t
Soybean meal	21,534,000 t	22,520,000 t	1.000 t
Loss (difference between input and output)	859,000 t	1,149,000 t	0.046 t

Table 12.1: Processing of soybeans and production of soybean oil and soybean meal in Brazil 2002/03 and 2003/04. (Oil World 2005)

12.2 Omitted inventory data in soybean oil mill stage

As in the LCI of the rapeseed oil mill and the palm oil mill lubricating oil is omitted. Also consumption of varies minor products such as tools, paper, computers, pencils, miscellaneous equipment etc. for process management and administration are omitted. Because of lack of data on water consumption it has been omitted.

12.3 Energy use

The energy use for processing of the soybeans is obtained from Dalgaard et al. (2007), see **Table 12.2**.

Source	Energy use
Electricity from the grid	56 MJ
Fuel oil	188 MJ
Natural gas	365 MJ

Table 12.2: Energy use per t soybean meal and attendant soybean oil, i.e. 1 t SM and 0.249 t SO.

Inventory data for electricity from the grid in Brazil are described in **Table 3.3**. Inventory data for burning of fuel oil are specified in **Table 9.4**: 'Light fuel oil, burned in boiler 100kW, non-modulating', ecoinvent (2004). The applied inventory data for burning of natural gas is: 'Natural gas, burned in industrial furnace >100kW/RER' (ecoinvent 2004). The inventory data for energy use in the soybean oil mill all include production, maintenance and disposal of capital goods.

12.4 Material use

Hexane for solvent extraction and water are the only materials used in the soybean oil mill. According to Dalgaard et al. (2007) the use of hexane is 0.52 kg per t soybean meal. The inventory data applied for hexane are described in **Table 9.5**.

Because of lack of data interventions related to water consumption have been omitted.

12.5 Emissions

The only emissions from the soybean oil mill are emissions to air of hexane and emissions from the power central, and contaminants in the discharged effluent. According to Dalgaartd et al. (2007) the emissions of hexane and nitrate in waste water are 0.26 kg/t soybean meal and 0.005 g/t soybean meal respectively. The emissions from the power central are included in the inventory data on burning of fuel oil and natural gas described in section 12.3.

12.6 Waste to treatment

There are no significant wastes sent to treatment from the soybean oil mill.

12.7 Overhead

As in the case for palm oil mills and palm kernel oil mills no data on electricity use in administration, research and laboratory buildings have been identified. Therefore it is assumed that electricity use in rapeseed oil milling per tonne input is representative for the soybean oil mill per tonne processed soybeans, i.e. 1.3 MJ/t soybean meal.

12.8 Capital goods

The interventions related to capital goods in the vegetable oil industry are described in section 9.7. There are three types of capital goods considered in the vegetable oil industry: '*Building, hall, steel construction*', '*Building, multi-storey*' and '*Facilities, chemical production*'.

It is assumed that capital goods in rapeseed oil milling per tonne input rapeseed is representative for the soybean oil mill per tonne input of soybeans. Thus, the capital goods can be determined as:

- $5.0 \cdot 10^{-4}$ m^2 '*Building, hall, steel construction*' per t soybean meal
- $9.2 \cdot 10^{-4}$ m^3 '*Building, multi-storey*' per t soybean meal
- 0.11 kg '*Facilities, chemical production*' per t soybean meal

Determination of capital goods is regarded as very uncertain. Therefore a sensitivity analysis is carried out in section 21.17.

12.9 Transport of raw materials and ancillaries to soybean oil mill

Soybeans and ancillary materials are transported with lorry to the oil mill. Since there are several suppliers and since there is a general lack of data on the specific marginal affected supplier, all transport distances are based on rough estimates. Determination of size of lorries is roughly based on **Table 4.3**.

Material	Amount per t soybeam meal	From	To	Distance	Lorry size
Soybeans	1.294 t	Seed trader	Oil mill	200 km	40t
Fuel oil	4.6 kg	Fuel oil supplier	Oil mill	200 km	28t
Hexane	0.52 kg	Abroad chemical plant	Oil mill	1000 km	40t
Soybean meal	1.000 t	Oil mill	Meal trader	300 km	40t

Table 12.3: Transport distances of the used raw materials and ancillaries in the oil mill stage. The return trip is included in the inventory data.

The amount of fuel oil is calculated from the use of 188 MJ fuel oil and data on fuel oil in Appendix 1: Data on fuels. The transport of soybean oil to the refinery is included in the refinery stage.

Inventory data per tkm transport by lorry are described in section 4.1.

12.10 LCI of soybean oil mill, summary

Table 11.3 summarises the inventory data relating to 1 tonne soybean meal.

Brazil: 1.000 t soybean meal from oil mill				
Interventions	**Soybean oil mill**	**Overhead**	**Total**	**Applied LCI data**
Soybean meal	1000 kg	-	**1000 kg**	Product of interest
Crude soybean oil	0,249 kg	-	**1,161 kg**	Co-product allocation is avoided by system expansion, see **Table 2.3**
Material use				
Soybeans	1,294 kg	-	**1,294 kg**	The interventions related to production of soybeans are included in the agricultural stage:Soybean, see section 7
Hexane	0.52 kg	-	**0.52 kg**	
Energy use				
Electricity from the grid	56 MJ	1.3 MJ	**57 MJ**	See **Table 3.3**
Fuel oil	188 MJ		**188 MJ**	‘Light fuel oil, burned in boiler 100kW, non-modulating’, ecoinvent (2004)
Natural gas	365 MJ		**365 MJ**	‘Natural gas, burned in industrial furnace >100kW/RER’ (ecoinvent 2004)
Emissions				
Hexane to air	0.26 kg		**0.26 kg**	Emission to air
Nitrate to water	0.005 g	-	**0.005 g**	Emission to water
Waste to treatment				
No interventions	-	-	-	
Capital goods				
Building halls	$5.0\cdot10^{-4}$ m^2	-	**$5.0\cdot10^{-4}$ m^2**	*‘Building, hall, steel construction*’, (ecoinvent 2004)
Building, multi story	-	$9.2\cdot10^{-4}$ m^3	**$9.2\cdot10^{-4}$ m^3**	’*Building, multi-storey’* (ecoinvent 2004)
Machinery	0.11 kg	-	**0.11 kg**	‘*Facilities, chemical production*’, (ecoinvent 2004)
Transport of raw materials and ancillaries to the oil mill				
Soybeans	259 tkm	-	**259 tkm**	‘*Transport, lorry 40t*’ (ecoinvent 2004)
Fuel oil	0.9 tkm	-	**0.9 tkm**	‘*Transport, lorry 28t*’ (ecoinvent 2004)
Hexane	0.5 tkm	-	**0.5 tkm**	‘*Transport, lorry 40t*’ (ecoinvent 2004)
Soybean meal	300 tkm	-	**300 tkm**	‘*Transport, lorry 40t*’ (ecoinvent 2004)

Table 12.4: Interventions per t soybean meal.

13 Refinery stage: Rapeseed oil

The refining process includes neutralisation, bleaching and deodorisation of the oil. The output from the refinery is then NBD rapeseed oil (neutralised, bleached and deodorised). Principally, there are two different ways of refining; chemical refining and physical refining (Bockisch 1998). The most widespread method for refining is chemical refining which is also used at AarhusKarlshamn. However, according to Hansen (2006) the tendency goes towards more and more physical refining of oil for food purposes. The inventory in this section takes point of departure in chemical refining. The description of the refining process is based on Hansen (2006) and Bockisch (1998).

The purpose of neutralisation, which includes degumming and neutralisation, is to remove lecithin and free fatty acids. Firstly, the lecithin is removed by applying phosphoric acid in the degumming process. After that the content of free fatty acids are removed by applying sodium hydroxide. When the sodium hydroxide reacts with the free fatty acids the outcome is soap and water. Next, the mix of oil, soap and water is centrifuged in order to separate out the soap. The soap is sent through the soap stock splitting process, where sulphuric acid is applied. The soap and acid react and the outcome are free fatty acids which are used as fodder and sodium sulphate which is sent with waste water to the municipal sewage water system (Hansen 2006). Loss in the neutralisation process includes the separated free fatty acids (1% of the oil) and loss of oil to the soap fraction (0.1%) (Hansen 2006). Thus the total loss of the crude oil input to the process is 1.1%.

The bleaching process is applied in order to remove undesired coloured particles and substances. In the bleaching process the oil is brought in contact with surface-active substances which absorb the undesired particles. Bleaching earth (bentonite) is the most common used agent for filtering the oil. Sometimes filter aid is added to the bleaching earth. This helps building up a filter structure and avoiding the filter to get clogged. Filter aid consists of e.g. cellulose fibres. However, at AarhusKarlshamn no filter aid is used. The oil content in used bleaching earth is 30-40% (Hansen 2006). In **Table 13.1** it appears that the use of bleaching earth is 9.0 g per kg NBD oil. Assuming oil content at 35% in used bleaching earth, loss of oil to the bleaching earth can be determined as 4.8 g oil per kg NBD oil.

Finally, the oil is sent through the deodorisation process. The purpose of deodorisation is to remove undesired odoriferous or flavouring compounds. In the deodorisation process minor amounts of different ancillaries are applied, e.g. citric acid, BHT, ascorbyl palmitate and A and D vitamins. Since these ancillaries constitute insignificant amounts (0.19 – 20 g per tons NBD oil) and since there is a lack of life cycle inventory data on these ancillaries, they are omitted from the study. 0.1% of the oil is lost in the deodorisation process (Hansen 2006). The loss goes with the separated compounds to the free fatty acids which are used as fodder.

The product flow related to 1 tonne NBD rapeseed oil is shown in **Figure 13.1**.

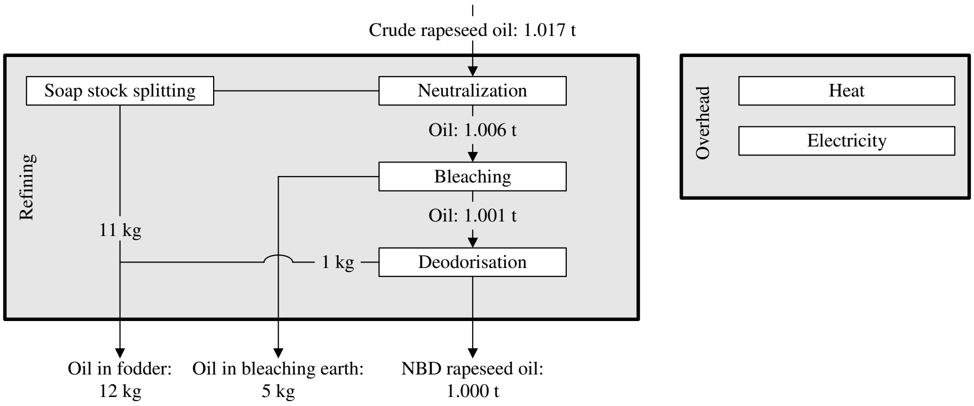


Figure 13.1: Product flow related to production of 1 t NBD rapeseed oil. Based on Hansen (2006).

13.1 Material use

Table 13.1 shows the material use per tonne NBD rapeseed oil. All numbers are based on refining of rapeseed oil at AarhusKarlshamn in 2004 and data are delivered by Hansen (2006).

The consumption of phosphoric acid in the degumming process amounts 0.08% of the input of oil. Since the density of phosphoric acid is 1.58 g/cm^3 the consumption is 1.3 g per kg NBD oil. The consumption of sodium hydroxide in the neutralisation process is 9.1 g (14% solution). Since sodium hydroxide is purchased in 50% solution, the 9.1 g is equivalent to 2.6 g (50% solution). The soap from the neutralisation process is sent to soap stock splitting where sulphuric acid is applied. The consumption of sulphuric acid equals 0.19 kg H_2SO_4 per kg free fatty acids (Hansen 2006)[23]. Since the content of free fatty acids is 10 g per kg NBD oil, the consumption of sulphuric acid is 1.9 g per kg NBD oil.

The water consumption in the neutralisation process amounts 2% of the input of oil, i.e. 20.3 g per kg NBD oil. Further, there is an input of water from the sodium hydroxide solution. At AarhusKarlshamn the purchased 50% sodium hydroxide solution is diluted to 14% by adding 7.0 g water per kg NBD oil. Thus the water consumption in the neutralisation process is 27.3 g per kg NBD oil.

In the bleaching process the consumption of bleaching earth amounts ~0.9% of the input of oil, i.e. 9.0 g. There is no use of water in the bleaching and deodorisation processes.

Ancillaries	Neutralisation	Bleaching	Deodorisation
Phosphoric acid	0.8 kg	-	-
Sodium hydroxide (NaOH in 50% water)	2.1 kg	-	-
Sulphuric acid (100%)	1.9 kg	-	-
Bleaching earth	-	9.0 kg	-
Tap water	27.3 kg	-	-

Table 13.1: Material uses in the refining stage. All numbers are related 1 t NBD oil. (Hansen 2006)

The following describes the used inventory data relating to the materials given in **Table 13.1**.

Phosphoric acid: Two life cycle inventories have been identified for production of phosphoric acid. Analysing the data sets in Simapro and using the EDIP97 for LCIA, it appears that global warming, acidification and toxicity are the most significant impact categories. In **Table 13.2** the data sets are compared within these categories.

---

[23] This is calculated using the reaction equation below. A surplus of 10% of H_2SO_4 is used.

$2C_{17}H_{33}COONa$ (soap) + H_2SO_4 (sulphuric acid)$\rightarrow$ $2C_{17}H_{33}COOH$ (fatty acid) + Na_2SO_4 (Sodium sulphate)

LCI-data for phosphoric acid	CO_2-eq.	SO_2-eq.	ETWC, m^3 water	Description of data
'Phosphoric acid', ETH-ESU database (Frischknecht et al., 1996)	1.17 kg	22 g	695 m^3	*Time:* Data from before 1980 *Geography:* Western Europe *Technology:* Average *Co-product allocation*: Not described *Capital goods:* Included for sub processes but not for the production of phosphoric acid
'Phosphoric acid, industrial grade, 85% in H2O, at plant', ecoinvent database (Althaus et al. 2003)	1.31 kg	34 g	2430 m^3	*Time:* Data from 1995-2000 *Geography:* Weighted average of production in US and Morocco *Technology:* Average *Co-product allocation*: Mass-allocation between phosphoric acid and fluosilicic acid *Capital goods:* Machinery, buildings

Table 13.2: Comparison of LCIs of phosphoric acid. The comparison is shown as characterised results using the EDIP97-method for LCIA. Both life cycle inventories are for 1 kg H_3PO_4 in water solution. The applied data are marked with a black dotted frame.

According to **Table 13.2** there is no significant difference between phosphoric acid from Frischknecht (1996) and Althaus et al. (2003) except from toxicity. Since the data from Althaus et al. are the newest and since they include capital goods it is chosen to use this data set.

Sodium hydroxide (NaOH): Several life cycle inventories on sodium hydroxide have been identified. As in the case of phosphoric acid an analysis of the data sets in Simapro and using the EDIP97-method for LCIA shows, that global warming, acidification and toxicity are the most significant impact categories. In **Table 13.3** the data sets are compared within these categories.

LCI-data for NaOH	CO_2-eq.	SO_2-eq.	ETWC, m^3 water	Description of data
'NaOH', BUWAL database (BUWAL 250, 1996)	1.20 kg	15 g	69 m^3	*Time:* Data from 1990-94 *Geography:* Western Europe *Technology:* Average *Co-product allocation*: Mass-allocation between sodium hydroxide and chlorine *Capital goods:* No
'NaOH', ETH-ESU database (Frischknecht et al., 1996)	0.88 kg	6 g	336 m^3	*Time:* Data from 1990-94 *Geography:* Western Europe *Technology:* Average *Co-product allocation*: Mass-allocation between sodium hydroxide and chlorine *Capital goods:* Included for sub processes but not for the production of NaOH.
'Sodium hydroxide, diaphragm cell, at plant', ecoinvent database (Althaus et al. 2003)	1.06 kg	6 g	1,020 m^3	*Time:* Data from 2000 *Geography:* Europe *Technology:* Present state of technology for diaphragm cells *Co-product allocation*: Mass-allocation between sodium hydroxide, chlorine and hydrogen *Capital goods:* Machinery, buildings
'Sodium hydroxide, membrane cell, at plant', ecoinvent database (Althaus et al. 2003)	0.87 kg	5 g	866 m^3	
'Sodium hydroxide, mercury cell, at plant', ecoinvent database (Althaus et al. 2003)	0.94 kg	5 g	928 m^3	
'Sodium hydroxide, production mix, at plant', ecoinvent database (Althaus et al. 2003)	0.95 kg	5 g	937 m^3	

Table 13.3: Comparison of LCIs of sodium hydroxide. The comparison is shown as characterised results using the EDIP97-method for LCIA. All the life cycle inventories are for 1 kg NaOH in 50% water solution. The applied data are marked with a black dotted frame.

It appears that the differences in environmental burden from the different data sets are relatively small concerning global warming and acidification. Within ecotoxicity the data from BUWAL 250 (1996) and Frischknecht et al. (1996) shows significant lower values than the data from Althaus et al. (2003). It has not been possible to identify the reason for this difference, but the two first mentioned data sets are based on other data for both the production processes for NaOH and for sub processes. It is chosen to use data from Althaus et al. (2003) since these data include capital goods and they are 7-10 years newer than the data in BUWAL 250 (1996) and Frischknecht et al. (1996). Further it is chosen to use the data for production mix of the three technologies; diaphragm cell, membrane cell and mercury cell. Since there is no significant difference between the three data sets and since the use of sodium hydroxide in the oil mill stage is very small this choice will not have any substantial effects on the result of the LCA.

Sulphuric acid: Three life cycle inventories have been identified for production of sulphuric acid. As in the case for sodium hydroxide, analysis of the data sets in Simapro and using the EDIP97 for LCIA shows that global warming, acidification and toxicity are the most significant impact categories. In **Table 13.4** the data sets are compared within these categories.

LCI-data for sulphuric acid	CO_2-eq.	SO_2-eq.	ETWC, m^3 water	Description of data
'Sulphuric acid', BUWAL database (BUWAL 250 1996)	92 g	26 g	2.1 m^3	*Time:* Data from before 1995 *Geography:* Europe *Technology:* Not specified *Co-product allocation*: Not relevant *Capital goods:* Not included
'Sulphuric acid, liquid, at plant', ecoinvent database (Althaus et al. 2003)	111 g	13 g	241 m^3	*Time:* Data from 1994-2003 *Geography:* Europe *Technology:* Data based on sources on averages as well as state-of-art technologies *Co-product allocation*: Not relevant *Capital goods:* Machinery, buildings
'Svovlsyre (H2SO4)' EDIP database (EDIP 1996)	160 g	43 g	0.009 m^3	*Time:* Data from before 1995 *Geography:* Europe *Technology:* Not specified *Co-product allocation*: Not relevant *Capital goods:* Not included

Table 13.4: Comparison of LCIs of sulphuric acid. The comparison is shown as characterised results using the EDIP97-method for LCIA. All the life cycle inventories refer to 1 kg 100% H_2SO_4. The applied data are marked with a black dotted frame.

According to **Table 13.4** there is some difference between the contributions to global warming and acidification. The contribution to toxicity varies with a factor 27,000 from the lowest value to the highest value. Since the data from Althaus et al. are the newest and since they include capital goods it is chosen to use this data set.

Bleaching earth: Only one life cycle inventory of production of bleaching earth has been identified; Bentonite, at processing/DE (Kellenberger et al. 2003). This inventory is part of the ecoinvent database and it is available in SimaPro. The data represents a mix of alkaline activated bentonite (61%), acid activated bentonite (38%) and catalytic converters (1%). Only the acid activated bentonite is used in oil mills. Some of the most important uses of the other bentonites are for casting moulds, as a cement product in building industry, wine clarification and for removal of printing ink in the recycling process of waste paper. The data set covers data for 1998 for one German company which comprises 70% of the total German production in 1998 (Kellenberger et al. 2003). The data includes mining and processing of the bentonite, transport and production, maintenance and breaking down of capital goods.

Tap water: Three life cycle inventories for tap water have been identified; 'Water, tap' (Nielsen et al. 2005), 'Vandværksvand, dansk' (EDIP, 1996) and 'Tap water, at user/RER' (Althaus et al. 2003). It is chosen to use a modified version of the data from Nielsen et al. (2005). The data in Nielsen et al. (2005) describes tap water in Copenhagen in 1999. Capital goods are not included. The modifications include adjustment of LCI data for electricity to be consistent with section 3.1 and clarification of LCI data on auxiliaries. The two other data sets for tap water are omitted because the data from EDIP (1996) only include energy consumption and the data from Althaus et al. (2003) cover water supply in Germany and Switzerland. The modifications of the data from Nielsen et al. (2005) are shown in **Table 13.5**.

LCI-data for tap water	Amount	Original LCI used in Nielsen et al. (2005)	LCI data used in this study
Ground water	1.05 kg	resource	resource
Electricity	1.3 kJ	'Electricity gas power plant in NL', ETH-ESU database (Frischknecht et al., 1996)	See **Table 3.3**
Sodium hypochlorite	4 mg	'Chemicals organic', ETH-ESU database (Frischknecht et al., 1996)	'Sodium hypochlorite, 15% in H2O, at plant/RER', ecoinvent (2004)
Ammonium sulphate	0.46 mg		'Ammonium sulphate, as N, at regional storehouse/RER', ecoinvent (2004)
Sodium hydroxide	0.06 mg		'Sodium hydroxide, production mix, at plant', ecoinvent (2004)

Table 13.5: Modification of LCI of 1 kg tap water delivered to consumer in Nielsen et al. (2005).

13.2 Energy use

Table 13.6 shows the energy use per tonne NBD rapeseed oil. All numbers are based on refining of rapeseed oil at AarhusKarlshamn in 2004 and data are provided by Hansen (2006).

Energy	Neutralisation	Bleaching	Deodorisation	Total
Electricity	20 MJ		84 MJ	**104 MJ**
Heat	41 MJ	41 MJ	144 MJ	**226 MJ**

Table 13.6: Energy use in the refining stage relating to 1 t NBD rapeseed oil. (Hansen 2006)

The interventions related to production of electricity are described in section 3.1. The heat is produced at the power central at AarhusKarlshamn, see interventions in **Table 9.4**

13.3 Emissions

There are no direct emissions from refining.

13.4 Waste to treatment/co-products

Table 13.7 shows the waste/co-products identified in **Figure 13.1** and the section 'Material use'. Also, **Table 13.7** specifies the further treatment or application of the flows.

Waste/co-product	Amount	Treatment
Free fatty acids from soap splitting	10 kg	9.1 g is sold as fodder and 0.09 is lost with waste water, see 'Waste water' below
Oil loss from neutralisation	1 kg	Sold as fodder
Oil loss from deodorisation	1 kg	Sold as fodder
Phosphoric acid (H_3PO_4) (100%)	0. 8 kg	This is neutralised with NaOH in the neutralisation process. The P is discharged with the waste water from soap stock splitting to the municipal sewage system, see 'Waste water' below
Sodium hydroxide (NaOH) (100%)	1.05 kg	The NaOH reacts with the free fatty acids in the neutralisation process and forms soap ($C_{17}H_{33}COONa$)
Sulphuric acid (H_2SO_4) (100%)	1.9 kg	The H_2SO_4 reacts with the soap in the soap stock splitting process and forms sodium sulphate (Na_2SO_4) and free fatty acids (which is used as fodder, see above). Na_2SO_4 is a salt and is discharged with the waste water from soap stock splitting to the municipal sewage system, see 'Waste water' below
Bleaching earth	9 kg	The used bleaching earth is sent to biogas. The oil content in the bleaching earth is 35%.
Oil loss from bleaching: oil in bleaching earth	5 kg	
Waste water	79 litre	The 79 litre waste water has the following content: COD: 0.54 kg (Aarhus United, 2005a) Fat: 0.09 kg (Aarhus United, 2005a) P: 0.26 kg (Calculated from the consumption of phosphoric acid) Na_2SO_4: 2.5 kg (Determined from stoichiometric calculation from reaction between soap and H_2SO_4 to FFA and Na_2SO_4 The waste water is sent the municipal sewage system where it is lead to the municipal waste water treatment plant

Table 13.7: Overview of waste and co-product flows and their treatment/application. All numbers refer to 1 t NBD oil. Based on (Hansen 2006).

The different co-products/wastes to treatment from the refinery stage include: 1) Fodder fat, 2) Waste water and 3) Bleaching earth sent to biogas. The interventions related to these three outputs of co-products/wastes are described in the following.

Fodder fat

This co-product is treated in the LCI by system expansion, see section 2.2.

Waste water, COD and P

Interventions related to waste water and its contents of COD and P are described in **Table 9.9**.

Biogas (residual from rapeseed and bleaching earth)

In the biogas plant the residual from rapeseed screening and oil containing bleaching earth is digested. According to Kromann (1996) the production of biogas can be estimated from the content of fat, protein, cellulose (difficult digestible carbon) and glucose (easy digestible carbon) in the biomass. The only digestible component in bleaching earth is fat and the residual from rapeseed screening is presumed to mainly consist of cellulose. According to Kromann (1996, p 37) biogas production (methane) can be expected as 0.81 Nm^3 per kg fat and 0.12 Nm^3 per kg cellulose. The energy content in biogas is 36.1 MJ/Nm^3 (methane) and the density is 0.72 kg/m^3 (Kromann, 1996, p 36 and Kromann et al. 2004).

The following data for the biogas plant, i.e. energy production and emissions are based on Kromann et al. (2004). Before the biomass is sent to digestion it is hygienized, i.e. heated from approximately 15C to 75C, requiring 281 kWh per tonne DS. Assuming water content at ~10% in residual and bleaching earth, the energy for hygienization is 312 kWh per tonne. The produced gas (methane) is burned at the biogas plant with co-production of electricity and heat in a gas motor with 37% electrical efficiency and 48% heat efficiency. The electricity use at the biogas plant is 9 kWh per tonne biomass. Emission of methane is estimated to 1.5% of the input of gas to the motor. Other emission from the gas motor include 0.018 g SO_2/MJ input of energy in biogas and 0.200 g NO_x/MJ input of energy in biogas. In an LCA of organic waste from catering sent to biogas, the emission of ammonia constitutes the most significant contribution to eutrophication and acidification (Kromann et al. 2004). In Kromann et al. (2004) the emission of ammonia from storing of the biomass material before the digesting process is estimated as 4% of the total N content. The emission of ammonia from slurry spreading after digestion is estimated as 10-15% of the N content. The content of N in riddle from rapeseed and bleaching earth would be contained in the protein. It is presumed that the content of protein in the riddle is very little. Furthermore, there is no protein in the fat in bleaching earth. Thus, emission of ammonia is assumed as 0. Since the content of N is estimated as 0 the emission of N_2O from slurry spreading can also be set to 0. Furthermore, since the content of N is estimated as 0, displacement of fertilizers from slurry spreading is also estimated as insignificant. Another significant emission in Kromann et al. (2004) is methane from storing the biomass before digestion. However, the riddle from rapeseed and bleaching earth are stored with a low content of water. Thus anaerobic conditions, which are required for biogas production, will not be likely to appear. In Kromann (1996, p 41) transport of the digested biomass to field application is estimated to 50 MJ/tonne DS of biomass input to the plant including transport with truck, slurry spreading and ploughing. The 50 MJ/tonne is based on 20% weight reduction in the digester. Assuming of water content of riddle from rapeseed and bleaching earth at 10%, the energy use for transport is 56 MJ/tonne. There is assumed no emissions to soil/water from the digested riddle and bleaching earth. Buildings and machinery is not included for the biogas plant.

The inventory data for 1 kg rapeseed residual and 1 kg bleaching earth (35% fat) is shown in **Table 13.8**.

1 kg residual from rapeseed screening	**Amount**	**Applied LCI data**
Produced gas	0.12 Nm^3/4.3 MJ	The gas is incinerated and electricity and heat are produced, see below.
Electricity (from energy production at the plant)	-1.6 MJ	See **Table 3.3**
District heating (from energy production at the plant)	-2.1 MJ	See section 3.6
Heat for hygienization	1.1 MJ	This is taken from own production of heat, see above
Electricity, own consumption	0.03 MJ	See **Table 3.3**
Emission of methane (CH_4)	1.3 g	Emission to air
Emission of SO_2	0.078 g	Emission to air
Emission of NO_x	0.87 g	Emission to air
Transport of digested biomass to field application	56 KJ	'Diesel, burned in building machine/GLO', ecoinvent (2004)
1 kg bleaching earth (35% fat)	**Amount**	**Applied LCI data**
Produced gas	0.28 Nm^3/10.2 MJ	The gas is incinerated and electricity and heat are produced, see below.
Electricity (from energy production at the plant)	-3.7 MJ	See **Table 3.3**
District heating (from energy production at the plant)	-4.9 MJ	See section 3.6
Heat for hygienization	1.1 MJ	This is taken from own production of heat, see above
Electricity, own consumption	0.03 MJ	See **Table 3.3**
Emission of methane (CH_4)	3.0 g	Emission to air
Emission of SO_2	0.18 g	Emission to air
Emission of NO_x	2.0 g	Emission to air
Transport of digested biomass to field application	56 KJ	'Diesel, burned in building machine/GLO', ecoinvent (2004)

Table 13.8: Inventory data for 1 kg rapeseed riddle and 1 kg bleaching earth sent to biogas.

13.5 Overhead

The energy consumption related to overhead at AarhusKarlshamn is described in section 9.6. 10% of the total energy consumption from overhead, i.e. administration, laboratories, marketing etc., is allocated to refining. Since three oils constitute the main oils used at AarhusKarlshamn; rapeseed oil, shea oil and palm oil, refinery of rapeseed oil constitute one third of the 10%. Hence, assuming that one third of the refined oils was rapeseed oil the proportion related to rapeseed activities can be estimated as 3.3%.

According to Aarhus United (2005b) electricity consumption for administration and laboratories was approximately 1220 MWh in 2004. In 2004 the production of refined oils at AarhusKarlshamn was 200,000 tonne (Aarhus United 2005b). Thus, the electricity consumption for overhead related to refining of rapeseed oil can be estimated as 0.7 MJ/t NBD rapeseed oil. This amounts 0.5% of the total electricity consumption for production of refined rapeseed oil at AarhusKarlshamn, see **Table 13.11**.

Heat consumption for administration and laboratories was approximately 550 MWh in 2004 (Aarhus United, 2005b). Using abovementioned allocation factor and the annual production of refined oils, the heat consumption can be found as 0.3 MJ/t NBD rapeseed oil. Administration buildings and laboratories are heated with municipal district heat. Interventions from district heating in Aarhus are described in section 3.6.

13.6 Capital goods

The interventions related to capital goods in the vegetable oil industry are described in section 9.7. There are three types of capital goods considered in the vegetable oil industry: '*Building, hall, steel construction*', '*Building, multi-storey*' and '*Facilities, chemical production*'.

The area covered by buildings is estimated from the municipal district plan for the current district (Århus Kommune 2004).

Refinery buildings

Refining and storage of finished products: The buildings for refining cover approximately 4000 m^2 and silos for storage of oil are estimated to cover approximately 300 m^2. Thus, the buildings for refining and storage of finished products are estimated as 4,300 m^2 building hall. An average life time of building halls is estimated to 50 years. The annual amount of NBD oil at AarhusKarlshamn is approximately 200,000 tonne. Hence the building hall required per kg of pressed and extracted oil can be determined as approximately $4.3 \cdot 10^{-4}$ m^2 building hall/t oil.

Overhead: In section 9.7 the area of administration buildings per tonne NBD rapeseed oil has been estimated. Half this is ascribed to the oil mill and the other half to the refinery. Thus, the area of administration buildings related to refining of rapeseed oil at AarhusKarlshamn has been estimated as $3.3 \cdot 10^{-3}$ m^3 multi story building/t oil divided by 2, i.e. $1.7 \cdot 10^{-3}$ m^3 multi story building/t oil.

Refinery machinery (facilities)

The weight of machinery is very roughly estimated from personal communication with Kronborg (2006). The relevant numbers are given in **Table 13.9**.

Process	Weight of machinery incl. pipes	Estimated life time	Annual production	Machinery (kg) per kg oil
Refining	300 tonne	10 years	200,000 tonne	0.15 kg/t oil

Table 13.9: Required machinery (kg) per t oil produced at AarhusKarlshamn. Numbers are based on very rough estimates.

13.7 Transport of raw material and ancillaries to refinery

It is assumed that refineries are attached to oil mills. Thus there is no transport of crude rapeseed oil to the refinery. This is also the case at AarhusKarlshamn. **Table 13.10** provides an overview of the ancillaries transported to AarhusKarlshamn, both in terms of total annual amounts and amounts per tonne NBD oil. Since there are several suppliers and since there is a general lack of data on the specific marginal affected suppliers, all transport distances are based on rough estimates. Determination of size of lorries is based on **Table 4.3**.

Material	Amount to AarhusKarlshamn	Amount per t NBD oil	From	To	Distance	Lorry size
Phosphoric acid	~21 tonne/year	0.8 kg	Abroad chemical plant	Aarhus	1000 km	28t
NaOH	~55 tonne/year	2.1 kg	Abroad chemical plant	Aarhus	1000 km	28t
Sulphuric acid	~49 tonne/year	1.9 kg	Abroad chemical plant	Aarhus	1000 km	28t
Bleaching earth	~230 tonne/year	9.0 kg	Abroad chemical plant	Aarhus	1000 km	40t
Light fuel oil	~36,000 t/year	6.4 kg	Fuel oil supplier	Aarhus	200 km	28t
Fodder fat	~3,700 t/year	12 kg	Refinery	Fodder trader	10 km	28t

Table 13.10: Transport distances of the used raw materials and ancillaries in the refinery stage. The return trip is included in the inventory data.

The amounts in the column ‘Amount to AarhusKarlshamn’ are calculated from figures in **Table 9.1** and **Table 13.11**, the amount of fuel oil is given in **Table 9.12**. The amounts in the column ‘Amount per t NBD oil’ are obtained from figures in **Table 13.11**.

13.8 LCI of rapeseed oil refinery, summary

Table 13.11 summarises the inventory data relating to 1 kg NBD rapeseed oil.

Denmark: 1.000 t NBD rapeseed oil from refinery				
Interventions	**Refining**	**Overhead**	**Total**	**Applied LCI data**
Product output				
NBD rapeseed oil	1.000 t	-	**1.000 t**	Product of interest
Fodder fat	12 kg	-	**12 kg**	Co-product allocation is avoided by system expansion, see **Table 2.3**
Material use				
Crude rapeseed oil	1.017 t	-	**1.017 t**	The interventions related to production of rapeseed oil are included in the oil mill stage stage, see section 9
Phosphoric acid	0.8 kg	-	**0.8 kg**	‘*Phosphoric acid, industrial grade, 85% in H2O, at plant*’ (ecoinvent 2004)
NaOH	2.1 kg	-	**2.1 kg**	‘*Sodium hydroxide, production mix, at plant*’ (ecoinvent 2003)
Sulphuric acid	1.9 kg	-	**1.9 kg**	‘*Sulphuric acid, liquid, at plant*’ (ecoinvent 2004)
Bleaching earth	9.0 kg	-	**9.0 kg**	’*Bentonite, at processing/DE*’ (ecoinvent 2004)
Tap water	27.3 kg	-	**27.3 kg**	See **Table 13.5**
Energy use				
Electricity	104 MJ	0.7 MJ	**105 MJ**	See **Table 3.3**
Heat (steam)	226 MJ	-	**226 MJ**	See **Table 9.4**
Heat (district heat)	-	0.3 MJ	**0.3 MJ**	See section 3.6
Waste to treatment				
Waste water, quantity	79 ltr.	-	**79 ltr.**	see **Table 9.9**
Waste water, P	0.26 kg	-	**0.26 kg**	see **Table 9.9**
Waste water, COD	0.54 kg	-	**0.54 kg**	see **Table 9.9**
Bleaching earth (35% veg. oil) to biogas	14 kg	-	**14 kg**	See **Table 13.8**
Capital goods				
Building halls	$4.3 \cdot 10^{-4}$ m^2	-	**$4.3 \cdot 10^{-4}$ m^2**	‘*Building, hall, steel construction*’ (ecoinvent 2004)
Building, multi story	-	$1.7 \cdot 10^{-3}$ m^3	**$1.7 \cdot 10^{-3}$ m^3**	’*Building, multi-storey’* (ecoinvent 2004)
Machinery	0.15 kg	-	**0.15 kg**	‘*Facilities, chemical production*’, (ecoinvent 2004)
Transport of raw materials and ancillaries to oil mill				
Phosphoric acid	0.8 tkm	-	**0.8 tkm**	‘*Transport, lorry 28t*’ (ecoinvent 2004)
NaOH	2.1 tkm	-	**2.1 tkm**	‘*Transport, lorry 28t*’ (ecoinvent 2004)
Sulphuric acid	1.9 tkm	-	**1.9 tkm**	‘*Transport, lorry 28t*’ (ecoinvent 2004)
Bleaching earth	9.0 tkm	-	**9.0 tkm**	‘*Transport, lorry 40t*’ (ecoinvent 2004)
Light fuel oil	1.3 tkm	-	**1.3 tkm**	‘*Transport, lorry 28t*’ (ecoinvent 2004)
Fodder fat	0.1 tkm	-	**0.1 tkm**	‘*Transport, lorry 28t*’ (ecoinvent 2004)

Table 13.11: Interventions per t NBD rapeseed oil.

14 Refinery stage: Palm oil

Refining of palm oil is principally similar to refining of rapeseed oil. However, the interventions may differ due to different practices in the refinery. Also the loss of oil during neutralisation differs because of different content of free fatty acids (FFA) to be removed. The FFA content of crude palm oil produced at United Plantations Berhad is maximum 2.5% while the maximum limit for traded crude palm oil is 5% (Singh 2006). According to Kang (2006) CPO normally has a content of free fatty acid at 3 to 5%. Thus, it is assumed that CPO sent to refining has FFA content at 4%.

Losses of oil take place in the deodorisation, bleaching and neutralisation processes. The loss in the deodorisation process is assumed to be the same as in rapeseed refining, i.e. 0.1%. In the bleaching process oil is lost due to oil content of approximately 30% in the spent bleaching earth (Singh 2006). Since the use of bleaching earth is 4.53 kg/t NBD palm oil (UPRD 2004) the loss of oil in the bleaching process can be calculated as 1.94 kg palm oil. The loss in the neutralisation process can be calculated from the content of FFA at 4%. The loss of oil from deodorisation is assumed to be discharged with effluent. The product flow related to production of 1 tonne NBD palm oil is shown in **Figure 14.1**.

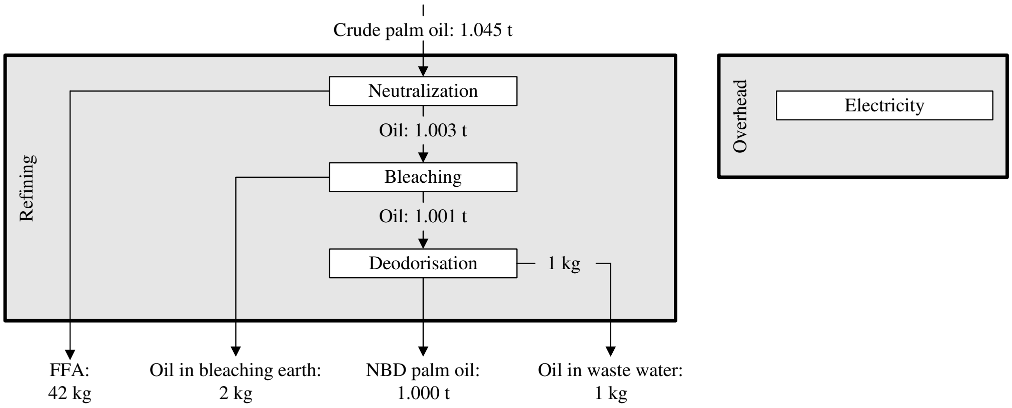


Figure 14.1: Product flow related to production of 1 t NBD palm oil.

14.1 Material use

Table 14.1 shows the material use per tonne NBD palm oil. The consumption of sodium hydroxide in the neutralisation process is 10.4 kg per t, see **Table 14.1**, (assumed 14% solution as in AarhusKarlshamn). Since sodium hydroxide is purchased in 50% solution, the 10.4 kg/t NBD oil is equivalent to 2.9 kg/t (50% solution). The soap from the neutralisation process is sold to soap manufacturing. It is assumed that there is excess of soap from oils and fat refineries. Thus, the soap does not displace any other soap material in the market.

Ancillaries	Neutralisation	Bleaching	Deodorisation
Phosphoric acid	0.25 kg	-	-
Sodium hydroxide (NaOH in 50% water)	2.9 kg	-	-
Bleaching earth	-	4.53 kg	-
Water	700 kg	-	-

Table 14.1: Material uses in the refining stage. All numbers are related 1 t NBD oil. (UPRD 2004)

The used inventory data for phosphoric acid, sodium hydroxide, bleaching earth and water are described in section 13.1. For water, it is assumed that the interventions related to water in Malaysia are the same as in Denmark. The energy and material use pr. m^3 water are very low; 1.3 MJ electricity/m^3 and 4.5 g chemicals/m^3 (see **Table 13.5**). Thus, this assumption may only cause insignificant impacts on the result.

14.2 Energy use

Table 13.6 shows the energy use per tonne NBD palm oil

Energy	Neutralisation, bleaching and deodorisation
Electricity from the grid	126 MJ
Heat (burning of diesel)	328 MJ

Table 14.2: Energy use in the refining stage relating to 1 t NBD palm oil. The use of heat energy is based on diesel consumption at 9 litres/t NBD palm oil and calorific value given in Appendix 1: Data on fuels.

The interventions related to production of electricity are described in section 3.2. Interventions related to burning of diesel in boiler are obtained from ecoinvent: '*Light fuel oil, burned in boiler 100kW, non-modulating/CH*' (ecoinvent 2004). This data set includes air emissions from combustion, production of fuel oil and capital goods (boiler, chimney and storage of fuel oil).

14.3 Emissions

There are no direct emissions from refining.

14.4 Waste to treatment/co-products

Table 14.3 shows the waste to treatment and co-products from the refining of palm oil. The table is based on **Table 13.7** (describing the waste to treatment and co-products from the refining of rapeseed oil) and the material inputs identified in section 14.1.

Waste/co-product	Amount	Treatment
FFA	42 kg	It is assumed that the distillate formed from the FFA displaces the marginal source of fodder energy, i.e. barley.
Oil loss from deodorisation	1 kg	Discharged with effluent
Phosphoric acid (H_3PO_4) (100%)	0. 25 kg	This is neutralised with NaOH in the neutralisation process. The P is discharged with the waste water
Sodium hydroxide (NaOH) (100%)	1.5 kg	The NaOH reacts with the free fatty acids in the neutralisation process and forms soap ($C_{17}H_{33}COONa$)
Bleaching earth	4.5 kg	The 6.4 kg used bleaching earth is landfilled. The oil content in the bleaching earth is 30%.
Oil loss from bleaching: oil in bleaching earth	1.9 kg	
Waste water	700 litre	The 700 litre waste water has the following content: COD: 630 g (900 mg/litre), (Ma 1999b) Fat: 1 kg P: 0.08 kg (Calculated from the consumption of phosphoric acid) The waste water is sent the municipal sewage system where it is lead to the municipal waste water treatment plant

Table 14.3: Overview of waste and co-product flows and their treatment/application relating to 1 t NBD oil.

Interventions from disposal of the waste streams given in **Table 14.3** are described in the following.

Waste water, COD and P

The waste water is treated in an aerobic lagoon, see **Figure 14.2**. The amount of N in the effluent is assumed to be insignificant because clean vegetable oil does not contain N. The content of COD (organic matter) reacts with oxygen and form CO_2. However, this is of biotic origin. Therefore, it has no impacts. There may be minor emissions of methane from small anaerobic pockets in the aerobic ponds. However, this is regarded as insignificant. The content of P will be discharged with the treated effluent to a water stream, i.e. 0.08 kg P/t NBD palm oil.

Figure 14.2: Pond for aerobic treatment of palm oil refinery effluent (Picture taken in United Plantation Berhad 2006).

Used bleaching earth to landfill

The used bleaching earth is normally disposed of to landfill locally. Over time the oil content will be decomposed into CO_2 and water. Since the CO_2 is of biotic origin, it does not contribute to any impacts. There may be forming of methane in anaerobic pockets in the landfill. However, this is regarded as insignificant. Bleaching earth mainly consists of silicon dioxide, aluminium oxide, ferric oxide, magnesium oxide and calcium oxide (AVL 2006). None of these substances cause environmental effects of significance. Thus, no interventions are included for landfilling of used bleaching earth.

FFA used for animal fodder

This co-product is treated in the LCI by system expansion, see section 2.2.

14.5 Overhead

No data on overhead in palm oil refining are available. Therefore, the same data as for refining of rapeseed oil are applied. However, no heating of administration buildings are applied since refining takes place in Malaysia. According to section 13.5 the electricity use per tonne NBD rapeseed oil is 0.7 MJ.

14.6 Capital goods

No data on capital goods in palm oil refineries have been identified. Thus, it is assumed that data for capital goods for a rapeseed oil refinery are representative for a palm oil refinery. The data are described in section 13.6.

14.7 Transport of raw material and ancillaries to refinery

It is assumed that refineries are attached to oil mills. Thus there is no transport of crude palm oil to the refinery. This is also the case at United Plantation Berhad. **Table 14.4** provides an overview of the ancillaries transported to the refinery. Since there are several suppliers and since there is a general lack of data on the specific marginal affected suppliers, all transport distances are based on very rough estimates. Lorry sizes in Malaysia are all assumed to be 28t

Material	Amount per t NBD oil	From	To	Distance	Lorry size
Phosphoric acid	0.25 kg	Abroad chemical plant	Refinery	1000 km	28t
NaOH	2.9 kg	Abroad chemical plant	Refinery	1000 km	28t
Bleaching earth	4.5 kg	Abroad chemical plant	Refinery	1000 km	28t
Diesel	7.8 kg	Fuel oil supplier, Malaysia	Refinery	200 km	28t
Fodder fat	42 kg	Refinery	Fodder trader	200 km	28t

Table 14.4: Transport distances of the used raw materials and ancillaries in the refinery stage. The return trip is included in the inventory data.

The amounts in the column ‘Amount per t NBD oil’ are obtained from the figures in **Table 14.5**, and for diesel also the calorific value given in ‘Appendix 1: Data on fuels’ has been used.

14.8 LCI of palm oil refinery, summary

Table 14.5 summarises the inventory data relating to 1 kg NBD palm oil.

Malaysia and Indonesia: 1.000 t NBD palm oil from refinery				
Interventions	**Refining**	**Overhead**	**Total**	**Applied LCI data**
Product output				
NBD palm oil	1.000 t	-	**1.000 t**	Product of interest
FFA	42 kg	-	**42 kg**	Co-product allocation is avoided by system expansion, see **Table 2.3**
Material use				
Crude palm oil	1.045 t	-	**1.045 t**	The interventions related to production of palm oil are included in the oil mill stage stage, see section 10
Phosphoric acid	0.25 kg	-	**0.25 kg**	‘*Phosphoric acid, industrial grade, 85% in H2O, at plant*’ (ecoinvent 2004)
NaOH	2.9 kg	-	**2.9 kg**	‘*Sodium hydroxide, production mix, at plant*’ (ecoinvent 2003)
Bleaching earth	4.5 kg	-	**4.5 kg**	’*Bentonite, at processing/DE*’ (ecoinvent 2004)
Water	700 kg	-	**700 kg**	See **Table 13.5**
Energy use				
Electricity	126 MJ	0.7 MJ	**127 MJ**	See **Table 3.3**
Heat (steam)	328 MJ	-	**328 MJ**	‘*Light fuel oil, burned in boiler 100kW, non-modulating/CH*’ (ecoinvent 2004)
Emissions to water				
Phosphorus	0.08 kg	-	**0.08 kg**	Emission to water (from waste water)
Waste to treatment				
Waste water	700 kg	-	**700 kg**	Emission of P, see above
Bleaching earth to landfill	6.4 kg	-	**6.4 kg**	No interventions
Capital goods				
Building halls	$4.3 \cdot 10^{-4}$ m^2	-	**$4.3 \cdot 10^{-4}$ m^2**	‘*Building, hall, steel construction*’ (ecoinvent 2004)
Building, multi story	-	$1.7 \cdot 10^{-3}$ m^3	**$1.7 \cdot 10^{-3}$ m^3**	’*Building, multi-storey’* (ecoinvent 2004)
Machinery	0.15 kg	-	**0.15 kg**	‘*Facilities, chemical production*’, (ecoinvent 2004)
Transport of raw materials and ancillaries to oil mill				
Phosphoric acid	0.25 tkm	-	**0.25 tkm**	‘*Transport, lorry 28t*’ (ecoinvent 2004)
NaOH	2.9 tkm	-	**2.9 tkm**	‘*Transport, lorry 28t*’ (ecoinvent 2004)
Bleaching earth	4.5 tkm	-	**4.5 tkm**	‘*Transport, lorry 28t*’ (ecoinvent 2004)
Diesel	1.6 tkm	-	**1.6 tkm**	‘*Transport, lorry 28t*’ (ecoinvent 2004)
Fodder fat	8.4 kg	-	**8.4 tkm**	‘*Transport, lorry 28t*’ (ecoinvent 2004)

Table 14.5: Interventions per t NBD palm oil.

15 Refinery stage: Palm kernel oil

Refining of palm kernel oil is principally similar to refining of palm oil and rapeseed oil. However, the interventions may differ due to different practices in the refinery. Also the loss of oil during neutralisation differs because of different content of free fatty acids (FFA) to be removed.

No data on refining of palm kernel oil have been identified. Therefore, it is assumed that refining of palm kernel oil is similar to refining of palm oil. The only difference is the content of FFA in crude PKO which is lower than in crude palm oil. It is assumed that the FFA content is 1% as in crude rapeseed oil, see section 13. The product flow chart including this modification of the refining process of palm oil is shown in **Figure 15.1**.

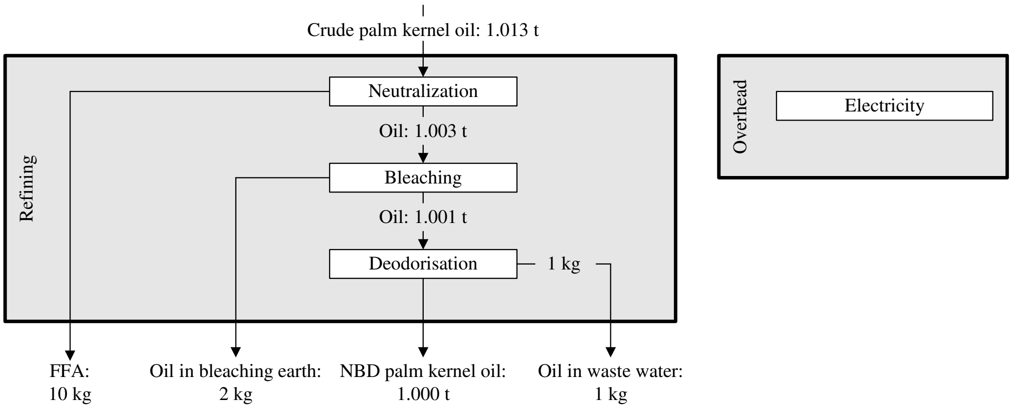


Figure 15.1: Product flow related to production of 1 t NBD palm kernel oil.

The interventions related to refining of palm kernel oil are described in section 14. The only difference is the amount of the co-product, 10 kg FFA sold as fodder fat, which displaces palm oil, barley and soybean meal. The system expansion is described in section 2.2.

15.1 LCI of palm kernel oil refinery, summary

Table 15.1 summarises the inventory data relating to 1 tonne NBD palm kernel oil.

Malaysia and Indonesia: 1.000 t NBD palm kernel oil from refinery				
Interventions	**Refining**	**Overhead**	**Total**	**Applied LCI data**
Product output				
NBD palm kernel oil	1.000 t	-	**1.000 t**	Product of interest
FFA	10 kg	-	**10 kg**	Co-product allocation is avoided by system expansion, see **Table 2.3**
Material use				
Crude palm kernel oil	1.013 t	-	**1.013 t**	The interventions related to production of palm kernel oil are included in the oil mill stage stage, see section 11
Phosphoric acid	0.25 kg	-	**0.25 kg**	‘*Phosphoric acid, industrial grade, 85% in H2O, at plant*’ (ecoinvent 2004)
NaOH	2.9 kg	-	**2.9 kg**	‘*Sodium hydroxide, production mix, at plant*’ (ecoinvent 2003)
Bleaching earth	4.5 kg	-	**4.5 kg**	’*Bentonite, at processing/DE*’ (ecoinvent 2004)
Water	700 kg	-	**700 kg**	See **Table 13.5**
Energy use				
Electricity	126 MJ	0.7 MJ	**127 MJ**	See **Table 3.3**
Heat (steam)	328 MJ	-	**328 MJ**	‘*Light fuel oil, burned in boiler 100kW, non-modulating/CH*’ (ecoinvent 2004)
Emissions to water				
Phosphorus	0.08 kg	-	**0.08 kg**	Emission to water (from waste water)
Waste to treatment				
Waste water	700 kg	-	**700 kg**	Emission of P, see above
Bleaching earth to landfill	6.4 kg	-	**6.4 kg**	No interventions
Capital goods				
Building halls	$4.3 \cdot 10^{-4}$ m^2	-	**$4.3 \cdot 10^{-4}$ m^2**	‘*Building, hall, steel construction*’ (ecoinvent 2004)
Building, multi story	-	$1.7 \cdot 10^{-3}$ m^3	**$1.7 \cdot 10^{-3}$ m^3**	’*Building, multi-storey*’ (ecoinvent 2004)
Machinery	0.15 kg	-	**0.15 kg**	‘*Facilities, chemical production*’, (ecoinvent 2004)
Transport of raw materials and ancillaries to oil mill				
Phosphoric acid	0.25 tkm	-	**0.25 tkm**	‘*Transport, lorry 28t*’ (ecoinvent 2004)
NaOH	2.9 tkm	-	**2.9 tkm**	‘*Transport, lorry 28t*’ (ecoinvent 2004)
Bleaching earth	4.5 tkm	-	**4.5 tkm**	‘*Transport, lorry 28t*’ (ecoinvent 2004)
Diesel	1.6 tkm	-	**1.6 tkm**	‘*Transport, lorry 28t*’ (ecoinvent 2004)
Fodder fat	2.0 tkm	-	**2.0 tkm**	‘*Transport, lorry 28t*’ (ecoinvent 2004)

Table 15.1: Interventions per t NBD palm kernel oil.

16 Refinery stage: Soybean oil

No data on refining of soybean oil have been identified. Therefore it is assumed that the interventions related to 1 tonne NBD rapeseed oil is the same as 1 tonne NBD soybean oil. The inventory data for refining rapeseed oil are summarised in **Table 13.11**.

However a few adjustments to the inventory for rapeseed oil refining are done:

- Electricity from the grid: Marginal electricity in Brazil is applied, see See **Table 3.3**
- District heat: No district heating is used
- Bleaching earth to biogas: This is not sent to biogas in Brazil, disposal is assumed to be landfilling without any interventions
- Transport distance of fodder fat from refinery to fodder trader is assumed to be 300 km instead of 10 km as in Denmark

17 Transport stage

The transport stage includes transportation of the finished refined rapeseed oil and palm oil to final consumption which is assumed to be in central Europe represented by Amsterdam.

The refined rapeseed oil is transported in a 40 t lorry from AarhusKarlshamn in Aarhus in Denmark to Amsterdam in the Netherlands, i.e. 791 km (Krak 2006).

The refined palm oil produced in Malaysia and Indonesia is regarded as being transported 200 km in a 28 t lorry to a port. From there it is transported in an oceanic tanker 8,117 nautical miles corresponding to 15,033 km[24] (Distances 2006). The distance is represented by the distance from Port Kelang in Malaysia to the port in Amsterdam, the Netherlands.

The interventions related to transportation of the refined oil to final consumption are summarised in **Table 17.1**. The interventions related to each tonne kilometre (tkm) are described in section 4.

Transport of NBD oil	Rapeseed oil	Palm oil	Applied LCI data
Lorry, 28 t	-	200 tkm	'*Transport, lorry 28t*' (ecoinvent 2004)
Lorry, 40 t	791 tkm	-	'*Transport, lorry 40t*' (ecoinvent 2004)
Ocean tanker	-	15,033 tkm	'*Transport, transoceanic tanker/OCE*' (ecoinvent 2004)

Table 17.1: Interventions per t NBD vegetable oil in the transport stage.

---

[24] 1 nautical mile corresponds to 1.852 km.

18 Emissions from intensified cultivation

The emissions from intensified production are mainly determined from the business as usual cultivation of crops described in sections 5, 6, 7 and 8. Firstly the marginal technologies of increasing yields are determined. After that, the parameters representing the identified means of changing the yields are changed in the business as usual cultivation of crops in sections 5, 6, 7 and 8.

18.1 Identification of methods of increasing yields

Based on Schmidt (2007b) **Table 18.1** provides an overview of the most common means of achieving increased productivity in agriculture.

Increased agricultural inputs	Alternative technology	Management
Fertiliser	Agricultural machinery (man, ox or tractor)	Scheduling of agricultural inputs
Irrigation	GMO	Integrated pest management (weed control)
Pesticides (weed control)	Variety selection	Double-cropping (more crop rotations per year)
-	Seed improvement	-
-	Drainage	-

Table 18.1: Overview of most important means of inccreasing yields.

Identifying the marginal method of increasing productivity in agriculture is very difficult. Some improvements take place regardless of changes in demand for the crop of interest. Thus, most farmers seek to maximise economical benefit of their farm which often imply changes in agricultural inputs, technology and management. The marginal changes are those which are directly related to increased demand for the desired crop.

According to Weidema (2003) the marginal method of increasing yields in Europe is by additional nitrogen fertiliser input. Based on discussions with United Plantations Research Department (Singh 2006) nitrogen fertiliser is also considered as the marginal source of increasing yields of oil palm. Soybean is only fertilised with phosphate, thus it is assumed that there are no significant yield responses to input of N-fertiliser. According to Jales et al. (2006) and USDA (2006) the most important method used for increasing yields of soybean in Argentina and Brazil has been increased double-croppping. The use of biotechnology has resulted in a shorther crop cycle of soybean which has made increased double-cropping possible (USDA 2006). Therefore, the marginal method for increasing yields in Brazil is assumed to be increased double-croppping. According to **Table 8.1** the yield of barley in Canada is considerable lower than in Denmark and according to IFA et al. (2002) the use of fertilisers in Canadian barley cultivation is also significant lower than in Denmark. Therefore, corresponding to the EU, it is assumed that N-fertiliser is also the marginal method for increasing the yields in Canada.

18.2 Determination of changed parameters

In the previous section the marginal methods for increasing yields of rapeseed, oil palm, soybean and barley have been identified. In order to calculate the emissions from intensified cultivation, the changed parameters firstly have to be determined.

Level of intensification

Rapeseed, oil palm and barley: For increased yields of rapeseed, oil palm and barley which are achived by additional N-fertiliser, intensified cultivation is assumed to be with an additional fertiliser input of 5%.

The level of intensification at 5% increase is chosen abitrary since there is no information on how much fertiliser application is increased in order to increase yields. However, since the N- and P-related emissions that will be affected by additional fertiliser are proportional with N and P input this assumption will not affect the results.

Soybean: Intensified soybean cultivation is assumed to take place with 5% points increase in the area which is double-cropped, i.e. the double-cropped area is inreased from 25% to 30%.

Yield responses to fertiliser (rapeseed, oil palm, barley)

In **Table 18.2**, which is directly obtained from Schmidt (2007b), yield responses to additional N-fertiliser are given for different levels of N-application.

	Δyield (kg/ha) /ΔN-rate (kg N/ha)			
Crop and region	0-50 kg N/ha	50-100 kg N/ha	100-150 kg N/ha	150-200 kg N/ha
Maize (Nebraska, USA)	56	19	7	4
Maize (Oklahoma, USA)	24	22	12	8
Winter wheat (Oklahoma, USA)	15	6	-	-
Winter wheat (Sweden)	40	17	12	4
Rapeseed (Denmark)	13	15	9	4
Rapeseed (Germany)	10	12	10	4
Soybean (Argentina)	0	0	0	0
Fresh fruit bunches from oil palm (Malaysia)	149	87	62	48

Table 18.2: Yield responses to increased N-fertiliser input. (Schmidt 2007b).

It appears from **Table 18.2** that the yield response is very sensitive to the desired region/study (e.g. compare winter wheat in USA and Sweden) and the level of N-application (e.g. compare maize responses to additional fertiliser in Nebraska for low and high levels of N-application). Therefore, determination of emissions related to increased production by increased yields is associated with considerable uncertainties. These uncertainties are assessed in a sensitivity analysis in section 21.20.

The levels of N-application are obtained from section 5.4, 6.5 and 8.4. In **Table 18.2** the data for rapeseed in Sweden are applied for rapeseed cultivation, the data for winter wheat in Sweden are applied for barley cultivation and the data for FFB in Malaysia are applied for oil palm cultivation. The yield responses to additional application of N-fertiliser applied in this study are summarised in **Table 18.3**.

Crop and region	Level of N-application	N-application interval in Table 18.2	Present yield, t/ha	Yield response, kg crop/ha per kg N/ha
Rapeseed, Denmark	167 kg N/ha	150-200	3.24	4
Oil palm, Malaysia and Indonesia	105 kg N/ha	100-150	18.87	62
Barley, Denmark	121 kg N/ha	100-150	5.23	12
Barley, Canada	67 kg N/ha	50-100	2.91	17

Table 18.3: Yield responses applied in this study.

Based on the present levels of N-application and the yield responses to additional N-fertiliser in **Table 18.3** and the increase in N-fertiliser at 5%, the N-application and yields in intensified cultivation are summarised in **Table 18.4**.

Crop and region	Additional N-application, ΔN (5% increase)	New level of N-application	Yield response, ΔY kg crop/ha	Yield, kg/ha
Rapeseed, Denmark	7.0 kg N/ha	147.0 kg N/ha*	28 kg/ha	3,268 (3,240+28)
Oil palm, Malaysia and Indonesia	5.3 kg N/ha	110.3 kg N/ha	329 kg/ha	19,199 (18,870+329)
Barley, Denmark	6.1 kg N/ha	127.1 kg N/ha	73 kg/ha	5,303 (5,230+73)
Barley, Canada	3.4 kg N/ha	70.4 kg N/ha	58 kg/ha	2,968 (2,910+58)

Table 18.4: N-application and yields in intensified cultivation. * The reason why N-application in rapeseed cultivation is less than specified in **Table 18.3** is that the value in **Table 18.3** is inclusive a 'previous crop' value at 27 kg N/ha.

When determining the emissions from intensified cultivation of rapeseed, oil palm and barley only the input of N-fertiliser and the yield is changed. In order to maintain balance in the application of different nutrients to the fields, P and K fertilisers are also increased by 5%.

The changes in yield affect energy for drying of seed and transport of crops and co-products to traders. The changes in application of fertilisers affect transportation of fertilisers to farm and N and P related emissions. The N and P related emissions are calculated establishing new N and P balances, and the emissions are calculated using the same method as described in sections 5.6, 6.7 and 8.6.

Yield responses to increased double-cropping (soybean)

According to **Table 7.1** the yield for single-cropping is 2.68 t/ha and for 25% double-croppping the yield is 3.35 t/ha. If the area that is double-cropped is 30% the yield yield for single-cropping must be multiplied by a factor of 1.3 (=0.30·2 + 0.70). Thus, the yield when 30% of the area is double-cropped is 3.484 t/ha.

When determining the emissions from intensified cultivation of soybean almost all interventions are proportional with the increase in yield. Thus these are simply multiplied with a facto of 3.484/3.350 = 1.04. However, the N-related emissions are not directly proportional with increased in yield. This is because the input of N from atmospheric deposition is not changed as a consequence of double-cropping. Therefore, a new N-balance is established and the N-related emissions are calculated using the same method as described in section 7.5.

18.3 LCI of intensified cultivation, summaries

In this section the summary tables of the inventories of intensified cultivation of rapeseed (Denmark), FFB (Malaysia and Indonesia), soybean (Brazil), barley (Denmark) and barley (Canada) are presented. The inventories are based on data and methods described in sections 5, 6, 7 and 8 and the changed parameters presented in previous section (section 18.2).

LCI of intensified rapeseed cultivation (Denmark), summary

Table 18.5 summarises the inventory data relating to 1 ha y rapeseed field.

Denmark: 1 ha y intensified rapeseed field		
Interventions	**Amount**	**Applied LCI data**
Product output		
Rapeseed	3.259 t*	Product of interest, 3,259 kg (=3,268 kg minus 9 kg for seed production)
Straw removed from field	381 kg	Co-product allocation between rapeseed and straw is avoided by system expansion, see below
System expansion		
Burning of straw in biomass plant	381 kg	See **Table 5.25**
Energy use		
Traction, burned diesel	3,612 MJ	See **Table 4.5**
Drying of rapeseed (evaporated water)	101 kg*	Modified version of: ‘*Grain drying, low temperature/CH*’ (ecoinvent 2004), see section 5.3
Miscellaneaus transport (passenger car)	79 km	‘*Transport, passenger car/RER*’ (ecoinvent 2004)
Material use		
Seed	5 kg	See **Table 5.12**
N-fertiliser (as N)	147 kg*	‘*Calcium ammonium nitrate, as N, at regional storehouse/RER*’, (ecoinvent 2004)
P-fertiliser (as P_2O_5)	60 kg*	Modified version of: ‘*Triple superphosphate, as P_2O_5, at regional storehouse/RER’* (ecoinvent 2004), see section 5.4
K-fertiliser (as K_2O)	104 kg*	‘*Potassium chloride, as K_2O, at regional storehouse/RER’* (ecoinvent 2004)
Herbicide (clomazone)	0.050 kg	Modified version of: ‘*Pesticide unspecified, at regional storehouse/RER*’ (ecoinvent 2004), see section 5.4
Herbicide (propyzamid)	0.18 kg	Modified version of: ‘*Pesticide unspecified, at regional storehouse/RER*’ (ecoinvent 2004), see section 5.4
Herbicide (clopyralid)	0.020 kg	Modified version of: ‘*Pesticide unspecified, at regional storehouse/RER*’ (ecoinvent 2004), see section 5.4
Insecticide (Pyrethroid, cypermethrin)	0.0070 kg	Modified version of: ‘*Pyretroid-compounds, at regional storehouse/RER*’ (ecoinvent 2004), see section 5.4
Insecticide (Pyrethroid, alpha-cypermethrin)	0.0020 kg	Modified version of: ‘*Pyretroid-compounds, at regional storehouse/RER*’ (ecoinvent 2004), see section 5.4
Insecticide (Pyrethroid, tau-fluvalinat)	0.0072 kg	Modified version of: ‘*Pyretroid-compounds, at regional storehouse/RER*’ (ecoinvent 2004), see section 5.4
Capital goods		
Agricultural buildings	0.070 m^2	‘*Shed/CH/I*’ (ecoinvent 2004)
Machinery, tractor	7.5 kg	‘*Tractor, production/CH/I*’ (ecoinvent 2004)
Machinery, combine harvester	6.3 kg	‘*Harvester, production/CH/I*’ (ecoinvent 2004)
Machinery, tillage	9.2 kg	‘*Agricultural machinery, tillage, production/CH/I*’ (ecoinvent 2004)
Machinery, general/miscellaneous	3.5 kg	‘*Agricultural machinery, general, production/CH/I*’ (ecoinvent 2004)
Transport		
16t lorry	0.5 tkm	‘*Transport, lorry 16t*’ (ecoinvent 2004)
28t lorry	366 tkm*	‘*Transport, lorry 28t*’ (ecoinvent 2004)
40t lorry	1,942 tkm*	‘*Transport, lorry 40t*’ (ecoinvent 2004)

… table continued on the next page…

Table 18.5: Interventions per ha y intesified rapeseed field in Denmark. Parameters which are changed compared to the inventory in section 5 are marked with a *. Table continued on the next page…

… continued from previous page…

Emissions	Air	Water	Soil
Ammonia (NH_3)	9.6 kg*	-	-
Dinitrogen oxide (N_2O)	5.3 kg*	-	-
Nitric oxide (NO)	3.0 kg*	-	-
Nitrate (NO_3)	-	188 kg*	-
Phosphorus (P)	-	0.17 kg*	-
Clomazone	0.017 kg	0.017 kg	0.017 kg
Propyzamid	0.060 kg	0.060 kg	0.060 kg
Clopyralid	0.0067 kg	0.0067 kg	0.0067 kg
Cypermethrin	0.0023 kg	0.0023 kg	0.0023 kg
Alpha-cypermethrin	0.0067 kg	0.0067 kg	0.0067 kg
Tau-fluvalinat	0.0024 kg	0.0024 kg	0.0024 kg
Arsenic (As)	-	-	1.2 g*
Cadmium (Cd)	-	0.61 g*	-0.20 g*
Chromium (Cr)	-	0.19 g*	35 g*
Cobalt (Co)	-	0.045 g*	0.24 g*
Copper (Cu)	-	1.0 g*	7.0 g*
Mercury (Hg)	-	0.037 g*	-0.010 g*
Molybdenum (Mo)	-	-	1.2 g*
Nickel (Ni)	-	1.0 g*	11 g*
Lead (Pb)	-	2.0 g*	-0.60 g*
Selenium (Se)	-	0.016 g*	2.5 g*
Zink (Zn)	-	16 g*	68 g*

Table 18.5: Interventions per ha y intesified rapeseed field in Denmark. Parameters which are changed compared to the inventory in section 5 are marked with a *.

LCI of intensified oil palm cultivation (Indonesia and Malaysia), summary

Table 18.6 summarises the inventory data relating to 1 ha y cultivated with oil palm.

<table>
<tr><th colspan="4">Malaysia and Indonesia: 1 ha y intensified oil palm plantation</th></tr>
<tr><th>Interventions</th><th>Amount</th><th colspan="2">Applied LCI data</th></tr>
<tr><td colspan="4">Product output</td></tr>
<tr><td>FFB</td><td>19,199 kg*</td><td colspan="2">Product of interest</td></tr>
<tr><td colspan="4">Energy use</td></tr>
<tr><td>Traction, burned diesel</td><td>2,118 MJ</td><td colspan="2">See section 4.3</td></tr>
<tr><td>Electricity for overhead</td><td>0.053 MJ</td><td colspan="2">See Table 3.3</td></tr>
<tr><td colspan="4">Material use</td></tr>
<tr><td>N-fertiliser, ammonium sulphate (as N)</td><td>80.3 kg*</td><td colspan="2">‘<i>Ammonium sulphate, as N, at regional storehouse/RER</i>’ (ecoinvent 2004)</td></tr>
<tr><td>N-fertiliser, urea (as N)</td><td>29.7 kg*</td><td colspan="2">‘<i>Urea, as N, at regional storehouse/RER</i>’, (ecoinvent 2004)</td></tr>
<tr><td>P-fertiliser (as P_2O_5)</td><td>73 kg*</td><td colspan="2">Phosphate rock, see section 6.5: Fertilisers</td></tr>
<tr><td>K-fertiliser (as K_2O)</td><td>215 kg*</td><td colspan="2"><i>Potassium chloride, as K_2O, at regional storehouse/RER’</i>, ecoinvent (2004)</td></tr>
<tr><td>Herbicide, typically glyphosate</td><td>2.4 kg</td><td colspan="2">‘Glyphosate, at regional storehouse/RER’ (ecoinvent 2004)</td></tr>
<tr><td>Insecticide, typically cypermethrin</td><td>0.31 kg</td><td colspan="2">‘Pesticide unspecified, at regional storehouse/RER’ (ecoinvent 2004)</td></tr>
<tr><td>Fungicides, various different</td><td>0.013 kg</td><td colspan="2">‘Pesticide unspecified, at regional storehouse/RER’ (ecoinvent 2004)</td></tr>
<tr><td>Rodenticide, typically warfarin</td><td>0.00021 kg</td><td colspan="2">‘Pesticide unspecified, at regional storehouse/RER’ (ecoinvent 2004)</td></tr>
<tr><td colspan="4">Capital goods</td></tr>
<tr><td>Agricultural buildings, shed</td><td>0.041 m^2</td><td colspan="2">‘<i>Shed/CH/I</i>’ (ecoinvent 2004)</td></tr>
<tr><td>Agricultural buildings, administration etc.</td><td>0.00139 m^3</td><td colspan="2">‘<i>Building, multi-storey</i>’ (ecoinvent 2004)</td></tr>
<tr><td>Machinery, tractor</td><td>4.4 kg</td><td colspan="2">‘<i>Tractor, production/CH/I</i>’ (ecoinvent 2004)</td></tr>
<tr><td>Machinery, tillage</td><td>0.4 kg</td><td colspan="2">‘<i>Agricultural machinery, tillage, production/CH/I</i>’ (ecoinvent 2004)</td></tr>
<tr><td>Machinery, general/miscellaneous</td><td>2.1 kg</td><td colspan="2">‘<i>Agricultural machinery, general, production/CH/I</i>’ (ecoinvent 2004)</td></tr>
<tr><td colspan="4">Transport</td></tr>
<tr><td>40t lorry</td><td>1,208 tkm*</td><td colspan="2">‘<i>Transport, lorry 40t</i>’ (ecoinvent 2004)</td></tr>
<tr><td>Oceanic tanker</td><td>12,080 tkm*</td><td colspan="2">‘<i>Transport, transoceanic tanker/OCE</i>’ (ecoinvent 2004)</td></tr>
<tr><th>Emissions</th><th>Air</th><th>Water</th><th>Soil</th></tr>
<tr><td>Carbon dioxide (CO_2)</td><td>1,500 kg</td><td></td><td></td></tr>
<tr><td>Ammonia (NH_3)</td><td>18.9 kg*</td><td>-</td><td>-</td></tr>
<tr><td>Dinitrogen oxide (N_2O)</td><td>10.4 kg*</td><td>-</td><td>-</td></tr>
<tr><td>Nitric oxide (NO)</td><td>3.3 kg*</td><td>-</td><td>-</td></tr>
<tr><td>Nitrate (NO_3)</td><td>-</td><td>375 kg*</td><td>-</td></tr>
<tr><td>Phosphorus (P)</td><td>-</td><td>1.7 kg*</td><td>-</td></tr>
<tr><td>Glyphosate</td><td>0.80 kg</td><td>0.80 kg</td><td>0.80 kg</td></tr>
<tr><td>Cypermethrin</td><td>0.10 kg</td><td>0.10 kg</td><td>0.10 kg</td></tr>
<tr><td>Fungicides, various different</td><td colspan="3">Not included, no characterisation data exist in LCIA methods</td></tr>
<tr><td>Warfarin</td><td colspan="3">Not included, no characterisation data exist in LCIA methods</td></tr>
<tr><td>Arsenic (As)</td><td>-</td><td>-</td><td>1.1 g*</td></tr>
<tr><td>Cadmium (Cd)</td><td>-</td><td>-</td><td>2.0 g*</td></tr>
<tr><td>Chromium (Cr)</td><td>-</td><td>-</td><td>47 g*</td></tr>
<tr><td>Cobalt (Co)</td><td>-</td><td>-</td><td>0.25 g*</td></tr>
<tr><td>Copper (Cu)</td><td>-</td><td>-</td><td>12 g*</td></tr>
<tr><td>Mercury (Hg)</td><td>-</td><td>-</td><td>0.028 g*</td></tr>
<tr><td>Molybdenum (Mo)</td><td>-</td><td>-</td><td>0.12 g*</td></tr>
<tr><td>Nickel (Ni)</td><td>-</td><td>-</td><td>5.4 g*</td></tr>
<tr><td>Lead (Pb)</td><td>-</td><td>-</td><td>2.1 g*</td></tr>
<tr><td>Selenium (Se)</td><td>-</td><td>-</td><td>0.44 g*</td></tr>
<tr><td>Zink (Zn)</td><td>-</td><td>-</td><td>72 g*</td></tr>
</table>

Table 18.6: Interventions per ha y intensified oil palm plantation in Malaysia and Indonesia. Parameters which are changed compared to the inventory in section 6 are marked with a *.

LCI of intensified soybean cultivation (Brazil), summary

Table 18.7 summarises the inventory data relating to 1 ha y soybean field.

Brazil: 1 ha y intensified soybean field		
Interventions	**Amount**	**Applied LCI data**
Product output		
Soybean	3.341 t*	Product of interest, 3,341 kg (=3,484 kg minus 143 kg for seed production)
Energy use		
Traction, burned diesel	1,987 MJ*	See **Table 4.5**
Drying of soybeans (evaporated water)	71 kg*	Modified version of: ‘*Grain drying, low temperature/CH*’ (ecoinvent 2004), see section 5.3
Material use		
Seed	143 kg*	See **Table 7.2**
P-fertiliser (as P_2O_5)	48 kg*	Phosphate rock, see section 6.5: Fertilisers
Herbicide, glyphosate	2.4 kg*	‘Glyphosate, at regional storehouse/RER’ (ecoinvent 2004)
Herbicide, 2-4 D	-	-
Herbicide, imazethapyr	-	-
Insecticide, pyrethroid, cypermethrin	0.014 kg*	‘Pyretroid-compounds, at regional storehouse/RER’ (ecoinvent 2004)
Insecticide, Chlorpyrifos	0.21 kg*	‘Pesticide unspecified, at regional storehouse/RER’ (ecoinvent 2004)
Capital goods		
Agricultural buildings	0.038 m^2*	‘*Shed/CH/I*’ (ecoinvent 2004)
Machinery, tractor	4.2 kg*	‘*Tractor, production/CH/I*’ (ecoinvent 2004)
Machinery, combine harvester	3.4 kg*	‘*Harvester, production/CH/I*’ (ecoinvent 2004)
Machinery, tillage	5.0 kg*	‘*Agricultural machinery, tillage, production/CH/I*’ (ecoinvent 2004)
Machinery, general/miscellaneous	2.0 kg*	‘*Agricultural machinery, general, production/CH/I*’ (ecoinvent 2004)
Transport		
40t lorry	1,769 tkm*	‘*Transport, lorry 40t*’ (ecoinvent 2004)
Oceanic tanker	843 tkm*	‘*Transport, transoceanic tanker/OCE*’ (ecoinvent 2004)

Emissions	**Air**	**Water**	**Soil**
Ammonia (NH3)	0 kg	-	-
Dinitrogen oxide (N2O)	4.9 kg *	-	-
Nitric oxide (NO)	1.2 kg*	-	-
Nitrate (NO3)	-	0 kg	-
Phosphorus (P)	-	0.072 kg*	-
Glyphosate	0.80 kg*	0.80 kg*	0.80 kg*
2-4 D	No LCI data on a.i., and no characterisation data exist in LCIA methods		
Imazethapyr	No LCI data on a.i., and no characterisation data exist in LCIA methods		
Cypermethrin	0.0045 kg*	0.0045 kg*	0.0045 kg*
Chlorpyrifos	0.070 kg*	0.070 kg*	0.070 kg*
Arsenic (As)	-	-	-
Cadmium (Cd)	-	0.023 g*	1.2 g*
Chromium (Cr)	-	0.20 g*	29 g*
Cobalt (Co)	-	0.030 g*	-0.016 g*
Copper (Cu)	-	5.9 g*	1.5 g*
Mercury (Hg)	-	0 g*	0.00048 g*
Molybdenum (Mo)	-	-	-
Nickel (Ni)	-	2.0 g*	0.60 g*
Lead (Pb)	-	0.030 g*	0.56 g*
Selenium (Se)	-	0.038 g*	0.046 g*
Zink (Zn)	-	18 g*	10 g*

Table 18.7: Interventions per ha y intensified soybean field in Brazil. Parameters which are changed compared to the inventory in section 7 are marked with a *.

LCI of intensified barley cultivation (Denmark), summary

Table 18.8 summarises the inventory data relating to 1 ha y spring barley field in Denmark.

Denmark: 1 ha y intensified spring barley field		
Interventions	**Amount**	**Applied LCI data**
Product output		
Spring barley (Denmark)	5.193 t*	Product of interest, 5,193 kg (=5,303 kg minus 110 kg for seed production)
Straw removed from field	2,207 kg*	Co-product allocation between barley and straw is avoided by system expansion, see below
System expansion		
Burning of straw in biomass plant	2,207 kg*	See **Table 5.25**
Energy use		
Traction, burned diesel	4,029 MJ	See **Table 4.5**
Drying of barley (evaporated water)	108 kg*	Modified version of: '*Grain drying, low temperature/CH*' (ecoinvent 2004), see section 5.3
Material use		
Seed	110 kg	See **Table 8.2**
N-fertiliser (as N)	127.1 kg*	'*Calcium ammonium nitrate, as N, at regional storehouse/RER*', (ecoinvent 2004)
P-fertiliser (as P_2O_5)	48 kg*	Modified version of: '*Triple superphosphate, as P_2O_5, at regional storehouse/RER*' (ecoinvent 2004), see section 5.4
K-fertiliser (as K_2O)	69 kg*	'*Potassium chloride, as K_2O, at regional storehouse/RER*' (ecoinvent 2004)
Capital goods		
Agricultural buildings	0.078 m^2	'*Shed/CH/I*' (ecoinvent 2004)
Machinery, tractor	8.4 kg	'*Tractor, production/CH/I*' (ecoinvent 2004)
Machinery, combine harvester	7.0 kg	'*Harvester, production/CH/I*' (ecoinvent 2004)
Machinery, tillage	10.3 kg	'*Agricultural machinery, tillage, production/CH/I*' (ecoinvent 2004)
Machinery, general/miscellaneous	3.9 kg	'*Agricultural machinery, general, production/CH/I*' (ecoinvent 2004)
Transport		
40t lorry	2,050 tkm*	'*Transport, lorry 40t*' (ecoinvent 2004)

Emissions	**Air**	**Water**	**Soil**
Ammonia (NH3)	9.2 kg*	-	-
Dinitrogen oxide (N2O)	4.3 kg*	-	-
Nitric oxide (NO)	2.6 kg*	-	-
Nitrate (NO3)	-	147 kg*	-
Phosphorus (P)	-	0.10 kg*	-
Arsenic (As)	-	-	0.93 g*
Cadmium (Cd)	-	0.045 g*	0.29 g*
Chromium (Cr)	-	0.21 g*	28 g*
Cobalt (Co)	-	0.0056 g*	0.22 g*
Copper (Cu)	-	2.5 g*	4.2 g*
Mercury (Hg)	-	0.034 g*	-0.0076 g*
Molybdenum (Mo)	-	-	1.0 g*
Nickel (Ni)	-	0.22 g*	9.1 g*
Lead (Pb)	-	0.23 g*	0.86 g*
Selenium (Se)	-	0.023 g*	2.1 g*
Zink (Zn)	-	21 g*	48 g*

Table 18.8: Interventions per ha y intensified barley field in Denmark. Parameters which are changed compared to the inventory in section 8 are marked with a *.

LCI of intensified barley cultivation (Canada), summary

Table 18.9 summarises the inventory data relating to 1 ha y barley in Canada.

Canada: 1 ha y intensified barley field			
Interventions	**Amount**	**Applied LCI data**	
Product output			
Barley (Canada)	2.858 t*	Product of interest, 2,858 kg (=2,968 kg minus 110 kg for seed production)	
Straw removed from field	0	-	
System expansion			
Burning of straw in biomass plant	0	-	
Energy use			
Traction, burned diesel	4,029 MJ	See **Table 4.5**	
Drying of barley (evaporated water)	61 kg*	Modified version of: ‘*Grain drying, low temperature/CH*’ (ecoinvent 2004), see section 5.3	
Material use			
Seed	110 kg	See **Table 8.2**	
N-fertiliser (as N)	70.4 kg*	‘*Ammonium nitrate, as N, at regional storehouse/RER*’, (ecoinvent 2004)	
P-fertiliser (as P_2O_5)	27 kg*	Phosphate rock, see section 6.5: Fertilisers	
K-fertiliser (as K_2O)	11 kg*	‘*Potassium chloride, as K_2O, at regional storehouse/RER*’ (ecoinvent 2004)	
Capital goods			
Agricultural buildings	0.078 m^2	‘*Shed/CH/I*’ (ecoinvent 2004)	
Machinery, tractor	8.4 kg	‘*Tractor, production/CH/I*’ (ecoinvent 2004)	
Machinery, combine harvester	7.0 kg	‘*Harvester, production/CH/I*’ (ecoinvent 2004)	
Machinery, tillage	10.3 kg	‘*Agricultural machinery, tillage, production/CH/I*’ (ecoinvent 2004)	
Machinery, general/miscellaneous	3.9 kg	‘*Agricultural machinery, general, production/CH/I*’ (ecoinvent 2004)	
Transport			
40t lorry	1,502 tkm*	‘*Transport, lorry 40t*’ (ecoinvent 2004)	
Emissions	**Air**	**Water**	**Soil**
Ammonia (NH3)	7.8 kg*	-	-
Dinitrogen oxide (N2O)	2.4 kg*	-	-
Nitric oxide (NO)	1.6 kg*	-	-
Nitrate (NO3)	-	60 kg*	-
Phosphorus (P)	-	0.090 kg*	-
Arsenic (As)	-	-	0.17 g*
Cadmium (Cd)	-	0.025 g*	0.73 g*
Chromium (Cr)	-	0.12 g*	17 g*
Cobalt (Co)	-	0.0032 g*	0.064 g*
Copper (Cu)	-	1.4 g*	2.8 g*
Mercury (Hg)	-	0.019 g*	-0.0049 g*
Molybdenum (Mo)	-	-	0.27 g*
Nickel (Ni)	-	0.12 g*	2.1 g*
Lead (Pb)	-	0.13 g*	0.57 g*
Selenium (Se)	-	0.013 g*	1.0 g*
Zink (Zn)	-	12 g*	9.5 g*

Table 18.9: Interventions per ha y intensified barley field in Canada. Parameters which are changed compared to the inventory in section 8 are marked with a *.

19 Emissions from transformation of land and from non-cultivated land

Increases in agricultural production are often achived by expanding the cultivated area. Emissions arise when non-cultivated land (e.g. set-aside land, forest, savannah, grassland) is transformed into agricultural land and the emissions from the non-cultivated land are displaced by the emissions from the new agricultural land.

In this section the emissions related to transformation of land are inventoried. As indicated above, this includes two sources of emissions: Firstly, there are emissions arised from the transformation itself, i.e. emissions related to difference in stading stock of carbon, nitrogen and other substances, and secondly, when non-cultivated land is transformed into agricultural land the contineous emissions from this non-cultivated land are avoided and subsequently displaced by the emissions from the new agricultural land.

The two sources of emissions are treated seperately because the emissions from the transformation itself are hard to relate to the functional unit, while the avoided contineous emissions from non-cultivated land are proportional with the annual yields and thereby easy to relate to the functional unit. The emissions from the transformation itself are referred to as emissions from transformation processes and the contineous emissions are referred to as avoided emissions from occupation of non-cultivated land. These terms are in accordance with the terms used i relation to land use in LCA and are described more in detail in Schmidt (2007c). The emissions from transformation processes are defined as all emissions that are related to a change in equilibrium of the standing stock of living and dead biomass. The annual change in the soil organic carbon and nitrogen due to land transformation years ago could be included as emissions related to occupation processes. This is actually the case in Nielsen et al. (2005). However, annual changes of carbon and nitrogen in the soil matter are not constant with time, and consequentily it is difficult to relate the changes to the functional unit. According to Petersen and Berntsen (2002), the duration before a new equilibrium state is reached may take up to more than 200 years.

In section 2.3, the affected land use types related to transfomation of 1 ha non-cultivated land into agriculture are specified, see **Table 19.1**.

Region	Transformation from…	Transformation to…
Denmark	Set-aside area	Cropland, rapeseed
Indonesia and Malaysia	Secondary/degraded tropical rainforest (50%) Alang-alang grass land (50%)	Perennial cropland, oil palm plantation
Brazil	Secondary/degraded tropical rainforest (5%) Cerrado savannah (95%)	Cropland, soybean
Canada	Prairie grass land	Cropland, barley

Table 19.1: Affected land use types when 1 ha non-cultivated land is transformed into agriculture in the relevant regions. The data are obtained from section 2.3.

For the land use types in **Table 19.1**, the following two sections describe the emissions that arise from transformation processes (section 19.1) and the avoided emissions from occupation of non-cultivated land (section 19.2).

19.1 Emissions from transformation processes

The relevant emissions related to transformation processes are those which are related to the C- and N-cycles. The emissions related to the C-cycle are CO_2, CO and CH_4. Because of lack of data the emissions of CO and CH_4 have been omitted. In the IPCC guidelines (IPCC 2003) emissions of CO and CH_4 are only considered in the case of burning of residues and therefore these emissions are considered as insignificant when claering forests wiothout burning. The emissions related to the N-cycle are N_2O, NO, N_2 and nitrate. The emissions of N_2O are calculated based on the change in the stock of nitrogen. Because of lack of data it has not been possible to calculate the emission of NO related to transformation processes. Therefore, this emission has been omitted. The emission of N_2 is based on generalised figures on the ration between N_2O and N_2 and the emission of nitrate is calculated as the residual from the N-balance.

There may also be emissions of P and heavy metals because the land transformation processes may contribute to a release of these substances. However, this is omitted from this study.

Table 19.2 and **Table 19.3** specify the carbon stocks in the different affected land use types. The carbon stock is constituted by soil organic carbon and carbon in biomass. In some cases, for carbon in biomass, data have only been available for above ground biomass. In these cases the total carbon in biomass have been calculated using the root-to-shoot ratios given in IPCC (2003, p 3.110).

Crop and region	**Applied data**		
	Carbon stock	**Reference**	**Determining parameters for calculation/estimation of carbon stock**
Rapeseed, Denmark			
Soil organic carbon	23 t C/ha	(IPCC 2003, p 3.75-3.77)	Cultivation: full tillage, low input of organic matter Conditions: cold temperate, dry, average of clay and sandy soils
Carbon in biomass	0 t C/ha	(IPCC 2003, p 3.84)	Since the dominant vegetation is removed allmost entirely every year the stock is assumed to be zero
Total	**23 t C/ha**	-	-
Plantation, Malaysia and Indonesia			
Soil organic carbon	50 t C/ha	Estimated from Henson (2004, p 17)	-
C in biomass	26 t C/ha	(Henson 2004, p 7)	Average value for 25 years replanting cycle in Malaysia
C in ground vegetation	1.3 t C/ha	(Henson 2004, p 10)	Average value for 25 years replanting cycle in Malaysia
C in frond piles	2.1 t C/ha	(Henson 2004, p 12)	Average value for 25 years replanting cycle in Malaysia
C in felled non-burned oil palm material	2.5 t C/ha	(Henson 2004, p 12)	Average value for 25 years replanting cycle in Malaysia
Total	**82 t C/ha**	-	-
Soybean, Brazil			
Soil organic carbon	26 t C/ha	(IPCC 2003, p 3.75-3.77)	Cultivation: reduced tillage, medium input of organic matter Conditions: tropical, moist, average of clay and sandy soils
Carbon in biomass	0 t C/ha	(IPCC 2003, p 3.84)	Since the dominant vegetation is removed allmost entirely every year the stock is assumed to be zero
Total	**26 t C/ha**	-	-
Barley, Canada			
Soil organic carbon	25 t C/ha	(IPCC 2003, p 3.75-3.77)	Cultivation: full tillage, medium input of organic matter Conditions: cold temerpate, dry, average of clay and sandy soils
Carbon in biomass	0 t C/ha	(IPCC 2003, p 3.84)	Since the dominant vegetation is removed allmost entirely every year the stock is assumed to be zero
Total	**25 t C/ha**	-	-

Table 19.2: Determination of carbon stock per hectare in the fields of the affected crops.

Land-use type and region	**Data**		
	Carbon stock	**Reference**	**Determining parameters for calculation/estimation of carbon stock**
Set-aside land, Denmark			
Carbon stock in set-aside	47 t C/ha	(IPCC 2003, p 3.75-3.77)	Carbon in soil is calculated using (IPCC 2003, p 3.75-3.77) and Cultivation: 20 year set-aside, no tillage, high input of organic matter, Conditions: cold temerpate, dry, average of clay and sandy soils, i.e. 38 t C/ha Carbon in biomass is assumed to be the same as grassland in cold, temperate, dry climate (IPCC 2003, p 3.109-3.110), i.e. 9 t C/ha.
Applied data	**47 t C/ha**	-	-
Secondary/degraded forest, Indonesia and Malaysia			
Carbon stock in tropical forest	195 t C/ha	(IPCC 2003)	Tropical forest, Asia, wet:: 57 t C/ha in soil (PCC 2003, p 3.43) and 138 t C/ha in biomass stock (IPCC 2003, 3.157)
Applied data	**195 t C/ha**	-	-
Alang-alang grassland, Malaysia and Indonesia			
Carbon stock in grassland	30 t C/ha	(Tian et al. 2000)	Grassland (Amazon)
Carbon stock in grassland	66 t C/ha	(IPCC 2003)	Grassland, tropical, moist, average of clay and sandy soils: 50 t C/ha in soil (IPCC 2003, p 3.117) and 16 t C/ha in biomass stock (IPCC 2003, pp 3.109-3.110)
Carbon stock in grassland	73 t C/ha	(IPCC 2003)	Grassland, tropical, wet, average of clay and sandy soils: 57 t C/ha in soil (IPCC 2003, p 3.117) and 16 t C/ha in biomass stock (IPCC 2003, pp 3.109-3.110)
Applied data	**73 t C/ha**	-	The figures from IPCC for wet tropical grassland are applied. The reason for chosing wet grassland is that oil palm requires >2000 mm precipitation annually (Corley and Tinker 2003, p 67)
Cerrado savannah, Brazil			
Carbon stock in savannah	204 t C/ha	(Chen et al. 2003)	Tropical savannah, Australia
Carbon stock in savannah	102 t C/ha	(Tian et al. 2000)	Savannah (Amazon)
Carbon stock in grassland	59 t C/ha	(IPCC 2003)	Grassland/savannah, tropical, moist, average of clay and sandy soils: 50 t C/ha in soil (IPCC 2003, p 3.117) and 9 t C/ha in biomass stock (IPCC 2003, pp 3.109-3.110)
Applied data	**102 t C/ha**	-	Singificant differences between compared data. The actual modelling of savannah in the Amazon at 102 t C/ha is close to the average of the three references. This is applied
Secondary/degraded forest, Brazil			
Carbon stock in tropical forest	226 t C/ha	(Tian et al. 2000)	Tropical evergreen forest (Amazon)
Carbon stock in tropical forest	243 t C/ha	(Tian et al. 2000)	Other forest/woodland (Amazon)
Carbon stock in tropical forest	231 t C/ha	(IPCC 2003)	Tropical forest, America, wet:: 57 t C/ha in soil (IPCC 2003, p 3.43) and 174 t C/ha in biomass stock (IPCC 2003, 3.157)
Applied data	**231 t C/ha**	-	The difference between the compared data is small. The data from IPCC are applied
Prairie, grassland, Canada			
Carbon stock in grassland	48 t C/ha	(IPCC 2003, p 3.117)	Grassland, cold temperate, dry, average of clay and sandy soils: 39 t C/ha in soil (IPCC 2003, p 3.117) and 9 t C/ha in biomass stock (IPCC 2003, pp 3.109-3.110)
Applied data	**48 t C/ha**	-	-

Table 19.3: Determination of carbon stock per hectare in the affected non-cultivated land use types that are transformed into agriculture.

In addition to the changes in the stock of carbon related to land transformation, there are also associated changes in the stock of nitrogen. IPCC (2003, p 3.94) suggest a C:N-ratio in soils at 15. Billore et al. (1995) suggest C:N-ratios for biomass of grassland and evergreen forests at 65 and 32 respectively. These ratios are applied to the carbon stocks given in **Table 19.2** and **Table 19.3**. The N in soil matter for the affected land use types is specified in **Table 19.4** and **Table 19.5**.

Crop and region	Carbon stock	C:N-ration	Nitrogen stock
Rapeseed, Denmark			
Soil	23 t C/ha	15	1.5 t N/ha
Biomass	0 t C/ha	-	-
Total	**23 t C/ha**	**-**	**1.5 t N/ha**
Plantation, Malaysia and Indonesia			
Soil	50 t C/ha	15	3.3 t N/ha
Biomass	32 t C/ha	32	1.0 t N/ha
Total	**82 t C/ha**	**-**	**4.3 t N/ha**
Soybean, Brazil			
Soil	26 t C/ha	15	1.7 t N/ha
Biomass	**0** t C/ha	-	-
Total	**26 t C/ha**	**-**	**1.7 t N/ha**
Barley, Canada			
Soil	25 t C/ha	15	1.7 t N/ha
Biomass	0 t C/ha	-	-
Total	**25 t C/ha**	**-**	**1.7 t N/ha**

Table 19.4: Determination of nitrogen stocks per hectare in the fields of the affected crops.

Land use type and region	Carbon stock	C:N-ration	Nitrogen stock
Set-aside, Denmark			
Soil	38 t C/ha	15	2.5 t N/ha
Biomass	9 t C/ha	65	0.1 t N/ha
Total	**47 t C/ha**	**-**	**2.6 t N/ha**
Secondary/degraded forest, Indonesia and Malaysia			
Soil	57 t C/ha	15	3.8 t N/ha
Biomass	138 t C/ha	32	4.3 t N/ha
Total	**195 t C/ha**	**-**	**8.1 t N/ha**
Alang-alang grassland, Malaysia and Indonesia			
Soil	57 t C/ha	15	3.8 t N/ha
Biomass	16 t C/ha	65	0.2 t N/ha
Total	**73 t C/ha**	**-**	**4.0 t N/ha**
Cerrado savannah, Brazil			
Soil	86 t C/ha	15	5.7 t N/ha
Biomass	16 t C/ha	65	0.2 t N/ha
Total	**102 t C/ha**	**-**	**5.9 t N/ha**
Secondary/degraded forest, Brazil			
Soil	57 t C/ha	15	3.8 t N/ha
Biomass	174 t C/ha	32	5.4 t N/ha
Total	**231 t C/ha**	**-**	**9.2 t N/ha**
Prairie, grassland, Canada			
Soil	39 t C/ha	15	2.6 t N/ha
Biomass	9 t C/ha	65	0.1 t N/ha
Total	**48 t C/ha**	**-**	**2.7 t N/ha**

Table 19.5: Determination of nitrogen stocks per hectare in the affected non-cultivated land use types that are transformed into agriculture.

Table 19.6 summarises the changes in carbon and nitrogen stocks related to land use transformation.

Rapeseed	**From set-aside to rapeseed, Denmark**	
	Carbon release	**Nitrogen release**
Soil	15 t C/ha	1.0 t N/ha
Biomass	9 t C/ha	0.1 t N/ha
Total	**24 t C/ha**	**1.1 t N/ha**
Oil palm	**From secondary/degraded forest to oil palm, Malaysia and Indonesia**	
	Carbon release	**Nitrogen release**
Soil	7 t C/ha	0.5 t N/ha
Biomass	106 t C/ha	3.3 t N/ha
Total	**113 t C/ha**	**3.8 t N/ha**
Oil palm	**From alang-alang grassland to oil palm, Malaysia and Indonesia**	
	Carbon release	**Nitrogen release**
Soil	7 t C/ha	0.5 t N/ha
Biomass	-16 t C/ha	-0.8 t N/ha
Total	**-9 t C/ha**	**-0.3 t N/ha**
Soybean	**From cerrado savannah to soybean, Brazil**	
	Carbon release	**Nitrogen release**
Soil	60 t C/ha	4.0 t N/ha
Biomass	16 t C/ha	0.2 t N/ha
Total	**76 t C/ha**	**4.2 t N/ha**
Soybean	**From secondary/degraded forest to soybean, Brazil**	
	Carbon release	**Nitrogen release**
Soil	31 t C/ha	2.1 t N/ha
Biomass	174 t C/ha	5.4 t N/ha
Total	**205 t C/ha**	**7.5 t N/ha**
Barley	**From prairie grassland to barley, Canada**	
	Carbon release	**Nitrogen release**
Soil	14 t C/ha	0.9 t N/ha
Biomass	9 t C/ha	0.1 t N/ha
Total	**23 t C/ha**	**1.0 t N/ha**

Table 19.6: Summary of the changes in carbon and nitrogen stocks related to land use transformation.

Since open burning when clearing land in Indonesia and Malaysia is prohibited, it is assumed that clearing for oil palm is done without burning. Hereby, all the change in carbon is assumed to oxide to carbon dioxide and the change in nitrogen is assumed to be distributed between N_2O, N_2 and nitrate. According to IPCC (2003, p 3.94) the emission factor for N_2O related to changes in soil N is 0.0125 kg N_2O-N/kg N. Since degradation of biomass will end as nitrate in the soil, it is assumed that the emission factor provided by IPCC applies to the total change in the nitrogen stock. The emission of N_2 is based on a N_2/N_2O-ration at approximately 3 for mixed sand and clay soils in Denmark (Vinther and Hansen 2004). Thus it can be calculated that the relase of nitrogen is distributed on 1.25% N_2O-N, 3.75% N_2-N and 95% NO_3-N. However, when there is a net up-take of N as in the case of transformation of alang-alang grassland into oil palm in Malaysia and Indonesia, no emissions related to N are accounted for. This is because it is assumed, that the plant's need for nitrogen is met by N-fertiliser, i.e. no removal of N in soil matter. **Table 19.7** summarises the emissions that arise from transformation. The amounts of emissions per kg C or kg N are calculated using the molar proporties: 3.67 kg CO_2/kg C, 1.57 kg N_2O/kg N and 4.43 kg nitrate/kg N.

Rapeseed	**From set-aside to rapeseed, Denmark**
CO_2	88 t CO_2/ha
N_2O	0.022 t N_2O/ha
Nitrate	4.6 t NO_3/ha
Oil palm	**From secondary/degraded forest to oil palm, Malaysia and Indonesia**
CO_2	415 t CO_2/ha
N_2O	0.075 t N_2O/ha
Nitrate	16.0 t NO_3/ha
Oil palm	**From alang-alang grassland to oil palm, Malaysia and Indonesia**
CO_2	-33 t CO_2/ha
N_2O	0 t N_2O/ha
Nitrate	0 t NO_3/ha
Soybean	**From cerrado savannah to soybean, Brazil**
CO_2	279 t CO_2/ha
N_2O	0.082 t N_2O/ha
Nitrate	17.7 t NO_3/ha
Soybean	**From secondary/degraded forest to soybean, Brazil**
CO_2	752 t CO_2/ha
N_2O	0.147 t N_2O/ha
Nitrate	31.6 t NO_3/ha
Barley	**From prairie grassland to barley, Canada**
CO_2	84 t CO_2/ha
N_2O	0.020 t N_2O/ha
Nitrate	4.2 t NO_3/ha

Table 19.7: Summary of the changes in carbon and nitrogen stocks related to land use transformation.

19.2 Avoided emissions from occupation of non-cultivated land

This section describes emissions from non-cultivated land. The only relevant emissions from non-cultivated land are assumed to be N-related emissions. The only input is atmospheric deposition and this is distributed on the following emissions:

- N_2O and NO: These are determined from literature studies
- N_2: This is calculated assuming a N_2/N_2O-ratio at 3 correspondingly to determination of N_2 in section 19.1
- Nitrate: The emission of nitrate is regarded as the residual

Since non-cultivated land is assumed to be in an equilibrium state, there will be no changes in the soil matter of C and N.

N_2O- and NO-emissions

Set-aside area: Ruser et al. (2001) have measured the annual emission of dinitrogen oxide from set-aside areas in Southern Germany as 0.29 kg N_2O-N/ha. This is also applied as N_2O-emissions from set-aside areas in Denmark. No data on NO-emissions from set-aside areas have been identified. Therefore, it is assumed that the ratio between N_2O and NO emissions from set-aside areas is the same as for natural grassland described below. Thus, the emission of NO is 1.1 kg NO-N/ha.

Grassland: N_2O emissions from grassland, i.e. alang-alang grassland in Malaysia and Indonesia and prairie grassland in Canada, are obtained from Stehfest and Bouwman (2006). Stehfest and Bouwman (2006) compare the N_2O and NO emissions from soils under natural vegetation on the global scale calculated with two models. It is chosen to apply the average of the two emissions levels given in Stehfest and Bouwman (2006). Thus the emission of N_2O from grassland is 0.32 kg N_2O-N/ha. The NO-emission from grassland is 0.89 kg NO-N/ha.

Savannah: N_2O-emissions from the Cerrado savannah in Brazil are obtained from the same source as emissions from grassland described above. The N_2O-emission from savannah/open tropical forest in Stehfest and Bouwman (2006) is in average 0.59 kg N_2O-N/ha. The emission of NO is 1.8 kg NO-N/ha.

Tropical forests: Tropical forests in Indonesia and Malysia and to a lesser extent Brazil are affected in this study. According to Kiese and Butterbach-Bahl (2003) there are great variations of N_2O emissions from tropical forests from year to year. Thus, they show a difference with a factor of 6-7 from one year to the following year. Kiese and Butterbach-Bahl (2003) specify an emission at 0.97 kg N_2O-N/ha while Kiese and Butterbach-Bahl (2002) specify an emission at 6.2 kg N_2O-N/ha. Stehfest and Bouwman (2006) specify a N_2O-emission at 1.37 kg N_2O-N/ha. Werner et al. (2006) summarises varies studies of N_2O emissions from primary and secondary forests in South Easy Asia. The average N_2O emission from primary forests in Werner et al. (2006) is 0.34 kg N_2O-N/ha and from secondary forests it is 0.63 kg N_2O-N/ha. These figures are significant lower than those given in Kiese and Butterbach-Bahl (2002), Kiese and Butterbach-Bahl (2003) and Stehfest and Bouwman (2006). The variations may be due to differeces in soil types, precipiation, and methods of measurements and modelling. However, since Werner et al. (2006) include a summary of several real measurements and since these measurements are in South East Asia, it is chosen to apply the average value of primary and secondary forest, i.e. 0.49 kg N_2O-N/ha.

The only identified data on NO-emissions from tropical forests are found in Stehfest and Bouwman (2006) where the average of the given figures is 0.53 kg NO-N/ha. This is applied in this study.

N_2-emissions

The N_2-emissions are determined using a N_2/N_2O-ration at 3.

Nitrate

The emissions of nitrate are calculated as the input of N which is assumed to be the atmospheric N-deposition minus the emissions of N_2O, NO and N_2. The N-deposition is the affected areas are descibed in sections 5.6, 6.7, 7.5 and 8.6. The atmospheric N-depositions are Denmark (15 kg N/ha), Indonesia and Malaysia (17.5 kg N/ha), Brazil (8 kg N/ha) and Canada (3.3 kg N/ha). The nitrate emissions are shown in **Table 19.8**.

Summary of avoided emissions from occupation of non-cultivated land

Table 19.8 summarises the N-balance for non-cultivated land.

Region	DK	MY&IN		BR		CAN
Land-use type	**Set-aside**	**Forest**	**Grassland**	**Savannah**	**Forest**	**Grassland**
Input:						
N-deposition	15.0 kg N/ha	17.5 kg N/ha	17.5 kg N/ha	8.0 kg N/ha	8.0 kg N/ha	3.3 kg N/ha
Output						
Denitrification: N_2O	0.29 kg N/ha	0.49 kg N/ha	0.32 kg N/ha	0.59 kg N/ha	0.49 kg N/ha	0.32 kg N/ha
Denitrification: NO	1.1 kg N/ha	0.53 kg N/ha	0.89 kg N/ha	1.8 kg N/ha	0.53 kg N/ha	0.89 kg N/ha
Denitrification: N_2	0.87 kg N/ha	1.47 kg N/ha	0.96 kg N/ha	1.77 kg N/ha	1.47 kg N/ha	0.96 kg N/ha
Total denitrification	2.3 kg N/ha	2.5 kg N/ha	2.2 kg N/ha	4.2 kg N/ha	2.5 kg N/ha	2.2 kg N/ha
Surplus: Nitrate	12.7 kg N/ha	15.0 kg N/ha	15.3 kg N/ha	3.8 kg N/ha	5.5 kg N/ha	1.1 kg N/ha

Table 19.8: N-balance for non-cultivated land. All values are given in kg N/ha.

Table 19.9 Summarises the avoided emissions from occupation of non-cultivated land.

Region	DK	MY&IN		BR		CAN
Land-use type	**Set-aside**	**Forest**	**Grassland**	**Savannah**	**Forest**	**Grassland**
N_2O	0.46 kg N_2O/ha	0.77 kg N_2O/ha	0.50 kg N_2O/ha	0.93 kg N_2O/ha	0.77 kg N_2O/ha	0.50 kg N_2O/ha
NO	2.4 kg NO/ha	1.1 kg NO/ha	1.9 kg NO/ha	3.9 kg NO/ha	1.1 kg NO/ha	1.9 kg NO/ha
Nitrate	56 kg NO_3/ha	66 kg NO_3/ha	68 kg NO_3/ha	17 kg NO_3/ha	24 kg NO_3/ha	5 kg NO_3/ha

Table 19.9: Summary of the avoided emissions from non-cultivated land.

20 Life cycle impact assessment (LCIA)

The purpose of this report is to provide life cycle inventory data on the product systems of rapeseed oil and palm oil, not to carry out an LCIA. However, in order to carry out sensitivity analyses (see section 21), the characterised results for the inventoried scenarios are presented here but without comments and interpretation.

The scenarios are described in section 2.4.

Impact category	Scenario 1			Scenario 2			Scenario 3		Scenario 4		Scenario 5	
	RSOa	**RSOb**	**PO**	**RSOa**	**RSOb**	**PO**	**RSO**	**PO**	**RSO**	**PO**	**RSO**	**PO**
Global warming (t CO_2)	12.0	8.19	2.16	5.15	2.40	2.32	17.1	2.60	2.39	2.36	2.22	2.47
Ozone depletion (mg CFC11)	366	304	43.8	210	147	44.6	549	77.8	147	44.6	163	54.5
Acidification (kg SO_2)	52.2	47.9	13.8	39.2	25.8	13.0	82.4	23.5	26.0	13.3	20.2	14.8
Eutrophication (t NO_3)	1549	1159	80.6	201	172	102	2733	337	211	119	140	124
Photochemical smog (kg ethene)	1.36	1.30	0.526	1.22	0.869	0.509	1.95	0.617	0.869	0.509	0.887	0.551
ETWC (mio m^3 water)	-4857	-4857	1354	-4685	-4685	1423	-5748	-13.4	-4685	1423	75.2	1407
ETWA (mio m^3 water)	-133	-133	49.8	-127	-127	52.3	-161	-0.362	-127	52.3	3.12	51.6
ETSC (mio m^3 soil)	-25.1	-25.1	0.538	-24.5	-24.5	0.625	-27.6	-0.0602	-24.5	0.625	0.0473	0.670
Land use (ha y)	-0.281	0.170	0.235	0.960	0.337	0.175	0	0	0.337	0.175	0.548	0.242
Biodiversity (wS100)	1.11	6.97	6.64	2.36	10.8	6.84	0	0	10.8	6.84	7.13	6.78

Table 20.1: Characterised results of the inventoried scenarios. The results are obtained using the updated EDIP97-method for LCIA (see section 1.4). Biodiversity is obtained using the method of Schmidt (2007c)

21 Sensitivity analyses

Throughout the scope definition in section 2 and the LCI described in sections 3 to 19, several improvement options and uncertainties in assumptions and data have been identified. Most of these influencing factors are evaluated in this section. The sensitivity analyses presented in this section tests how sensitive the results of the inventory are to various assumptions, uncertainties of data and alternative cultivation practices/technologies (improvement options). In order to have consistency and to maintain comparability of the different sensitivity analyses, each sensitivity analysis is carried out using the same functional unit (1 tonne vegetable oil) and the same scenario (scenario 4). Scenario 4 is chosen because this scenario is not related to uncertainties regarding system expansion in the agricultural stage where especially modelling of increased yield is regarded as uncertain. These uncertainties are analysed in separate sensitivity analyses using other scenarios than scenario 4.

Table 21.1 provides an overview of the included sensitivity analyses. **Table 21.1** also provides references to the sections where the uncertainties of interest are described.

No.	Reference	Aim	Description of sensitivity analyses
1	Section 1.4	Uncertainty	**LCIA-methods:** EDIP97 is applied as default LCIA-method. This sensitivity analysis compares the results when using the LCIA-methods; Impact2002+ and Eco-indicator 99 (H)
2	Section 2.1	Uncertainty	**System delimitation, marginal supplier of crops:** The identification of marginal suppliers is related to uncertainty, especially the marginal supplier of barley (Canada). This sensitivity analysis shows results when the marginal suppliers of barley are EU25 and Russia, and when the marginal suppliers of FFB are either Indonesia or Malaysia alone. The identification of Brazil as the marginal supplier of soybean is less uncertain, and cultivation of soybean in Argentina is much similar to Brazil
3	Section 2.3 and 19.1	Uncertainty & Improvement option	**System delimitation, type of land transformed into agricultural land:** Uncertainties in identifying the affected land types are present. The uncertainties regarding land for oil palm in Indonesia/Malaysia and land for barley in Canada are regarded as the most significant. This sensitivity analysis compares the results when transformed land in Indonasia/Malaysia is alang-alang grassland, secondary forest and primary forest, and when transformed land in Canada is natural grassland (prairie) and degraded land (similar to EU set-aside land)
4	Section 3.1	Uncertainty	**Energy, marginal source of electricity:** This sensitivity analysis compares the results when marginal electricity is coal based and natural gas based
5	Section 3.6	Uncertainty	**Energy, representativiness of data on district heating in Denmark:** This sensitivity analysis assesses the uncertainties in the obtained results due to uncertainties in the applied data for district heating in Denmark
6	Section 5.6, 6.7, 7.5, 8.6	Uncertainty	**Agricultural cultivation, energy for traction:** Uncertainties in the determination of energy use for traction for the affected crops are assessed in this sensitivity analysis
7	Section 5.6	Uncertainty & Improvement option	**Rapeseed cultivation, soil type:** This sensitivity analysis compares the results when cultivating rapeseed on average soil, clay soils and sandy soils
8	Section 5.4	Improvement option	**Rapeseed cultivativation, N-fertiliser produced using best available techniques (BAT):** The tail gas from the production of nitric acid, which is used in the production of calcium ammonium nitrate, is treated using best available techniques. Hereby the N_2O in the tail gas is reduced by 85%
9	Section 5.6, 6.7, 7.5, 8.6	Uncertainty	**Agricultural cultivation, N changes in soil matter:** The changes in N in soil matter in this study are assumed to be zero for continuous cultivation and all the changes are ascribed to transformation of land use. This sensitivity analysis compares the obtained results with a situation when changes in N in soil matter for rapeseed, soybean and barley cultivation are included
10	Section 5.6, 6.7, 7.5	Uncertainty	**Agricultural cultivation, heavy metal contents in fertilisers:** The heavy metal content in fertilisers vary significantly in the used data sources. This sensitivity analysis assesses the uncertainties related to that
11	Section 5.6, 6.7, 7.5	Uncertainty	**Agricultural cultivation, initial compartment of pesticide emissions:** This sensitivity assess the uncertainties in the obtained results related to the assumption that the initial compartment of pesticide emissions are 33% air, 33% water and 33% soil
12	Section 6	Uncertainty	**Oil palm cultivation, yields:** The yield of oil palm is dependant on cultivation practices which again are depandant on the region (Malaysia and Indonesia) and the ownership plantation (smallholder, state-owned FELDA or private estate). This sensitivity analysis assesses the uncertainty in the obtained results relating the determination of the yield
13	Section 6 and 6.7	Uncertainty & Improvement option	**Oil palm cultivation, soil type:** This sensitivity analysis compares the results when cultivating oil palm on mineral soils versus peat soils
14	Section 6.7	Uncertainty	**Oil palm cultivation, uncertainties in CO_2-emissions from peat soil:** This sensitivity analysis assesses the uncertainties in the obtained results for palm oil relating to the determination of CO_2-emissions from peat soils
15	Section 8.4	Uncertainty	**Barley cultivation, omission of use and emissions of pesticides:** This sensitivity analysis assesses the uncertaines relating to the omission of pesticides in barley cultivation

Table continued on the next page…

Table 21.1: Sensitivity analyses. The numbers refer to the sensitivity analyses presented in the following sections. Table continued on the next page…

Table continued from the previous page…

No.	Reference	Aim	Description of sensitivity analyses
16	Section 9	Uncertainty & Improvement option	**Rapeseed oil mill, solvent extraction versus full press:** This sensitivity analysis compares the results when using the solvent extraction technology with a situation when using the full press technology
17	Section 9.7, 10.8, 11.8, 12.8	Uncertainty	**Oil mills, capital goods:** The amount of capital goods used in the oil mill stage is related to significant uncertainties. Therefore, this sensitivity analysis assesses the significans of these uncertainties
18	Section 10, 10.5	Uncertainty & Improvement option	**Palm oil mill, POME-treatment:** Normally the treatment of palm oil mill effluent is anaerobic and aerobic tretamtn in ponds. This sensitivity analysis applies a situation where digester tanks are used instead of anaerobic ponds and the collected biogas is utilised for electricity generation
19	Section 10, 10.1, 10.6	Uncertainty	**Palm oil mill, steam requirement:** This sensitivity analysis applies a steam requirement at 0.5 t instead of the 0.65 t which is applied as default in the study
20	Section 10	Improvement options	**Palm oil mill, alternative management options for EFB:** Empty fruit bunches (EFB) from the palm oil mill are applied as mulch in the plantation in the baseline scenario. This sensitivity analysis analyses the effect of two alternative management options for EFB: 1) Disposal in landfill and 2) Utilisation in a biomass plant with electricity production
21	Section 18.2	Uncertainty & Improvement option	**Insensified cultivation, yield-responses to additional fertiliser:** Great differences in yield-responses to additional fertiliser input have been identified. Therefore, this sensitivity analysis assesses the uncertainties related to that. In Malaysia and Indonesia there are great differences in the level of fertiliser application. Therefore, there may be potentials for improvements by additional fertiliser application in extensively cultivated areas

Table 21.1: Sensitivity analyses. The numbers refer to the sensitivity analyses presented in the following sections.

21.1 No. 1: LCIA-methods

The uncertainties in the obtained results related to the use of the EDIP97 LCIA-method are assessed in this sensitivity analysis. The following impact categories are assessed; global warming, acidification, eutrophication, photochemical smog and ecotocicity. For each of the impact categories the top-five of the most significant emissions is identified using the LCIA-methods: EDIP97 (see section 1.4), Impact2002+ (Jolliet et al. 2003) and Eco-indicator (Goedkoop and Spriensma 2001). For each impact category the intersection of sets is counted, i.e. the number of emissions that appears in all three compared methods. If the intersection of sets is 5, there is a high level of consistency among the compared methods while if the intersection of sets is zero, there is a low level of consistency.

EDIP97: Global warming		Impact2002+		Eco-indicator 99 (H)	
Emission	Contribution	Emission	Contribution	Emission	Contribution
CH_4	40%	CO_2	53%	CH_4	36%
CO_2	31%	N_2O	26%	CO_2	31%
N_2O	29%	CH_4	21%	N_2O	32%
CO	0,13%	CO	0,050%	CO	0.10%
NMVOC	0,04%	Sulfur hexaflouride	0.023%	Sulfur hexaflouride	0.010%
Total	**2,358 kg CO_2-eq**	**Total**	**1,371 kg CO_2-eq**	**Total**	**4.92E-4 DALY**

Table 21.2: Global warming, 1 t palm oil (scenario 4).

The intersection of sets is four. The difference between EDIP97 and Eco-indicator 99 is insignificant. But it appears that there are differences in the total kg CO_2-eq. between EDIP97 and Impact2002+. His is somehow surprising because characterisation models for global warming are normally regarded as relatively certain. The reason for the difference is primarily because EDIP97 applies a 100 years time horizon while Impact2002+ has applied a 500 years time horizon. This implies that the characterisation factors in Impact2002+ for methane is only one third of EDIP97 and for dinitrogenmonoxide it is only half of EDIP97.

EDIP97: Acidification		Impact2002+: Terrestrial acid/nutri		Eco-indicator 99 (H): Acidification/ Eutrophication	
Emission	**Contribution**	**Emission**	**Contribution**	**Emission**	**Contribution**
NH_3	59%	NH_3	73%	NH_3	73%
SO_2	17%	NO_x	18%	NO_x	18%
NO_x	15%	NO	6.6%	NO	6.6%
NO	5.4%	SO_2	2.6%	SO_2	2.6%
H_2S	3.8%	-	-	SO_4	-0.0068%
Total	**13.3 kg SO_2-eq**	**Total**	**85.9 kg SO_2-eq**	**Total**	**89.4 pdf*m2yr**

Table 21.3: Acidification, 1 t palm oil (scenario 4).

The intersection of sets is four. In general the consistency between the methods is regarded as relatively high. However, comparing the total contribution using the EDIP97-method and the Impact2002+ method the difference is significant. This is primarily because the category indicator of acidification in Impact2002+ covers acidification as well as eutrophication. Thus, the total of the results is not directly comparable.

EDIP97: Eutrophication		Impact2002+: Terrestrial acid/nutri		Eco-indicator 99 (H): Acidification/ Eutrophication	
Emission	**Contribution**	**Emission**	**Contribution**	**Emission**	**Contribution**
NO_3	71%	NH_3	73%	NH_3	73%
NH_3	13%	NO_x	18%	NO_x	18%
P	13%	NO	6.6%	NO	6.6%
NO_x	3.2%	SO_2	2.6%	SO_2	2.6%
NO	1.2%	-	-	NO_3	-0.0068%
Total	**119 kg NO_3-eq**	**Total**	**85.9 kg SO_2-eq**	**Total**	**89.4 pdf*m2yr**

Table 21.4: Eutrophication, 1 t palm oil (scenario 4).

The intersection of sets is three different emissions. It appears that nitrate which is a major contribor using EDIP97 is insignificant when using Impact 2002+ and Eco-indicator. Also phosphorus is not present as a contributor in Impact 2002+ and Eco-indicator. The reason why nitrate is insignificant in Impact2002+ and Eco-indicator is that these methods only concerns terrestrial eutrophication while EDIP97 covers aquatic as well as terrestrial eutrophication.

EDIP97: Photochemical smog		Impact2002+: Respiratory organics		Eco-indicator 99 (H): : Respiratory organics	
Emission	**Contribution**	**Emission**	**Contribution**	**Emission**	**Contribution**
CH_4	57%	CH_4	54%	CH_4	51%
NMVOC	25%	NMVOC	41%	NMVOC	39%
CO	8.8%	HC, aliphatic, alkanes	0.74%	HC, aliphatic, unsaturated	5.6%
HC, aliphatic, unsaturated	4.9%	Toluene	0.59%	HC, aliphatic, alkanes	0.69%
HC, aliphatic, alkanes	0.8%	Pentane	0.59%	Toluene	0.55%
Total	**509 g ethene-eq**	**Total**	**456 g ethylene-eq**	**Total**	**1.04E-6 DALY**

Table 21.5: Photochemical smog, 1 t palm oil (scenario 4).

The intersection of sets is three different emissions which indicates a relatively good consistency. However, the top-two which account for 82-95% of the total contribution is the same in all three methods, which indicates a very good consistency.

EDIP97: Ecotoxicity, water, chonic		**Impact2002+: Aquatic ecotoxicity**		**Eco-indicator 99 (H): Ecotoxicity**	
Emission	**Contribution**	**Emission**	**Contribution**	**Emission**	**Contribution**
Cypermethrin to water	101%	Cypermethrin to water	80%	Zinc to soil	40%
Chlorpyrifos to water	-0.83%	Copper to soil	11%	Chromium to soil	32%
Strontium to water	0.0013%	Zinc to soil	4.3%	Zinc to air	6.9%
Copper ion to water	0.00094%	Aluminium to soil	1.4%	Nickel to soil	6.5%
Glyphosate to water	0.00086%	Chromium to soil	0.79%	Nickel to air	4.3%
Total	**1.4E9 m^3 water**	**Total**	**5.51E5 kg TEG water**	**Total**	**1,270 PAF*m2yr**

Table 21.6: Ecotoxicity (aquatic), 1 t palm oil (scenario 4).

The intersection of sets is zero and the total number of different emissions identified is 12 out of 15 possible. This indicates a very low level of consistency among the compared methods. Since the number of included pesticides in the three methods vary, the comparison is also carried out when excluding the pesticides, see **Table 21.7**.

EDIP97: Ecotoxicity, water, chonic		**Impact2002+**		**Eco-indicator 99 (H)**	
Emission	**Contribution**	**Emission**	**Contribution**	**Emission**	**Contribution**
Strontium to water	31%	Copper to soil	55%	Zinc to soil	40%
Copper ion to water	24%	Zinc to soil	22%	Chromium to soil	32%
Aluminium to water	13%	Aluminium to soil	7.1%	Zinc to air	6.9%
Iron ion to water	9.0%	Chromium to soil	4.1%	Nickel to soil	6.5%
Zinc ion to water	8.8%	Aluminium to air	2.6%	Nickel to air	4.3%
Total	**5.7E4 m^3 water**	**Total**	**1.08E5 kg TEG water**	**Total**	**1,270 PAF*m2yr**

Table 21.7: Ecotoxicity (aquatic) excluding pesticides, 1 t palm oil (scenario 4).

Excluding the pesticides from the comparison does not affect the consistency among the compared LCIA-methods. The intersection of sets is still zero and the total number of different emissions identified is 13. Because of the very significant differences between the results and contributors in the LCIA-methods, the results obtained for ecotoxicity are regarded as extremely uncertain and almost useless.

It appears from the sensitivity analysis presented in this section that the LCIA-methods seem to be relatively consistent regarding global warming, acidification, eutrophication and photochemical smog. Thus, the results within these impact categories are not affected significantly by uncertainties in LCIA-methods. But when it comes to ecotoxicity the uncertainties are significant, and the value added by characterising the inventory results is regarded as very limited.

21.2 No. 2: System delimitation, marginal supplier of crops

When identifying the marginal suppliers of crops in section 2.1, the main uncertainties associated with that are regarded as identification of Canada as the marginal supplier of barley and identification of Indonesia and Malaysia together as the marginal supplier of palm oil. The identification of the marginal supplier of rapeseed (the EU) and soybean (Brazil) is regarded as more certain as well as the identification of the margional crop in the EU is regarded as relatively certain. In this section the following sensitivity analyses are carried out, see **Table 21.8**.

Most uncertain identifications of marginal suppliers	Description of sensitivity analyses
Marginal supplier of barley	Two sensitivity analyses are carried out: One where Russia is applied as the marginal supplier of barley and one where EU25 is applied as the marginal supplier of barley
Marginal supplier of palm oil	Two sensibility analyses are carried out: One where Malaysia is applied as the marginal supplier and one where Indonesia is applied as the marginal supplier

Table 21.8: Description of sensitivity analyses carried out in this section.

The presumptions for each sensibility analysis are described in the following. These data are the only ones that are changed in the inventory. Based on that new N- and P-balances and calculations of emissions are carried out following the methods described in section 6.7 for oil palm and section 8.6 for barley.

Russia as the marginal supplier of barley: Carrying out the sensitivity analysis where Russia is regarded as the marginal supplier of barley the following parameters are changed: The yield is changed from 2.91 t/ha to 1.85 t/ha (calculated for 2005 by regression from 1992 to 2005 based on FAOSTAT 2006) and the use of fertiliser is changed from 67 kg N, 26 kg P_2O_5 and 10 kg K_2O to 47 kg N, 20 kg P_2O_5 and 69 kg K_2O respectively (IFA et al. 2002). It is assumed that 0% of the straw is removed and utilised for energy purposes. The N deposition is assumed to be the same as in Canada.

EU25 as the marginal supplier of barley: Here the yield is changed from 2.91 t/ha to 4.38 t/ha (calculated for 2005 by regression from 1993 to 2005 based on FAOSTAT 2006). The same fertiliser input as in Denmark is assumed, i.e. 121 kg N/ha, 46 kg/ha P_2O_5 and 66 kg K_2O/ha. It is assumed that 50% of the straw is removed and utilised for energy purposes. The N deposition is assumed to the same as in Denmark.

The emissions related to N- and P-balances from barley cultivation in the default situation (Canada) and in the two sensitivity analyses are summarised in **Table 21.9**.

Emission	Barley, Canada	Barley, Russia	Barley, EU25
Ammonia (NH_3) to air	7.7 kg/ha	7.2 kg/ha	9.0 kg/ha
Dinitrogen oxide (N_2O) to air	2.2 kg/ha	1.6 kg/ha	4.6 kg/ha
Nitrix oxide (NO) to air	1.6 kg/ha	1.4 kg/ha	1.9 kg/ha
Nitrate (NO_3) to water	50 kg/ha	36 kg/ha	199 kg/ha
Phosphorus (P) to water	0.078 kg/ha	0.094 kg/ha	0.176 kg/ha

Table 21.9: Emissions related to the N- and P-balances for barley cultivation in the considered regions.

Indonesia as the marginal supplier of FFB: The yield is changed from 18.87 t/ha to 17.95 t/ha (calculated for 2005 by regression from 1990 to 2005 based on FAOSTAT 2006). The same fertiliser input as in Malaysia/Indonesia is assumed.

Malaysia as the marginal supplier of FFB: The yield is changed from 18.87 t/ha to 19.84 t/ha (calculated for 2005 by regression from 1990 to 2005 based on FAOSTAT 2006). The same fertiliser input as in Malaysia/Indonesia is assumed.

The emissions related to N- and P-balances from oil palm cultivation in the default situation (Malaysia and Indonesia tougether) and in the two sensitivity analyses are summarised in **Table 21.10**.

Emission	FFB, MY&IN	FFB, MY	FFB, IN
Ammonia (NH_3) to air	18.3	18.3	18.3
Dinitrogen oxide (N_2O) to air	10.1	10.0	10.1
Nitrix oxide (NO) to air	3.19	3.19	3.19
Nitrate (NO_3) to water	353	344	361
Phosphorus (P) to water	1.61	1.60	1.62

Table 21.10: Emissions related to the N- and P-balances for oil palm cultivation in the considered regions.

Table 21.11 and **Table 21.12** shows the characterised results of the baseline and the sensitivity analyses described for rapeseed oil and palm oil respectively. The results are all for scenario 4.

Impact category	1 t rapeseed oil (baseline)	1 t rapeseed oil (barley, RUS)	1 t rapeseed oil (barley, EU25)	1 t rapeseed oil (FFB, MY)	1 t rapeseed oil (FFB, IN)
Global warming (t CO_2)	2.39	2.35	2.45	2.38	2.41
Ozone depletion (g CFC11)	0.147	0.143	0.149	0.147	0.148
Acidification (kg SO_2)	26.0	25.3	26.4	25.8	26.1
Eutrophication (t NO_3)	0.211	0.209	0.207	0.209	0.214
Photochemical smog (kg ethene)	0.869	0.845	0.878	0.867	0.870
Land use (m^2y)	3.37	3.03	3.57	3.34	3.41

Table 21.11: Characterised results of 1 t rapeseed oil, baseline compared with the the sensitivity analyses were the margin suppliers of barley and FFB (oil palm fruit) are changed.

It appears from **Table 21.11** that the results of rapeseed oil are not very sensitive to the identification of marginal suppliers of barley and FFB. For global warming the results vary between -2% and +3% compared to the baseline situation. The most sensitive impact category is land use where the changes are within -10% and +6% compared to the baseline situation. The results of rapeseed are most sensitive to the identification of the marginal supplier of barley while the marginal supplier of FFB only affects the results -1% to +1%.

Impact category	1 t palm oil (baseline)	1 t palm oil (barley, RUS)	1 t palm oil (barley, EU25)	1 t palm oil (FFB, MY)	1 t palm oil (FFB, IN)
Global warming (t CO_2)	2.36	2.30	2.43	2.28	2.43
Ozone depletion (g CFC11)	0.0446	0.0389	0.0463	0.0431	0.0461
Acidification (kg SO_2)	13.3	12.4	13.7	12.7	13.8
Eutrophication (t NO_3)	0.119	0.116	0.113	0.111	0.127
Photochemical smog (kg ethene)	0.509	0.480	0.520	0.503	0.515
Land use (m^2y)	1.75	1.32	2.00	1.63	1.88

Table 21.12: Characterised results of 1 t palm oil, baseline compared with the the sensitivity analyses were the margin suppliers of barley and FFB (oil palm fruit) are changed.

The results of palm oil are slightly more sensitive to the identification of marginal suppliers of barley and FFB than rapeseed oil. The results of global warming vary between -3% to +3% compared to the baseline situation. The most sensitive impact category is land where the results vary from -25% to +14%. In general the results are more sensitive to the identification of the marginal supplier of barley than the identification of the marginal supplier of FFB.

Comparing **Table 21.11** and **Table 21.12** it appears that the results of rapeseed oil and palm oil change in the same direction when the marginal suppliers are displaced by alternative suppliers in the sensitivity analyses. Thus, the identification of marginal suppliers of barley and FFB has only little effect on the comparative results of rapeseed oil and palm oil.

21.3 No. 3: System delimitation, type of land transformed into agricultural land

Section 19.1 shows that the emissions from transformation of non-cultivated land into oil palm plantations in Malaysia and Indonesia and into soybean fields in Brazil vary significantly dependant on the affected type of land (grassland, savannah, forest). Also in the case of transformation into barley fields in Canada the results are regarded as uncertain because it is assumed that undisturbed prairie grassland is affected. There may be other types of land available for transformation into barley fields, e.g. set-aside land as in the EU.

This sensitivity analysis tests the effect on impacts of transformation of land from different assumptions regarding the affected land.

Sensitivity analyses	**Affected crops**			
	Rapeseed (DK)	Oil palm (MY&IN)	Soybean (BR)	Barley (CAN)
Baseline	Set-aside	50% alang-alang grassland 50% deg. forest	95% savannah 5% deg. forest	Grassland, natural prairie
MY&IN (grassland affected)	Set-aside	**Alang-alang grassland**	95% savannah 5% deg. forest	Grassland, natural prairie
MY&IN (deg. forest affected)	Set-aside	**Deg. forest**	95% savannah 5% deg. forest	Grassland, natural prairie
MY&IN (primary forest affected)	Set-aside	**Primary forest**	95% savannah 5% deg. forest	Grassland, natural prairie
BR (savannah affected)	Set-aside	50% alang-alang grassland 50% deg. forest	**Savannah**	Grassland, natural prairie
BR (deg. forest affected)	Set-aside	50% alang-alang grassland 50% deg. forest	**Deg. forest**	Grassland, natural prairie
BR (primary forest affected)	Set-aside	50% alang-alang grassland 50% deg. forest	**Primary forest**	Grassland, natural prairie
CAN (set-aside affected)	Set-aside	50% alang-alang grassland 50% deg. forest	95% savannah 5% deg. forest	**Set-aside**

Table 21.13: Description of sensitivity analyses testing affected land transformed into agricultural land.

The scenario analysed is scenario 2. Two different alternatives of scenario 2 exist for rapeseed oil; expansion of the cultivated takes place locally in Denmark or increased cultivation of rapeseed displace the marginal crop, which is barley. This is then compensated for by increased production in Canada. Here the alternative when increased rapeseed cultivation takes place locally in Denmark is applied. Scenario 4 is not suitable analysing impacts from transformation because it does not include any transformation processes.

Only two impact categories are analysed, i.e. global warming and biodiversity. Characterisation factors for biodiversity are based on Schmidt (2007c) and additional characterisation factors given in Appendix 4: Characterisation factors for land use in Brazil and Canada. Characterisation factors for transformation of primary forest in Malaysia/Indonesia are assumed to be representative for primary forest in Brazil, and transformation of set-aside land in Denmark is assumed to be representative for transformation of set-aside land in Canada. The characterised results for changed parameters in Malaysia/Indonesia, Brazil and Canada are shown in **Table 21.14**, **Table 21.15** and **Table 21.16** respectively.

The results shown here represent the needed land to be transformed in order to increase the production of rapeseed oil and palm oil with 1 tonne. This functional unit is not directly comparable to the one used when considering contineous cultivation/production because transformation of a piece of land can support several functional units over time. The results are calculated using the inventory data described in section 19.1.

Impact category	Baseline		MY&IN => grassland		MY&IN => deg. forest		MY&IN => prim. forest	
	1 t RSO	1 t PO	1 t RSO	1 t PO	1 t RSO	1 t PO	1 t RSO	1 t PO
Global warming (t CO_2)	-59.4	43.4	-74.2	-14.9	-44.6	102	-44.6	102
Biodiversity (wS100)	-385	-72.4	-402	-138	-368	-7.08	47.0	1628

Table 21.14: Characterised results of 1 t rapeseed oil (RSO) and 1 t palm oil (PO), baseline compared with the sensitivity analyses were different types of land in Malaysia/Indonesia (MY&IN) are transformed into oil palm. (Scenario 2 has been used for this sensitivity analysis)

It appears from **Table 21.14** that the contributions to global warming and biodiversity are very sensitive to assumptions regarding the affected land in Malaysia/Indonesia. Though, the results are sensitive to assumptions the ranking of rapeseed oil and palm oil is not affected in any of the sensitivity analyses shown in the table. The negative impacts associated with rapeseed oil are because of avoided transformation of savannah and forest in Brazil and prairie grassland in Canada. It also appears that when forest (degraded or primary) is transformed in order to expand oil palm cultivation the contribution to global warming is significant: more than 100 t CO_2-eq. per t palm oil. Assuming a contribution to global warming at 2.4 t CO_2-eq-/t palm oil from continuous cultivation/production the contribution at 102 t CO_2-eq. from transformation corresponds to approximately 43 years of cultiovation/production of palm oil from the transformed area.

Impact category	Baseline		BR => savannah		BR => deg. forest		BR => prim. forest	
	1 t RSO	1 t PO	1 t RSO	1 t PO	1 t RSO	1 t PO	1 t RSO	1 t PO
Global warming (t CO_2)	-59.4	43.4	-49.0	43.5	-256	43.0	-256	43.0
Biodiversity (wS100)	-385	-72.4	-393	-72.5	-229	-72.1	-3005	-78.6

Table 21.15: Characterised results of 1 t rapeseed oil (RSO) and 1 t palm oil (PO), baseline compared with the sensitivity analyses were different types of land in Brazil (BR) are transformed into soybean fields.

It appears from **Table 21.15** that palm oil is not sensitive to assumptions regarding affected land in Brazil while rapeseed oil is more sensitive. But still no of the tested assumptions can affect the ranking between rapeseed oil and palm oil.

Impact category	Baseline		CAN => set-side	
	1 t RSO	1 t PO	1 t RSO	1 t PO
Global warming (t CO_2)	-59.4	43.4	-59.4	43.4
Biodiversity (wS100)	-385	-72.4	-310	22

Table 21.16: Characterised results of 1 t rapeseed oil (RSO) and 1 t palm oil (PO), baseline compared with the sensitivity analysis were set-aide land in Canada (CAN) is transformed into barley fields.

Table 21.16 shows that the contribution to biodiversity from palm oil is very sensitive the assumptions regarding affected land in Canada while rapeseed oil is less sensitive. The sensitivity analysis show no effects on the impact of global warming. Again, the assumptions regarding affected land in Canada does not affect the ranking of rapeseed oil and palm oil.

21.4 No. 4: Energy, marginal source of electricity

This sensitivity tests the effect of uncertainties in identification of the marginal source of electricity in Denmark, Malaysia/Indonesia, Brazil and Canada. **Table 21.17** shows the marginal sources of electricity in the baseline situation and the included sensitivity analyses.

Region	Baseline	Coal	Natural gas
Denmark	Coal	Coal	Natural gas
Malaysia/Indonesia	Coal	Coal	Natural gas
Brazil	Natural gas	Coal	Natural gas
Canada	Natural gas	Coal	Natural gas

Table 21.17: Description of sensitivity analyses testing the marginal source of electricity.

Table 21.18 show the characterised results for the baseline situation and when the marginal source of electricity in all regions are coal and natural gas respectively. The results are not shown for land use and biodiversity because these impact categories are not affected in this sensitivity analysis.

	Baseline		Coal		Natural gas	
Impact category	1 t RSO	1 t PO	1 t RSO	1 t PO	1 t RSO	1 t PO
Global warming (t CO_2)	2.39	2.36	2.36	2.36	2.29	2.34
Ozone depletion (g CFC11)	0.147	0.045	0.154	0.045	0.169	0.048
Acidification (kg SO_2)	26.0	13.3	25.9	13.3	25.6	13.2
Eutrophication (t NO_3)	0.211	0.119	0.211	0.119	0.211	0.119
Photochemical smog (kg ethene)	0.869	0.509	0.873	0.509	0.880	0.511

Table 21.18: Characterised results of 1 t rapeseed oil (RSO) and 1 t palm oil (PO), baseline compared with the sensitivity analyses were the marginal source of electricity is coal and natural gas respectively.

It appears from **Table 21.18** that the source of marginal electricity has only little influence on the results. The result for rapeseed oil of global warming is somehow surprising because both the sensitivity analyses with only gas electricity and coal electricity respectively show lower contribution than the baseline situation. The reason why the sensitivity analysis that applies coal shows a lower contribution than the baseline is, that the electricity in the coutries of substituted commodities; Canada and Brazil, contributes with more CO_2 while Denmark is unchanged. The reason why the sensitivity analysis that applies gas shows a lower contribution than the baseline is that the electricity in Denmark contributes with less CO_2 (gas instead of coal) while Canada and Brazil are unchanged.

21.5 No. 5: Energy, representativiness of data on district heating in Denmark

In scenario 2 the two alternatives of rapeseed oil (local expansion versus crop displacement) show significant different results. The main reason for that is that in the 'constraint area scenario' the displaced spring barley in Denmark is associated with a significant smaller environmental impacy than the required extra barley in Canada. In the 'local expansion' scenario the cultivation of spring barley in Denmark is not affected. The main reason that spring barley in Denmark performs good is that the straw is utilised for heat and electricity production. The data for the displaced heat are based on site specific data only valid for the city Aarhus and its surroundings. Therefore, this sensitivity applies other data for district heating production. Many district heating plants in Denmark are small decentralised back pressure natural gas fired combined heat and power plants. Opposite to large central heat and power plants which can swich between condensating mode and back pressure mode, the small decentralised produce an output of electricity and heat with fixed ratio. According to Danish Energy Authority (2004), a typical decentralised heat and power plant (40-125 MW gas turbine) have a total energy efficuency at 91% and a electricity efficiency at 36-42% (assumed 39%). Thus, the energy output per 100% input is 39% electricity and 52% heat. The production is determined from the local demand for heat and co-produced electricity is sold to the grid where it substitutes the marginal source of electricity. The inventory data for production of 1 MJ heat are shown in **Table 21.19**.

Interventions	Amount	Applied LCI-data
Product outputs		
District heat	1 MJ	Product of interest
Electricity	0.75 MJ	Co-product, see system expansion below
System expansion		
Avoided electricity	-0.75 MJ	See **Table 3.3**
Energy use		
Natural gas burned in gas turbine	1.92 MJ	Natural gas, burned in power plant/NORDEL U

Table 21.19: Description of sensitivity analyses testing the marginal source of electricity.

The characterised results of the baseline and the sensitivity analysis are shown in **Table 21.20**. The results are not shown for land use and biodiversity because these impact categories are not affected in this sensitivity analysis.

	Baseline		Decentralised district heat	
Impact category	1 t rapeseed oil (constrained area)	1 t rapeseed oil (local expansion)	1 t rapeseed oil (constrained area)	1 t rapeseed oil (local expansion)
Global warming (t CO_2)	5.15	2.40	4.53	2.54
Ozone depletion (g CFC11)	0.210	0.147	0.208	0.148
Acidification (kg SO_2)	39.2	25.8	37.9	26.1
Eutrophication (t NO_3)	0.201	0.172	0.200	0.172
Photochemical smog (kg ethene)	1.22	0.869	1.18	0.878

Table 21.20: Characterised results of 1 t rapeseed oil (constrained area as well as local expansion), baseline compared with the sensitivity analyses were district heating from a centralised power plant is displaced by decentralised district heat. The results are for scenario 2.

Table 21.20 shows that the data for district heating have some influence. If decentralised district heating is applied instead of centralised heat as in the baseline situation, the impact of the constrained area scenario are reduced while impacts of the local expansion scenario are increased. The reason why the impacts in the constrained area scenario are reduced is that the district heating in the sensitivity analysis is associated with smaller impacts than the impacts from centralised heat as in the baseline situation. The constrained area scenario is associated with a considerable high use of district heat. This is because Danish spring barley is displaced and spring barley displaces heat from utilisation of straw. On the other hand, the reason why the impact in the local expansion scenario are increased in the sensitivity analysis is that this scenario is associated with a negative net use of heat because more is displaced (utilisation of rapeseed straw) than used (rapeseed oil mill and refinery).

21.6 No. 6: Agricultural cultivation, energy for traction

According to **Table 5.11** the energi use for traction per ha rapeseed field varies from 3,369 MJ to 4,488 MJ dependant on the soil type, cultivation practice and data source. These variations correspond to percentual deviations from the applied energy use for traction at 3,612 MJ between -7% and +24%. The sensitivity analysis presented in this section present the baseline situation compared with two situations; one situation where the energy use for traction for all crops are reduced by 7% and one where it is increased by 24%. These variations are also in good accordance with the variations for traction in oil palm plantations (see **Table 6.3**)

The characterised results of the sensitivity analyses are shown in **Table 21.21**. The results are not shown for land use and biodiversity because these impact categories are not affected in this sensitivity analysis.

	Baseline		Reduced traction all crops (-7%)		Increased traction all crops (+24%)	
Impact category	**1 t RSO**	**1 t PO**	**1 t RSO**	**1 t PO**	**1 t RSO**	**1 t PO**
Global warming (t CO_2)	2.39	2.36	2.38	2.36	2.44	2.36
Ozone depletion (g CFC11)	0.147	0.045	0.146	0.044	0.153	0.045
Acidification (kg SO_2)	26.0	13.3	25.9	13.3	26.4	13.3
Eutrophication (t NO_3)	0.211	0.119	0.211	0.119	0.212	0.119
Photochemical smog (kg ethene)	0.869	0.509	0.861	0.508	0.894	0.512

Table 21.21: Characterised results of 1 t rapeseed oil (RSO) and 1 t palm oil (PO), baseline compared with the sensitivity analyses were the marginal source of electricity is coal and natural gas respectively.

It appears from **Table 21.21** that variations in the energy use for traction affect the results insignificantly. Therefore, the uncertainties related to that are regarded as of minor importance.

21.7 No. 7: Rapeseed cultivation, soil type

The applied soil type on which Danish rapeseed is cultivated in the study is an average of 59% clay and 41% sand. The sensitivity analysis presented in this section shows the difference of cultivating rapeseed on clay and sandy soils. The inventory data for cultivation on clay and sand are comprehensively described in section 5. The characterised results are shown in **Table 21.22**.

Impact category	1 t rapeseed oil (baseline)	1 t rapeseed oil (clay soil)	1 t rapeseed oil (sandy soil)	Change (clay)	Change (sand)
Global warming (t CO_2)	2.39	2.17	2.79	-9%	17%
Ozone depletion (g CFC11)	0.147	0.138	0.164	-6%	11%
Acidification (kg SO_2)	26.0	24.3	28.9	-7%	11%
Eutrophication (t NO_3)	0.211	0.166	0.294	-21%	39%
Photochemical smog (kg ethene)	0.869	0.823	0.955	-5%	10%
Land use (m^2y)	3374	2716	4590	-19%	36%
Biodiversity (wS100)	10.8	9.90	12.3	-8%	15%

Table 21.22: Characterised results of 1 t rapeseed oil, baseline compared with rapeseed cultivated on clay and sandy soil.

It appears from **Table 21.22** that the impact categories eutrophication and land use are the ones most sensitive to the type of soil. In general cultivation on clay is environmental preferable to cultivation on sand. However, since most of Denmark is already occupied with agriculture, cities and infrastructure it is hard to move agriculture from cultivation on sandy soils to cultivation on clay soils. However, when agriculture is transformed into other types of land use it is environmental preferable to locate these transformations on sandy soils.

In section 5 it is assumed that rapeseed fields are evenly distributed on the 59% clay soil and 41% sandy soil in Denmark. Since the difference between cultivation on sand and clay is relatively limited, the actual distribution of rapeseed fields can deviate relatively much from these figures without changing the results of the LCA in the same rate. Therefore, it is not likely that the soil type cultivated can affect the ranking of rapeseed oil and palm oil (see baseline for palm oil in **Table 20.1**.

21.8 No. 8: Rapeseed cultivativation, N-fertiliser produced using best available techniques (BAT)

According to section 5.4 the emission of N_2O from the production of nitric acid, which is used for the production of ammonium nitrate fertilisers, can be significantly reduced using BAT. The European Commission (2006d) presents a range of different technologies to be considered in order to reduce N_2O emissions from production of nitric acid. Examples of technologies are alternative oxidation catalysts, extension of reactor chamber, catalytic N_2O decomposition in the oxidation reactor, combined NO_x and N_2O abatement in tail gases and non-selective catalytic reduction of NO_x and N_2O in tail gases. The presented technologies reduce the N_2O emission from 30-50% up to 98-99%. There are no trade offs in order to achieve the given reductions. This sensitivity analysis analyses the effect on the results if the emission of N_2O in the tail gas from nitric acid is reduced by 85%. This is done by reducing the N_2O emission from 8.39 g to 1.26 g per kg nitric acid. The change is implemented in the ecoinvent process: 'Nitric acid, 50% in H2O, at plant/RER' (ecoinvent 2004).

Table 21.23 shows the characterised results of the sensitivity analysis. The contributions to land use and biodiversity are not shown because these impact categories are not affected in this sensitivity analysis.

Impact category	1 t rapeseed oil (baseline)	1 t rapeseed oil (fertiliser produced with BAT)	Change
Global warming (t CO_2)	2.39	1.89	-21%
Ozone depletion (g CFC11)	0.147	0.147	0%
Acidification (kg SO_2)	26.0	26.0	0%
Eutrophication (t NO_3)	0.211	0.211	0%
Photochemical smog (kg ethene)	0.869	0.869	0%

Table 21.23: Characterised results of 1 t rapeseed oil, baseline compared with rapeseed oil produced in an oil mill using the full press technology.

It appears from **Table 21.23** that the only affected impact category is global warming. Using fertiliser produced with BAT reduces the contribution to global warming remarkably with 21%.

21.9 No. 9: Agricultural cultivation, N changes in soil matter

In section 5.6 the changes in N soil matter is assumed to be zero. The argument for that is that the the changes in N soil matter should be ascribed to transformation of land rather than continuous cultivation and therefore the changes in N soil matter are included in the impacts of transformation (see section 19.1). However, in order to monitor the effect of chosing that approach, this sensitivity analysis applies an annual decrease in N soil matter at 24 kg N/ha for rapeseed, barley and soybean. The 24 kg N/ha is estimated for rapeseed in section 5.6. The same change in N soil matter is assumed for barley in Canada and soybean in Brazil. However, the change in N soil matter for palm oil is regarded as of minor importance since input of N in crop residues are higher and because the crop rotation has a duration of 25 years compared to only one year for the other crops. Henson (2004) also regards the change in N soil matter under oil palm to be zero.

The change in N soil matter at 24 kg/ha is fed into the N-balances in sections 5.6, 7.5 and 8.6 as an input of N (which increases the N-surplus), and the corresponding emissions are calculated using the same methods as described in these sections. The affaected emissions are nitrate (which is calculated as the difference between the N-surplus and the other N-related emissions) and N_2O (indirect from increased nitrate emissions).

The characterised results of the sensitivity analysis are shown in **Table 21.24**. Only the contributions to global warming and eutrophication are shown since these are the only impact categories affected.

	Baseline		Change in N soil matter included	
Impact category	1 t RSO	1 t PO	1 t RSO	1 t PO
Global warming (t CO_2)	2.39	2.36	2.54	2.34
Eutrophication (t NO_3)	0.211	0.119	0.268	0.111

Table 21.24: Characterised results of 1 t rapeseed oil (RSO) and 1 t palm oil (PO), baseline compared with the sensitivity analyses were the annual change in N soil matter is 24 kg N/ha.

Table 21.24 shows that an annual change in N soil matter at 24 kg N/ha for soil under rapeseed increases the contribution to global warming and eutrophication 6% and 27% respectively. The change in N soil matter has only minor influence on the results of palm oil. If changes in N soil matter are included the ranking of rapeseed oil and palm oil regarding global warming changes from being almost even to a situation where palm oil performs 7% better than rapeseed oil.

21.10 No. 10: Agricultural cultivation, heavy metal contents in fertilisers

According to section 5.6 and 6.7 the determination of the contents of heavy metals in fertiliser is related to uncertainties. Therefore this sensitivity analysis assesses these uncertainties' influence on the LCIA results.

Heavy metals contribute to ecotoxicity and human toxicity. Human toxicity is not considered here because the LCIA methods for that are even more uncertain than of ecotoxicity (see description of uncertainties of ecotoxicity in section 21.1). Applying the EDIP97-method to the baseline situation and analysing the agricultural stage only, the contribution to ecotoxicity (chronical, water) is shown in **Table 21.25**.

Contributing processes	Rapeseed	FFB	Soybean	Barley
Heavy metals from fertilisers	0.065%	<0.00001%	0.00061%	5.4%
Pesticides	99.5%	>99.9%	>99.9%	not included
Other (e.g. production of fertiliser and transport)	0.46%	0%	0.0014%	94.6%

Table 21.25: Process contriobution to aquatic ecotoxicity for the affected crops (only the agricultural stage is included).

Table 21.25 shows that heavy metals constitute only a minor share of the total contribution to ecotoxicity. Thus, it is estimated that uncertainties in determination of the heavy metal content in fertilisers contribute with insignificant uncertainties in the result. The very low contribution to aquatic ecotoxicity from FFB is because it is assumed that all emissions are to soil, and most of those emissions do not contribute to aquatic ecotoxicity. If carrying out the same analysis for ecotoxicity to soil (EDIP97) for FFB the contribution from heavy metals are still insignificant.

In addition it should be mentioned that because of uncertainties in LCIA-methods, see section 21.1, toxicity should be dealt with in a more qualitative manner than the remaining impact categories.

21.11 No. 11: Agricultural cultivation, initial compartment of pesticide emissions

In sections 5.6, 6.7 and 7.5 it is assumed that the applied pesticides ends as evenly distributed emissions to air, water and soil. This is a very rough assumption. Therefore, this sensitivity analysis compares the baseline situation with situations where all applied pesticides ends as emissions to air, water and soil respectively. Only the contribution to ecotoxicities is included. The characterised results are shown in **Table 21.26**.

Impact category	Baseline		Compartment => air		Compartment => water		Compartment => soil	
	1 t RSO	1 t PO	1 t RSO	1 t PO	1 t RSO	1 t PO	1 t RSO	1 t PO
ETWC (mio m3)	-4685	1423	0.532	0.0567	-149600	3951	0.532	0.0567
ETWA (mio m3)	-127	52.3	0.0560	0.0082	-4168	148	0.0560	0.0082
ETSC (mio m3)	-24.5	0.625	0.0156	0.00249	0.0153	0.00249	-736	0.315

Table 21.26: Characterised results of 1 t rapeseed oil (RSO) and 1 t palm oil (PO), baseline compared with the sensitivity analyses were the compartment of pesticides are changed. Abbreviations: ETWC (ecotoxicity, water, chronic), ETWA (ecotoxicity, water, acute) and ETSC (ecotoxicity, soil, chronic)

It clearly appears from **Table 21.26** that the contribution to ecotoxicity is extremely sensitive to the intial compartment of pesticide emissions. E.g. the contribution to ETWC from rapeseed oil varies from -149600 mio m^3

(when the initial compartment is water) to 0.532 m^3 (when the initial compartment is either air or soil). Similar vaiations are found for the impact categories ETWA and ETSC and for palm oil.

Therefore, the characterised results for ecotoxicity are associated with very significant uncertainties and they do not provide useful information if not a more precise determination of compartment is carried out. However, referring to the uncertainties regading toxicity modelling in LCIA-methods in general as described in section 21.1, the characterised results will still be associated with significant uncertainties. Hence, improved modelling of compartments of pesticide emissions will not improve the certainty of the results of toxicity notably.

21.12 No. 12: Oil palm cultivation, yields

As described in section 21.2 the yield of oil palm may vary dependant on the supplier, i.e. Malaysia or Indonesia. The yields are also depandant on the cultivation practices (see section 6). Cultivation practices vary among the actors, i.e. small holders, FELDA and private estates. Thus, there may be significant differences in yields in a small holder plantation and in a large private estate, even if the same agricultural inputs are used. The differences may be due to water management (drainage), breeding of new palms, timing of harvest and replanting and weed control. No data correlating agricultural practices and yields (regardless fertiliser input) have been identified. Therefore, the sensitivity analysis presented in this section refers to the results of the sensitivity analysis in section 21.2 where FFB yields of 17.95 t/ha, 18.87 t/ha and 19.84 t/ha are compared (these yields represent Indonesia, Malaysia/Indonesia and Malaysia respectively). The variations above correspond to yield variations between -5% and +5%. The results of the sensitivity analysis in section 21.2 show that changes of oil palm yields at ±5% cause changes in the contribution to global warming at ±3% and changes in land use requirements at ±7%. Thus, the determination of yields and the effect of cultivation practice have a relative large effect on the obtained results. Thus, if the marginal suppliers of oil palm are represented by plantations with cultivation practice and corresponding yields well above average (20-25 t FFB/ha), the contribution to global warming and land use of palm oil may be reduced significantly, i.e. up to 20% for global warming and 45% for land use.

21.13 No. 13: Oil palm cultivation, soil type

It appears from section 6.7 that the levels of emissions from cultivation on peat and mineral soil vary significantly. According to Henson (2004) approximately 4.1% of the oil palm cultivated area in Malaysia is on peat. The same is assumed to be valid for Indonesia. According to Corley and Tinker (2003, p 81) much of the open land remaing land for expanding the oil palm cultivation in SE-Asia is peat soils. According to Wetland International (2007), more than 50% of the planned new plantations in Malaysia and Indonesia are on peat soils.

Therefore, the applied 4.1% peat may not represent the marginal land cultivated with oil palm. This sensitivity analysis compares cultivation on peat soil with cultivation on mineral soil. The inventory data relating to that are described in section 6.7. The characterised results are shown in **Table 21.27**. The results are only shown for global warming, acidification and eutrophication since these impact categories are only ones affected in this sensitivity analysis.

Impact category	1 t palm oil (baseline)	1 t palm oil (peat soil)	1 t palm oil (mineral soil)	Change (peat soil)	Change (mineral soil)
Global warming (t CO_2)	2.36	12.8	1.91	444%	-19%
Acidification (kg SO_2)	13.3	19.8	13.0	49%	-2%
Eutrophication (t NO_3)	0.119	0.105	0.119	-11%	1%

Table 21.27: Characterised results of 1 t palm oil, baseline compared with oil palm cultivated with low and high levels of CO_2-emissions from peat.

It appears from **Table 21.27**, that cultivation on peat contributes significantly more to global warming (4 to 5 times more) and to a lesser extent acidification than cultivation on average soil (of wich 4.1% is peat). The difference between average soil and mineral soil is less pronounced. The main reason why cultivation on peat contributes more to global warming is a higher level of CO_2-emission, but also a higher level of N_2O-emission contributes. The difference in contribution to acidification is due a higher level of nitric oxide (NO) from denitrification peat soil.

The significant high contribution to global warming from cultivation of oil palm on peat soil exceeds the contribution to global warming from rapeseed oil many fold. Though, the uncertain and probably overestimated contribution to global warming from rapeseed cultivated by increased yield (scenario 3) is not matched by oil palm cultivated on peat. However, as mentioned rapeseed oil in scenario 3 is not very likely to occur since regulations on N-fertiliser in the EU makes this way of increasing yields impossible in most regions. Another aspect is that increases by yield achieved by increased NPK-fertiliser will probably take place on the least fertilised soils. Thus, the crop response to additional fertiliser will probably by higher than the response modelled for rapeseed in scenario 3.

Hence, most efforts towards cleaner production and better environmental performance regarding global warming in the palm oil industry will be of little significance and will be overruled if the oil palm is cultivated on peat.

21.14 No. 14: Oil palm cultivation, uncertainties of CO_2-emissions from peat soil

According to section 6.7 the annual carbon emission from cultivation of 1 ha with oil palm is 10 t (corresponding to 37 t CO_2). However, this is related to some uncertainties. In section 6.7 annual emission levels of carbon from cultivation of peat between 7.5 t C/ha and 20 t C/ha have been identified. These figures correspond to 28 t CO_2 and 73 t CO_2 respectively. Thus, the sensitivity analysis presented in this section compare the baseline scenario with above mentioned CO_2 emission levels. The characterised results are shown in **Table 21.28**. The results are only shown for global warming since this is the only impact category affected in this sensitivity analysis.

Impact category	1 t palm oil (baseline)	1 t palm oil (low: 28 t CO_2/ha)	1 t palm oil (high: 73 t CO_2/ha)	Change compared to baseline (low: 28 t CO_2/ha)	Change compared to baseline (high: 73 t CO_2/ha)
Global warming (t CO_2)	2.36	2.27	2.73	-4%	16%

Table 21.28: Characterised results of 1 t palm oil, baseline compared with oil palm cultivated with low and high levels of CO_2-emissions from peat.

It appeat from **Table 21.28** that the uncertainties in the determination of CO_2-emissions from peat have some effect on the results for global warming. However, if more than the actual 4.1% of the oil palm is cultivated on peat, the uncertainties of determination of CO2 from peat may be more significant.

21.15 No. 15: Barley cultivation, omission of use and emissions of pesticides

The use of and the emissions of pesticides are omitted from the inventory of barley. As shown in section **Table 21.26** in section 21.10, the emissions of pesticides contribute significantly to ecotoxicity. Thus, when omitting the emissions of pesticides from the inventory of barley, the credit from displaced barley will be zero when performing system expansion. Since more barley is displaced in the product system of palm oil than for rapeseed oil, the omission of pesticides is therefore in the favour of rapeseed oil. However, as described in section 21.1 and 21.11 the uncertainties in LCIA-methods regarding toxicity and uncertainties in the determination of the receiving compartments of pesticide emissions make the results of toxicity so uncertain, that the results do not contribute with usable information.

21.16 No. 16: Rapeseed oil mill, solvent extraction versus full press

In the baseline cenario, the applied technology in the rapeseed oil mill is solvent extraction. This sensitivity analysis applies the full press technology instead. The inventory presented here is based on data provided by Emmersen (2006) for the rapeseed oil mill; Scanola in Aarhus, Denmark. This oil mill uses the full press technology. In 2005 Scanola processed 220,000 tonne rapeseed (Emmersen 2006).

When using the full press technology, no solvents are used for extraction. Not using solvents will affect the amount of oil in the oil meal. According to Emmersen (2006), the product flow in Scanola rapeseed oil mill in Aarhus Denmark related to 1 t crude rapeseed oil include an input of 2.597 t rapeseed and outputs of 1.558 t oil meal and 0.039 t loss (water). Based on the oil content in rapeseed given in Møller et al. (2000) it can be calculated that the oil content in the oil meal is 9.5%. The properties of rapeseed oil meal with 10% fat are given in **Table 21.29**.

Paramter	Rapeseed meal, per kg meal (10% fat)
Protein	310 g protein
Fodder energy*	1.059 SFU

Table 21.29: Relevant properties of rapeseed oil meal. * Fodder energy is measured in SFU (Scandinavian Fodder Units). (Møller et al. 2000)

Based on the figures in **Table 21.29** and the product flow in the full press rapeseed oil mill specified above, the product flow related to 1 t refined rapeseed oil produced with full press technology is given in **Figure 21.1** and **Equation (6)**. The losses in the refinery stage are the same as in **Figure 2.1**.

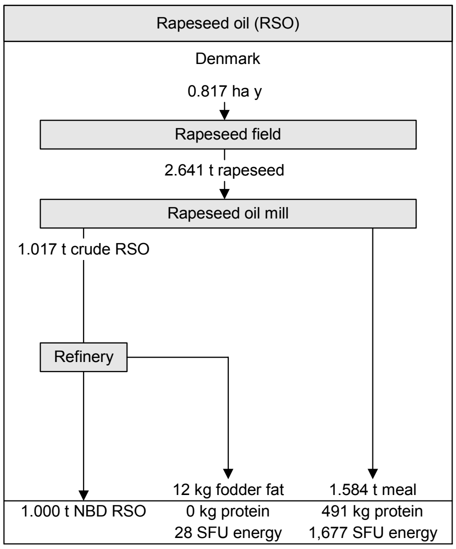


Figure 21.1: Product flow in the oil mill stage and refinery stage related to 1 t refined rapeseed oil (full press).

The affected palm oil, soybean meal and barley are calculated in **Equation (6)**.

$$1\,\text{t RSO}\cdot\begin{bmatrix}1\text{ t oil/t RSO}\\ 491\text{ kg prot./t RSO}\\ 1{,}705\text{ SFU/t RSO}\end{bmatrix}+\text{t PO}\cdot\begin{bmatrix}1\text{ t oil/t PO}\\ 19.2\text{ kg prot./t PO}\\ 191\text{ SFU/t PO}\end{bmatrix}+\text{t SM}\cdot\begin{bmatrix}0.244\text{ t oil/t SM}\\ 436\text{ kg prot./t SM}\\ 1{,}207\text{ SFU/t SM}\end{bmatrix}+\text{t BL}\cdot\begin{bmatrix}0\text{ t oil/t BL}\\ 91.8\text{ kg prot./t BL}\\ 952\text{ SFU/t BL}\end{bmatrix}=\begin{bmatrix}1\text{ t oil}\\ 0\text{ kg prot.}\\ 0\text{ SFU}\end{bmatrix}$$

$$\begin{aligned}&\Downarrow\\ &\text{t RSO}=1.000\\ &\text{t PO}=0.249\\ &\text{t SM}=-1.022\\ &\text{t BL}=-0.545\end{aligned} \qquad (6)$$

The energy use related to 1 t crude rapeseed oil at the full press rapeseed oil mill, Scanola are given in **Table 21.30**.

Energy	1 t rapeseed oil
Electricity	467 MJ
Heat (fuel oil)	852 MJ

Table 21.30: Energy use in the oil mill stage related to 1 t crude rapeseed oil using full press technology.

The remaining LCI data are similar to the solvent extraction oil mill as described in **Table 9.13** except the use and emission of hexane and waste water. The applied LCI data for burning of fuel oil is: 'Light fuel oil, burned in boiler 100kW, non-modulating' (ecoinvent 2004).

Applying the product flow given in **Equation (6)** and the inventory data described above to scenario 4, the characterised results can be calculated, see **Table 21.31**.

Impact category	1 t rapeseed oil (baseline)	1 t rapeseed oil (full press technology)	Change
Global warming (t CO_2)	2.39	2.27	-5%
Ozone depletion (g CFC11)	0.147	0.129	-12%
Acidification (kg SO_2)	26.0	24.6	-5%
Eutrophication (t NO_3)	0.211	0.212	0%
Photochemical smog (kg ethene)	0.869	0.537	-38%
Land use (m^2y)	3374	2723	-19%
Biodiversity (wS100)	10.8	11.5	6%

Table 21.31: Characterised results of 1 t rapeseed oil, baseline compared with rapeseed oil produced in an oil mill using the full press technology.

It appears from **Table 21.31** that the oil mill technology has only limited influence on the result regarding global warming, ozone depletion, acidification and eutrophication. The most significant change is the contribution to photochemical smog, which is reduced because of elimination of hexane emissions. The land occupation is reduced because of avoided barley production in Canada which is relatively larger than the increased land use in Denmark. The corresponding impact on biodiversity is increased in the full press sensitivity analysis. The reason for this is that occupation of land in Denmark is weighted higher than occupation of land in Canada (Schmidt 2007c and Appendix 4: Characterisation factors for land use in Brazil and Canada).

21.17 No. 17: Oil mills, capital goods

The determination of the use of capital goods in the oil mill stage is related to notable uncertainties. **Table 21.32** provides on overview of the assumed use of capital goods in the different affected oil mills and the associated contribution to global warming.

Capital goods	Oil mill	Baseline	Global warming (% of the oil mill stage)
Rapeseed oil mill	Building halls	$3.9\cdot10^{-4}\ \text{m}^2$	0.094%
	Building, multi story	$7.1\cdot10^{-4}\ \text{m}^3$	0.12%
	Machinery	0.085 kg	0.40%
	Total		**0.61%**
Palm oil mill	Building halls	$1.8\cdot10^{-4}\ \text{m}^2$	0.028%
	Building, multi story	$3.4\cdot10^{-4}\ \text{m}^3$	0.035%
	Machinery	0.040 kg	0.12%
	Total		**0.18%**
Palm kernel oil mill	Building halls	$3.9\cdot10^{-4}\ \text{m}^2$	0.081%
	Building, multi story	$7.1\cdot10^{-4}\ \text{m}^3$	0.10%
	Machinery	0.085 kg	0.35%
	Total		**0.53%**
Soybean oil mill	Building halls	$3.9\cdot10^{-4}\ \text{m}^2$	0.10%
	Building, multi story	$7.1\cdot10^{-4}\ \text{m}^3$	0.12%
	Machinery	0.085 kg	0.43%
	Total		**0.65%**

Table 21.32: The use of capital goods in the oil mill stage (per 1 t crop processed)

It appears from **Table 21.32** that the use of capital goods accounts for an insignificant share of the total contribution from the oil mill stage. The use of capital goods could be of magnitiude five fold larger and still be insignificant. Thus, uncertainties in the determination of the use of capital goods in the oil mill stage have insignificant effect on the results.

21.18 No. 18: Palm oil mill, POME treatment

One of the hotspots from palm oil is the emission of methane from anaerobic digestion of palm oil mill effluent which contributes to global warming. This sensitivity analysis examines the effect of installing a digester tank and utilisation of the biogas for electricity production in a gas turbine. The emissions related to that technology is based on UNFCCC (2006) which describes the emissions from a CDM project at United Plantation, Jendarata Palm Oil Mill. According to UNFCCC (2006, p 25, 28) 92.2% of the methane is captured. The remaining 7.8% is emitted to air from anaerobic pockets in the subsequently aerobic pond treatment. 8.4% of the methane that enters the combustion process is emitted due to incomplete combustion in boiler and flaring system (UNFCCC 2006, p 30). It is assumed that the total generation of biogas and methane is the same in the anaerobic lagoon system and when a digester tank is installed, i.e. 13.0 kg methane/t POME (see section 10.5). According to UNFCCC (2006) it can be estimated that 85% of the methane is utilised for energy purposes and the remaining 15% is flared. Thus, 10.2 kg of the 11.99 kg captured methane is utilised for energy purposes. The flaring efficiency is 50% (UNFCCC 2006, p 30). Thus the methane emission from incomplete flaring is 15% of 11.99 kg methane multiplied with 50%, i.e. 0.90 kg methane.

It is assumed that the methane is used for electricity production since most palm oil mills have excess of heat and that electricity can be sold to the national grid. An efficiency at 40% for the turbine is assumed and emissions related to displaced electricity in Malaysia and Indonesia are described in **Table 3.3**. The emissions from burning of biogas are described in section 13.4, i.e. emission of methane is 1.5% of the input of gas to the motor, emission of sulphur dioxide is 0.018 g SO_2/MJ input of energy in biogas and the emission of nitrogen oxides is 0.200 g NO_x/MJ input of energy in biogas. The energy content of methane is 50.4 MJ/kg (see Appendix 1: Data on fuels).

The emissions of hydrogen sulphide (H_2S) and ammonia (NH_3) in the baseline treatment (anaerobic lagoon) are assumed to be eliminated when applying the digester tank and utilisation of biogas. The emission of Dinitrogen oxide (N_2O) is assumed to be unchanged as done in UNFCCC (2006, p 10-11).

The inventory of treatment of 1 t POME when the anaerobic lagoon treatment is displaced with a digeter tank and ultilisation of the biogas is summarised in **Table 21.33**.

1 t POME	Baseline	Sensitivity analysis
Energy production	0 MJ	205 MJ electricity (40% of energy input at 10.2 kg CH_4 with energy content at 50.4 MJ/kg)
CH_4 from treatment (lagoon/digester tank)	13.0 kg CH_4	11.99 kg CH_4 captured (92.2%) 1.01 kg CH_4 emission (7.8%)
CH_4 from incomplete flaring	0 kg CH_4	0.90 kg CH_4 emission (50% of 15% of 11.99 kg)
CH_4 from gas motor	0 kg CH_4	0.15 kg CH_4 (85% of 1.5% of 11.99 kg)
SO_2 from gas motor	0 kg SO_2	0.0092 kg SO_2
NO_x from gas motor	0 kg NO_x	0.10 kg NO_x
H_2S from lagoon	0.0862 kg H_2S	0 kg H_2S
NH_3 from lagoon	0.058 kg NH_3	0 kg NH_3
N_2O from lagoon	0.0015 kg N_2O	0.0015 kg N_2O

Table 21.33: Inventory of treat ment of 1 t POME when digester tank and utilisation is installet.

The characterised results are shown in **Table 21.34**. The contributions to land use and biodiversity are not shown because these impact categories are not affected in this sensitivity analysis.

Impact category	1 t palm oil (baseline)	1 t palm oil (biogas POME treatment)	Change compared to baseline
Global warming (t CO_2)	2.36	1.36	-42%
Ozone depletion (g CFC11)	0.0446	0.0439	-2%
Acidification (kg SO_2)	13.3	12.2	-8%
Eutrophication (t NO_3)	0.119	0.118	0%
Photochemical smog (kg ethene)	0.509	0.256	-50%

Table 21.34: Characterised results of 1 t palm oil, baseline compared with palm oil produced in an oil mill treating POME in a digester tank and with utilisation of biogas for electricity production.

It appears from **Table 21.34** that applying the biogas treatment of POME affects the impact categories global warming and photochemical smog significantly. The reduction in the contribution to global warming is mainly due to reductions in methane emissions but also displacement of CO_2 from coal based electricity from the grid contributes. The reduction in the contribution to photochemical smog is due to the reduced methane emissions.

The reduction of the contribution to global warming is quite significant. If palm oil is produced using biogas treatment of POME instead of the normally anaerobic lagoon systems palm oil will perform better than rapeseed oil in all scenarios.

21.19 No. 19: Palm oil mill, steam requirement

According to section 10.1 the steam requirement in palm oil mills per t FFB is 0.65 t steam. Data on steam requirement have been indetified between 0.4 t steam and 0.65 t steam which corresponds to an interval between 1040 MJ and 1690 MJ. This sensitivity analysis applies a situation were the steam requirement is 0.5 t (1300 MJ).

In the baseline scenario 100% of the 130 kg fibre and 70 kg shell per t FFB are burned in the palm oil mill's boiler producing 1708 MJ steam and 104 MJ electricity. The small difference between the produced steam (1708 MJ) and the required steam (1690 MJ) is released to the atmosphere.

In the sensitivity analysis the reduced required steam is assumed to be produced from burning of 100% of the fibre and 50% of the shell. Applying the calorific values, moisture contentsm utilisation factors and heat to electricity ratio as described in section 10.3, the generated energy is then 1315 MJ steam and 78 MJ electricity.

The remaining 35 kg shell per t FFB are sold as fuel in the cement industry (Chavalparit et al. 2006). It is assumed that the shells substitutes coal in a ratio one to one by energy content. 35 kg shells have an energy content at 633 MJ. The avoided emissions associated with the avoided burning of 633 MJ coal are obtained from '*Hard coal, burned in power plant/NORDEL U*' (ecoinvent 2004). This inventory is modified so that only the emission from the burning of coal is included. It is assumed that the shells are transportated 300 km in a 28t lorry.

The electricity consumption in the oil mill is 73 MJ/t FFB (see **Table 10.5**). In the baseline situation the electricity production is 104 MJ. Thus, 31 MJ/t FFB electricity from the grid is displaced. In the sensitivity the electricity production is 78 MJ. Thus the displaced electricity is only 5 MJ/t FFB.

Table 21.35 shows the changed parameters in the sensitivity analysis compared to the baseline scenario.

Interventions	Baseline	Sensitivity	Applied LCI-data
Displaced products			
Displaced electricity from the grid	31 MJ	5 MJ	See **Table 3.3**
Displaced burning of coal in cement industry	0 MJ	633 MJ	Modyfied version of '*Hard coal, burned in power plant/NORDEL*' (ecoinvent 2004)
Energ use			
Steam from power central	1691 MJ	1300 MJ	The emissions are described below
Emissions			
From palm oil mill power central, burning of…	130 kg fibre 70 kg shell	130 kg fibre 35 kg shell	See **Table 10.4**
From cenment industry power central, burning of…	0 kg fibre 0 kg shell	0 kg fibre 35 kg shell	See **Table 10.4**
Transport			
Shells from oil mill to cement industry	0 tkm	10.5 tkm	'*Transport, lorry 28t*' (ecoinvent 2004)

Table 21.35: Changed parameters in the sensitivity analysis with low steam requirement in the palm oil mill.

The characterised results are shown in **Table 21.36**. The contributions to land use and biodiversity are not shown because these impact categories are not affected in this sensitivity analysis.

Impact category	1 t palm oil (baseline)	1 t palm oil (low steam requirement)	Change compared to baseline
Global warming (t CO_2)	2.36	2.13	-10%
Ozone depletion (g CFC11)	0.0446	0.0465	4%
Acidification (kg SO_2)	13.3	12.8	-4%
Eutrophication (t NO_3)	0.119	0.118	0%
Photochemical smog (kg ethene)	0.509	0.504	-1%

Table 21.36: Characterised results of 1 t palm oil, baseline compared with palm oil produced in an oil mill with low steam requirement and where excess shells are used in the cement industry where it displaces coal as fuel.

Table 21.36 shows that the steam requirement and the use of excess biomass (shells) have a relatively large influence on the results for global warming. Reducing the steam requirement from 0.65 t steam with 23% to 0.5 t steam and utilising the excess shells as biofuel causes a reduction of 10% contribution to global warming equalling 230 kg CO_2 per t palm oil.

21.20 No. 20: Palm oil mill, alternative management options for EFB

Different uses/waste management options are available for the empty friut bunches (EFB) from the palm oil mill. Application of the EFB as mulch in the plantation is used in the baseline scenario since this is regarded as the most widespread management option.

In less well managed palm oil mills the EFB is disposed of in landfill sites while the EFB is used as biofuel in the most well managed palm oil mills. This sensitivity analysis compares the three management options for EFB.

Table 21.37 provides the relevant characteristics of EFB.

Characteristics of EFB	Value	Source
Amount of EFB per t FFB	0.225 t EFB/t FFB	**Table 10.1**
Calorific value (lower) (fresh weight basis)	7.52 MJ/kg EFB	(Subranamiam et al. 2004)
Water content	60%	**Table 6.9**
N content (fresh weight basis)	3.2 kg N/t EFB	**Table 6.9**
P content (fresh weight basis)	0.38 kg P/t EFB	**Table 6.9**
K content (fresh weight basis)	9.6 kg K/t EFB	(Singh 1999)

Table 21.37: Relevant characteristics of EFB for the sensitivity analysis presented in this section.

In both sensitivity analyses, it is assumed that the ‘missing’ application of N, P and K from the EFB (which is not applied as mulch) is compensated for by additional application of artificial fertiliser. The additional application of fertiliser is determined from the content of N, P and K in the EFB given in **Table 21.37**. Since the removal of the EFB is compensated for, the nutrient balances are not affected in the two sensitivity analyses.

Emissions from the burning of EFB in the biomass plant are assumed to be the same per burned MJ biomass as in the power central in the palm oil mill burning fibre and shell. **Table 10.4** shows the emissions per burned kg of fibre and shell. Since the burned composition of fibre and shell has a calorific value at 13.8 MJ/kg (see section 10.3), the emissions per MJ can easily be determined. The production of electricity is based on a biomass plant burning EFB in Malaysia. The plant is documented as a CDM project in UNFCCC (2007). It appears from UNFCCC (2007) that the electricity output is 1.25 MJ/kg burned EFB (fresh weight). This corresponds to an energy efficiency of the biomass plant at 17% (output of electricity compared to input of EFB in terms of calorific value).

Only three emissions from the landfilling of the EFB have been accounted for, i.e. methane to air, leaching of nitrate and leaching of phosphorous. The emission of methane has been calculated using the the model described in UNFCCC (data of issue not given) and the model parameters presented in UNFCCC (2007). The methane emission from the landfilling of EFB has been calculated as 18 kg CH_4/t EFB. The emissions of nitrate and phosphorous have been determined assuming that all the content of N and P in the EFB will leach as nitrate and phosphorous.

Table 21.38 shows the changed parameters in the sensitivity analysis compared to the baseline scenario.

Interventions	Baseline	Sensitivity (EFB is disposed off by landfilingl)	Sensitivity (EFB is utilised in a biomass plant)	Applied LCI-data
Displaced products				
Displaced electricity from the grid	0 MJ	0 MJ	281 MJ	See **Table 3.3**
Additional use of fertiliser in agricultural stage				
Additional N-fertiliser (as N), ammonium sulphate	0 kg N	0.53 kg N	0.53 kg N	'*Ammonium sulphate, as N, at regional storehouse/RER*' (ecoinvent 2004)
Additional N-fertiliser (as N), urea	0 kg N	0.19 kg N	0.19 kg N	'*Urea, as N, at regional storehouse/RER*', (ecoinvent 2004)
Additional P-fertiliser (as P_2O_5)	0 kg P_2O_5	0.20 kg P_2O_5	0.20 kg P_2O_5	Phosphate rock, see section 6.5: Fertilisers
Additional K-fertiliser (as K_2O)	0 kg K_2O	2.61 kg K_2O	2.61 kg K_2O	*Potassium chloride, as K_2O, at regional storehouse/RER'*, ecoinvent (2004)
Emissions				
Emission from burning of EFB in biomass plant	-	-	225 kg EFB	See **Table 10.4**
Emissions from EFB disposed off at landfill	-	4.1 kg CH_4 3.2 kg NO_3 0.086 kgP	-	-

Table 21.38: Changed parameters in the sensitivity analyses with alternative management options for EFB from the palm oil mill. All values are given per t of processed FFB (this is equivalent to 0.225 t EFB).

The characterised results are shown in **Table 21.39**. The contributions to land use and biodiversity are not shown because these impact categories are not affected in this sensitivity analysis.

Impact category	1 t palm oil (baseline)	1 t palm oil (EFB at landfill)	1 t palm oil (EFB as biomass)	Change compared to baseline (EFB at landfill)	Change compared to baseline (EFB as biomass)
Global warming (t CO_2)	2.36	2.81	1.95	19%	-17%
Ozone depletion (g CFC11)	0.0446	0.0464	0.0451	4%	1%
Acidification (kg SO_2)	13.3	13.3	12.9	0%	-3%
Eutrophication (t NO_3)	0.119	0.146	0.119	23%	0%
Photochemical smog (kg ethene)	0.509	0.648	0.529	27%	4%

Table 21.39: Characterised results of 1 t palm oil, baseline compared with alternative management options for EFB.

It appears from **Table 21.39** that land filling of EFB increases the contributions to global warming, eutrophication and photochemical smog remarkable. The increased contributions to global warming and photochemical smog are caused by increased methane emissions from the landfill site while the increased contribution to eutrophication is caused by leaching of nitrate and phosphorous from the landfill site.

Utilising EFB for energy purposes in a biomass plant reduces the contribution to global warming remarkably. This is due to displaced electricity production. No other impact categories are remarkably affected.

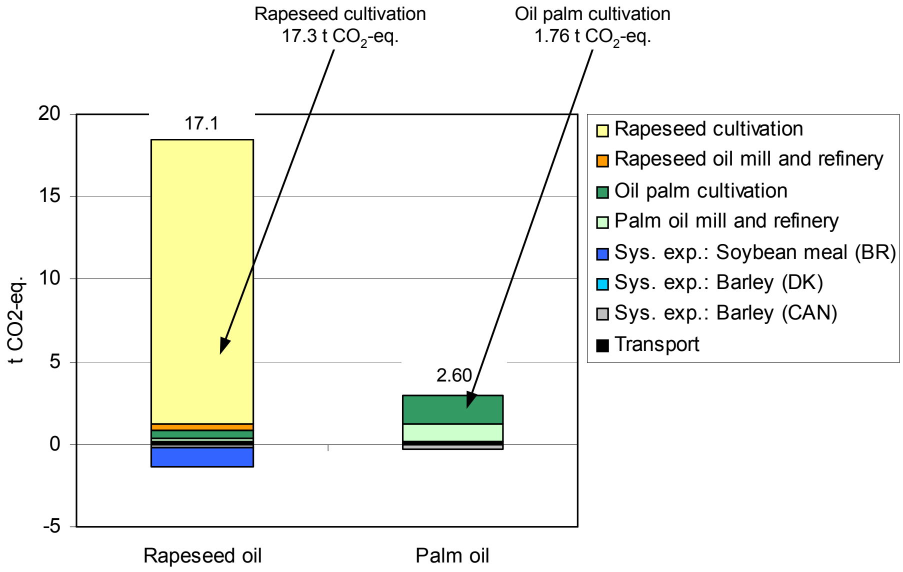
21.21 No. 21: Insensified cultivation, yield-responses to additional fertiliser

As it appears from section 18.2 and **Table 18.2** the determination of yield-responses to additional fertiliser application is related to considerable uncertainties. Uncertainties in the determination of crop responses are directly proportional with the associated emissions in the agricultural stage. The yield-responses to additional fertiliser appliacation are highly dependant on the present level of fertiliser application that is changed. In this study the level of fertiliser application is determined as the average fertiliser application in the region of interest. However, it is more likely that additional fertiliser application will take place in fields where the highest yield-response can be achieved and that is in the fields fertilised below the average level. Thus, it is likely that the scenarios that represent increased yield underestimate the yield responses and correspondingly overestimate the environmental impact. Therefore, this sensitivity analysis tests the significance of these uncetainties. **Table 21.40** shows the applied yield responses and the intervals from which the yield resposnes are determined.

Crop	Applied yield-response ΔY/ΔN (kg crop/kg N)	Interval ΔY/ΔN (kg crop/kg N)
Rapeseed	4	4-15
FFB	62	48-149
Barley, DK (represented by wheat)	12	4-40
Barley, CAN (represented by wheat)	17	4-40

Table 21.40: Applied yield-responses to additional fertiliser and the interval of identified yield-responses indicating the uncertainties.

It appears from **Table 21.40** that the applied yield-responses are in the lower end of the intervals. Because of proportionalibility between yield-responses from fertiliser application and some of the environmental impacts (global warming and eutrophication), a doubling of the yield-response will lead to a halving of the associated environmental impacts. Therefore, knowing the contribution to e.g. global warming from the agricultural stage, it is earsy to determine the characterised results for scenario 3 (increased yield) for different yield resposnes. **Figur 21.2** shows the characterised results of scenario 3 for global warming and the contribution from the different stages.



Figur 21.2: Characterised results for global warming of scenario 3 per 1 t oil and the contribution from the agricultural stage.

Table 21.41 shows the characterised results for rapeseed oil and palm oil when the yield responses for rapeseed and FFB are changed.

Vegetable oil	Sensitivity analysis	Yield-response	Contribution to global warming
Rapeseed oil	Baseline	4 kg rapeseed per ha/kg N	17.1 t CO_2/t oil
	Moderate yield response	8 kg rapeseed per ha/kg N	8.45 t CO_2/t oil
	High yield response	15 kg rapeseed per ha/kg N	4.41 t CO_2/t oil
Palm oil	Baseline	62 kg FFB per ha/kg N	2.60 t CO_2/t oil
	Low yield-response	48 kg FFB per ha/kg N	3.11 t CO_2/t oil
	High yield-response	149 kg FFB per ha/kg N	1.57 t CO_2/t oil

Table 21.41: Characterised results for 1 t rapeseed oil and 1 t palm oil when different yield-responses are applied (scenario 3).

It appears from **Table 21.41** that the contribution to global warming is highly dependant on the determination of yield-responses. For rapeseed oil the interval of yield-responses represent a factor 3.9 difference in the contribution to global warming, and for palm oil the interval represents a factor 2.0 difference.

Since the determination of yield-responses and the identification of means of increasing the yields are related to considerable uncertainties and since the results are very sensitive to yield-responses, the results of the scenarios where increases are met with yield (scenarion 1 and 3) are considered as very uncertain. However, the sensitivity analysis shows that uncertainties in the determination of yield-responses can not change the ranking of palm oil as the environmental preferable to rapeseed oil regarding global warming.

There are great differences in the level of fertiliser application in different managed oil palm plantations (see section 21.12). Well managed plantations typically apply more fertiliser than poor managed small holder plantations. The extremes of the intervals of yield responses given in **Table 21.40** can be considered as the yield responses in highly intensified and very extensive cultivation. It appears that the environmental performance of increasing FFB yields is markable in extensive cultivated areas (see high yield response of FFB in **Table 21.41**). Thus additional fertiliser application in extensively cultivated oil palm cultivations is regarded as an improvement option. The level of fertiliser application on rapeseed in Denmark/the EU is considered as more uniform and closer to the N and P norms. It also appears that the contribution to global warming from rapeseed oil produced by increased yield with high yield responses is relatively high, i.e. 4.41 t CO_2-eq./t rapeseed oil. Thus additional fertiliser application in rapeseed cultivation is not considered as an improvement option.

21.22 Summary of sensitivity analyses

Table 21.42 provides an overview of the main findings of the sensitivity analyses presented in this section. The table is organised to provide information on which sources of uncertainties (tested in the single sensitivity analyses) that causes significant uncertainty to the results, and which uncertainties that may change the ranking of rapeseed oil and palm oil. The significance of uncertainties of results are classified as low (<10% changes in results), moderate (10-30% changes in results) and high (>30% changes in results). If the tested sources of uncertainties cause uncertainties of high significance, they are marked with bold text. Corresponding to that the sources of uncertainties that change the ranking of rapeseed oil and palm oil are also maked with bold text.

	Significanse of the tested source of uncertainty…	
Sensitivity analysis	**… the results**	**… ranking of rapeseed oil/palm oil**
1: LCIA-methods	**High** for toxicities and Low/moderate for the remaining impact categories	-
2: System delimitation, marginal supplier of crops	Low	Not affected
3: System delimitation, type of land transformed into agricultural land	**High**	Not affected
4: Energy, marginal source of electricity	Low	Not affected
5: Energy, representativiness of data on district heating in Denmark	Low/moderate in scenario 1a and 2a, and low for all other scenarios	Not affected
6: Agricultural cultivation, energy for traction	Low	Not affected
7: Rapeseed cultivation, soil type	Moderate	Not affected
8: Rapeseed cultivativation, N-fertiliser produced using best available techniques (BAT)	Moderate for global warming and low for the remaining impact categories	**Global warming:** The ranking is changed from even to a situation where rapeseed oil performs better when fertiliser produced with BAT is used
9: Agricultural cultivation, N changes in soil matter	Moderate for eutrophication from rapeseed oil and Low for remaining impact categories and for palm oil	**Global warming:** The ranking is changed from even to a situation where palm oil performs better when N changes in soil matter are included
10: Agricultural cultivation, heavy metal contents in fertilisers	Low	Not affected
11: Agricultural cultivation, initial compartment of pesticide emissions	**High** for ecotoxicity. No effect on other impact categories	**Ecotoxicity:** The ranking is affected. However, the results are very uncertain
12: Oil palm cultivation, yields	**High** for land use if FFB yields of marginal suppliers is significant higher than the applied 18.87 t/ha and moderate for the remaining impact categories	**Global warming:** The ranking is changed from even to a situation where palm oil performs better if FFB yields are significantly higher than the applied 18.87 t/ha
13: Oil palm cultivation, soil type	**High** if land on peat soil is developed for oil palm cultivation	**Global warming:** The ranking is changed from even to a situation where rapeseed oil performs significantly better if oil palm is cultivated on peat soil
14: Oil palm cultivation, uncertainties in CO$_2$-emissions from peat soil	Moderate for global warming from palm oil.	**Global warming:** The ranking is changed from even to a situation where rapeseed oil performs better if CO$_2$-emissions are significantly higher than the applied 37 t CO$_2$/ha per year
15: Barley cultivation, omission of use and emissions of pesticides	-	-
16: Rapeseed oil mill, solvent extraction versus full press	**High** for photochemical smog from rapeseed oil and low/moderate for the remaining impact categories	Not affected
17: Oil mills, capital goods	Low	Not affected
18: Palm oil mill, POME-treatment	**High** for global warming and photochemical smog from palm oil and low for the remaining impact categories	**Global warming:** The ranking is changed from even to a situation where palm oil performs significantly better if a digester tank is installed
19: Palm oil mill, steam requirement	Low	**Global warming:** The ranking is changed from even to a situation where palm oil performs better if the steam requirement is lower than the applied 0.65 t steam/t FFB
20: Palm oil mill, alternative management options for EFB	Moderate	**Global warming:** The ranking is changed. Rapeseed oil performs best if the EFB is disposed off by landfill, and palm oil performs best if the EFB is used in a biomass plant
21: Insensified cultivation, yield-responses to additional fertiliser	**High** for scenario 1 and 3	Not affected

Table 21.42: Overview of the main findings in the sensitivity analyses presented in this section.

It appears from **Table 21.42** that 8 out of the 21 tested sources of uncertainty potentially affect the result significantly, i.e. at least one of the impact categories are affected with more than 30%. Futhermore 9 of the 21 sensitivity analyses show that the tested sources of uncertainty may change the ranking of rapeseed oil and palm oil within at least one impact category.

In general the sensitivity analyses show that the uncertainties associated with ecotoxicity are so significant, that these results do not provide usable information. The causes of these uncertainties are primarily related to uncertainties in LCIA-methods, but also to uncertain determination of the initial compartment of pesticide emissions. The characterised results of the remaining impact categories seem to be less associated with uncertainties relating to LCIA-methods.

Regarding the uncertainties that affects the ranking of rapeseed oil and palm oil, the only relevant impact category is global warming (when not taking ecotoxicity into account). In scenario 4 which is the scenario used in most sensitivity analyses the difference between rapeseed oil and palm oil regarding global warming is insignificant. The following uncertainties point in the direction that rapeseed performs better than palm oil:

- the ammonium nitrate fertiliser used is produced with BAT
- oil palm is cultivated on peat soil
- CO_2-emissions from peat are significantly higher than the presumed 37 t CO_2/ha per year
- EFB from the palm oil mill is disposed off in a landfill instead of being applied as mulch in the plantation

On the other side, the following uncertainties point in the direction that palm oil performs better than rapeseed oil:

- N changes in soil matter are included
- FFB yields are significantly higher than the applied 18.87 t/ha
- palm oil mill effluent (POME) is treated in a digester tank and the biogas is utilised
- the steam requirement in the palm oil mill is lower than the applied 0.65 t steam/t FFB
- EFB from the palm oil mill is utilised for energy purposes in a biomass plant instead of being applied as mulch in the plantation

The last sensitivity analysis (no. 21) shows that the modelling of increased yield is a significance source of uncertainty. Therefore, the results of scenario 1 and 3 are associated with a significantly higher level of uncertainty than the other scenarios.

22 Identification of improvement options

In the previous section both improvement options and data uncertainties have been treated together as sources of uncertainties in results. The reason for treating them together is that both the identification of the actual cultivation practice/technologies and the uncertainty in data may contribute to uncertainties in results. One of the purposes of this life cycle inventory is to identify improvement options. Therefore, this section presents those of the sensitivity analyses which represent improvement options. **Table 22.1** summarises the identified improvement options. Only the effects on global warming and biodiversity have been considered. Each improvement option is compared with the baseline scenario in terms of index number (baseline = index 100)

Ref. to sensitivity analysis	Improvement option, rapeseed oil	Improvement options	Global warming	Land use	Biodiversity
Rapeseed oil					
7	When agricultural land is transformed into other land use types, transformation of clay soils should be avoided since these soils give the highest yield	Cultivation on clay	91	81	92
		Baseline (59% clay, 41% sand)	100	100	100
		Cultivation on sand	129	136	114
8	Using N-fertiliser produced with best available techniques (BAT)	Fertiliser produced with BAT	79	-	-
		Baseline (BAT is not used)	100	-	-
16	Using full press technology in the oil mill stage instead of solvent extraction technology	Full press technology	95	81	106
		Baseline (solvent extraction)	100	100	100
Palm oil					
3	Expanding the oil palm planted area on grassland and avoiding transformation of forests	Expanding on grassland	-	-	-191
		Baseline (50% secondary forest and 50% grassland)	-	-	-100
		Expanding in land covered with secondary forest	-	-	-10
13	Avoiding cultivation on peat	Cultivation on mineral soils	81	-	-
		Baseline (96% mineral soil and 4% peat)	100	-	-
		Cultivation on peat soils	542	-	-
18	Installation of digester tank and utilisation of biogas instead of open anaerobic ponds for palm oil mill effluent (POME) treatment	Treating POME in digester tank with biogas capturing and utilisation of the methane for energy purposes	58	-	-
		Baseline (treatment of POME in open anaerobic ponds)	100	-	-
20	Utilising EFB for energy purposes in a biomass plant instead of application as mulch in the plantation. Avoiding landfill as a magement option for EFB	EFB disposed of by landfilling	119	-	-
		Baseline (EFB applied as mulch in the plantation)	100	-	-
		Utilising EFB in biomass plant with electricity production	83	-	-
21	Yield increases by additional fertiliser application in extensively cultivated areas	Extensively cultivated plantation (assumed yield response at 149 kg FFB/kg N)	60	-	-
		Baseline (assumed yield response at 62 kg FFB/kg N)	100	-	-
		Baseline (assumed yield response at 62 kg FFB/kg N)	120	-	-

Table 22.1: Overview of the effect of the considered improvement options. Only the effects on global warming and biodiversity have been considered.

It appears from **Table 22.1** that the greatest improvement potentials have been identified for palm oil. It should also be mentioned that the effect of the improvement options relating to the transformation of land only refer to the transformation process and not the overall environmental performance of the supply. That is because a piece of transformed land can support many functional units.

23 Sensitivity, completeness and consitency checks

According to ISO 14044 (2006) en evaluation in the interpretation phase including sensitivity, completeness and consistency check must be carried out in order to establish confidence in the results of the LCA.

23.1 Sensitivity check

The objective of the sensitivity check is to assess the reliability of the results and how they are affected by uncertainties in data, assumptions and LCIA-methods (ISO 14044 2006). Sensitivity has been assessed on three levels in this study: System boundaries, uncertainty in data and LCIA-methods.

Regarding system boundaries the definition of scenarios represents a sensitivity analysis. In addition the sensitivity analyses in section 21.2 and 21.3 assess the result's sensitivity to uncertainties in and alternative system boundaries. The differences between scenarios show that the approach to system delimitation (consequential/attributional) significantly affects the results (see **Table 20.1**). The sensitivity analyses in section 21 show that the identification of marginal suppliers has only little influence on the results while the impacts of transformation of different non-cultivated land use types into agricultural land has major effects on the results.

Sensitivity regarding uncertainty in data is assessed during the inventory of each stage where different data sources have been compared and in section 21 where several sensitivity analyses have carried out in order to assess uncertainties in data. The results of the sensitivity analyses are summarised in section 21.22.

LCIA-methods and the related uncertainties are assessed in section 21.1 where the characterised results of EDIP97, Impact2002+ and Eco-indicator are compared. The sensitivity analysis shows that the results of toxicities are related to so significant uncertainties that the information obtained from the characterised results is useless. The other impact categories are more consistent among the different LCIA-methods.

The main sources of uncertainties are identified as:

- The characterised results of toxicities do not provide usable information
- The results of the scenarios where increased cultivation is achiedv by increased yields are associated with a significantly high level of uncertainty, i.e. scenario 1 and 3
- The impacts from transformation of non-cultivated land into agricultural land are associated with considerable uncertainties due to determination of which type of land that is transformed
- The contribution to global warming from palm oil may be significantly higher if the share of peat soil of new land development for oil palm is larger that the present applied value at 4.1%
- The contribution to global warming from palm oil may be lower of the yields are higher than the applied 18.87 t FFB/ha, if POME is treated in a digester tank with utilisation of biogas, and and if the steam requirement is lower than the applied 0.65 t steam/t FFB

If the uncertainty of the first three bullets should be reduced it would require a workload and further development of methodologies that exceeds the allocation of time for this study. Regarding the fourth bullets it is likely that a large part of future development of land for oil palm cultivation will take place on peat soil. According to Corley and Tinker (2003) much of the remaining land available for expansion of oil palm cultivation in South-East Asia is peat soil. Regarding the fifth bullet, it is likely that the marginal supplier of palm oil is represented by large private estates with good agricultural practices rather than private small-holders with poor cultivation practices. Therefore, the applied average yield at 18.87 t/ha may be too low. However, according to MPOB (2005 and 2006) the share of private estates in Malaysia has increased from 59.1% in 2003 to 60.2% in 2005, and the share of small-holders has increased from 10.2% in 2003 to 10.5% in 2005. Thus, statistics do not support that hypothesis. Regarding POME treatment, the technology of today is open anaerobic digestion in lagoons. However, several digester tanks and utilisation of biogas have been installed as CDM-projects within the Kyoto-protocol framework. Thus, digester tanks may very well be the technology of the future. Regarding steam requirement, the applied 0.65 t steam/t FFB is in the high end of the interval. And in addition increased focus on the value of excess shells as biofuel may be an incentive for reducing the steam consumption. Therefore, it is likely that the contribution to global warming per t palm oil will decrease in the future.

23.2 Completeness check

The objective of a completeness check is to ensure that the information provided in the difference phases of the LCA are sufficient in order to interpretate the results (ISO 14044 2006).

In general the system boundaries and inventory data are described comprehensively in this report. The point of departure for each life cycle stage is that all environmental relevant processes are included in the inventory. Environmental relevant means relevant for the impact categories included in the study, see section 1.4. In the beginning of each section representing the life cycle stages included in the study, the omission of data, if any, is described. In general it assessed that all relevant information is included, except from the use of pesticides in barley cultivation. However, as described in section 21.1, the results of ecotoxicity are regarded so uncertain that the characterised results do not provide usable information. Therefore, the impact categories of toxicity are not supported sufficiently by the inventory data and LCIA-models available.

Though, the relevant data are present and included, some of the data are related to significantly uncertainties. Thus, the following uncertainties in data affect the interpretation of the results:

- The ratio between increased yield and increased area when cultivation of a certain crop is increased
- The determination of the affected means of increasing yield (only increased yield by additional NPK-fertiliser has been modelled)
- The modelling of yield-responses by additional fertiliser application
- The affected type of land use when transforming non-cultivated land into agricultural land
- There share of new land developed for oil palm that is peat soil

If abovementionned uncertainties should be reduced, it would require a workload and further development of methodologies that exceeds the allocation of time for this study. Therefore, these uncertainties are tested in sensitivity analyses (see section 21) and when conclusions are drawn they should be considered.

23.3 Consistency check

The objective of the consistency check is to verify that assumptions, methods and data are consistent with the goal and scope. Especially the consistency regarding data quality along the product chain, regional/temporal differences, allocation rules/system boundaries and LCIA are important (ISO 14044).

As described in section 23.2 the point of departure of the inventory for each life cycle stage has been to include all environmental relevant processes. Among the traditional processes capital goods (machinery and buildings) have been included for all processes. Only very few data has been omitted from the inventory. When data have been taken from life cycle inventory databases, the largest and most comprehensive database available, ecoinvent, has been used in all cases. Thus, differences between LCI-databases do not contribute to inconsistency in this study.

Regarding regional differences the location of the marginal supplier has been identified for all crops inventoried. Regarding temporal differences data have been collected for 2005 for crop yields and oil mills. However, most of the applied database data are of older date.

Regarding allocation and system delimitation, the consequential approach has been consistently applied to most included technologies (electricity, heat, fertiliser, oil mills) and suppliers (crops). But the ecoinvent database uses average technology and allocate by using allocation factors which do not comply with the consequential approach. However, the effect of using allocation factors and of applying average technology has been assessed and when significant differences were identified, the processes from ecoinvent have been modifyied in order to represent consequential modelling.

The updated version of EDIP97 has been applied for the impact categories; global warming, ozone depletion, acidification, eutrophication, photochemical smog and ecotoxicity. Land use has been assessed using inventory data (occupied and transformed area in units of m^2y and m^2) and the method of Schmidt (2007c). EDIP as well as the method of Schmidt are so-called bottom-up LCIA-methods. However, the methods differ in the way that the indicator of Schmidt is representing an end-point indicator while the indicators of EDIP represent mid-point indicators. There is no overlapping between the impact categories in EDIP97 and in the method of Schmidt. Normalisation and weighting have not been carried out.

24 References

Aarhus United (2004a), *Aarhus United - Miljørapport* (English: Aarhus United – Environmental report). Aarhus United, Aarhus

Aarhus United (2004b), Aarhus United - *Energirapport* (English: Aarhus United - Energy report). Aarhus United, Aarhus

Aarhus United (2005a), *Aarhus United - Miljørapport* (English: Aarhus United – Environmental report). Aarhus United, Aarhus

Aarhus United (2005b), Aarhus United - *Energirapport* (English: Aarhus United - Energy report). Aarhus United, Aarhus

Althaus H J, M Chudacoff M, S Hellweg, R Hischier, N Jungbluth, M Osses and A Primas (2003), *Life cycle inventories of chemicals*. ecoinvent report No. 8. Swiss Centre for Life Cycle Inventories, Dübendorf

Andersen E S, P Jespersgaard and O G Østergaard (1981), *Databog, fysik, kemi* (English: Data book, physics, chemistry). F&K forlaget, Copenhagen

Andersen J M, H D Poulsen, C F Børsting, H B Rom, S G Sommer and N J Hutchings (2001), *Ammoniakemission fra landbruget siden midten af 80'erne* (English: Ammonia emission from agriculture since the mid 80ies). Faglig rapport fra DMU, nr. 353, Danmarks Miljøundersøgelser, Miljøministeriet, Copenhagen

Andersen J B (2005), Personal communication with Jørgen Brix Andersen, engineer, support division, Studstrupværket, Elsam, Skødstrup

Andriesse J P (1988), *Nature and Management of Tropical Peat Soils*. FAO Soils Bulletin 59, Soil Resources, Management and Conservation Service, FAO Land and Water Development Division, and Agriculture Organization of the United Nations (FAO), Rome. http://www.fao.org/docrep/x5872e/x5872e00.htm#Contents (Accessed January 2007)

APERC (2006), *APEC Energy Demand and Supply Ooutlook 2006 - Projections to 2030, Economy Review*. Asia Pacific Energy Research Centre (APERC), Tokyo. http://www.ieej.or.jp/aperc/2006pdf/Outlook2006/Whole_Report.pdf (Accessed January 2007)

Arulandoo X (2006), Personal communication with Researcher Dr. Xavier Arulandoo, United Plantations Berhad, Research Department, Jendarata Estate, Teluk Intan, Malaysia

Austin A T, Piñeiro G, Gonzalez-Polo M (2006), *More is less: agricultural impacts on the N cycle in Argentina*. Biogeochemistry 79, pp 45-60

AVL (2006), *Product profile - Properties of GALLEON EARTH*. Ashapura Volclay Limited. http://www.avlgalleon.com/products/properties.htm (Accessed December 2006)

Bamgboye A I and S O Jekayinfa (2006), *Energy Consumption Pattern in Palm Kernel Oil Processing Operations*. Agricultural Engineering International: the CIGR Ejournal.Manuscript EE 05 013. Vol. VIII. March, 2006. http://cigr-ejournal.tamu.edu/ (Accessed December 2006)

Bauer C (2003), *Holzenergie*. In Dones R, C Bauer, R Bolliger, B Burger, T Heck, A Röder, M F Emmenegger, R Frischknecht and N Jungbluth (2003), *Sachbilanzen von Energiesystem, Datenbestand v1.01 (2003)*. Final report ecoinvent 2000 No. 6-IV, Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf

Bauer C (2005), Personal communication with Christian Bauer, Systems/Safety Analysis Section, Paul Scherrer Institut, Villigen Switzerland

Bek-Nielsen C (2006), Personal Communication with Carl Bek-Nielsen, Executive Director, United Plantations Berhan, Teluk Intan, Malaysia

Bentley R W (2002), *Global oil & gas depletion - an overview*. Energy Policy 30 (2002) 189-205. Elsevier

Bergström A-K and M Jansson (2006), *Atmospheric nitrogen deposition has caused nitrogen enrichment and eutrophication of lakes in the northern hemisphere*. Global Change Biology (2006) 12, 635 -643, Blackwell Publishing

Berntsen J and B M Petersen (2007), C-TOOL. Tool for calculation of C and N in the soil pool. Danmarks Jordbrugsforskning, Tjele, Denmark. Available online: http://web.agrsci.dk/jbe/bin/ctool.html (Accessed April 2006)

Billore S K, Ohsawa M, Numata M and Okano S (1995), *Microbial biomass nitrogen pool in soils from a warm temperate grassland, and from deciduous and evergreen forests in Chiba, central Japan*. Biology and Fertility of Soils (1995) 19:124-128, Springer-Verlag

Bockisch M (1998), *Fats and Oils - Handbook*. AOCS Press, Illinois

Brandt S (2003), *Tillage practices that reduce soil erosion*. Conservation Tillage Subcommittee of the Saskatchewan Advisory Council on Soils and Agronomy. Agriculture and Agri-food Canada.
http://www.agr.gc.ca/pfra/soil/tillage_e.htm (Accessed March 2006)

Bugge J (2000), *Notat: Rapsolie til transport 1, Energibalance og CO_2-balance* (English: Note: Rapeseed oil for transport 1, Energy balance and CO_2 balance). Nordvestjysk Folkecenter for Vedvarende Energi, Hurup, Denmark

BUWAL 250 (1996), *Ökoinventare für Verpackungen*. Schriftenreihe Umwelt 250, Bern

Casson A (2003), *Oil Palm, Soybeans & Critical Habitatloss*. WWF, Switzerland

Chavalparit O, Rulkens W H, Mol A P J and Khaodhair S (2006), *Options for environmental sustainability of the crude palm oil industry in Thailand through enhancement of industrial ecosystems*. Environment, Development and Sustanability (2006) 8, pp. 271-287. Springer

Chen X, Hutley L B and Eamus D (2003), *Carbon balance of a tropical savanna of northern Australia*. Oecologia (2003) 137, pp 405–416, Ecosystem Ecology, Springer-Verlag

Chew P S, Kee K K and Goh K J (1999), *Cultural Practices and Their Impact*. In: Singh G, L K Huan, Leng T and D L Kow (1999), Oil Palm and the Environment – A Malaysian Perspective. Malaysian Oil Palm Growers Council, Kuala Lumpur

Chun and Jaafar (2005), Personal communication with Choong Mei Chun and Norlin Jaafar, Officers in Strategic Communication Division, 27th of July 2005, Department of Environment, Putrajaya, Malaysia

Clausen D (2002), *Kvælstoffrigivelse fra frøgræshalm fra engrapgræs, strandsvingel og alm. rajgræs* (English: Nitrogen release from seed grass straw from different crops). Speciale i planters ernæring. Institut for Jordbrugsvidenskab. KVL, Frederiksberg

Corley R H V and Tinker P B (2003), *The Oil Palm*. Fourth edition. Blackwell Publishing

Corley H (2006), Ten steps towards sustainability of palm oil production. Announcement within the Round Table on Sustainable Palm Oil initiative. http://www.rspo.org/PDF/Main%20page/Ten%20steps%20towards%20increased%20sustainability.pdf (Accessed January 2007)

Dalgaard T, N Halberg, J R Porter (2001), *A model for fossil energy use in Danish agriculture used to compare organic and conventional farming*. Agriculture, Ecosystems and Environment 87 (2001), 51-65. Elsevier

Dalgaard (2007), Personal communication with Randi Dalgaard. Co-author of the LCAfood database. Ph.D. fellow at Department of Development and Planning, Aalborg University and Danish Institute of Agricultural Science. Denmark

Dalgaard R, N Halberg, I S Kristensen and I Larsen (2006), *Modelling representative and coherent farm types based on accountancy data for use in environmental assessments*. Agriculture, Ecosystems and Environment Vol. 117, No. 4 (2006) 223-237.

Dalgaard R, Schmidt J H, Halberg N, Christensen P, Thrane M and Pengue W A (2007), *LCA of soybean meal*. International Journal of Life Cycle Assessment (in press), Ecomed Publishers, Landsberg

Danish Energy Authority, Elkraft and Eltra (2004), *Technology data for electricity and heat generating plants*. Danish Energy Authority, Copenhagen

Danish Government (2002), *A shared future - balanced development, Denmark's national strategy for sustainable development*. The Danish Government

Danish Institute for Agricultural Science (2005), Geodata on soils in Denmark for GIS. Danish Institute for Agricultural Science, Ministry of Food, Agriculture and Fisheries, Tjele

Danmarks Statistik (2006), *Danmarks Statistik - statistikbanken.dk* (English: Statistics Denmark - statbank.dk). Copenhagen. http://www.dst.dk/ (Accessed September 2006)

Dansk Landbrug (2004), *Kornafregningsaftalen* (English: Agreement on payment of cereals). Dansk Landbrug, Copenhagen

Dansk Landbrugsrådgivning (2005a), *Dyrkningsvejledning, Vinterraps* (English: Cultivation guideline, Winther rapeseed). Dansk Landbrugsrådgivning, Landscentret, Aarhus

Dansk Landbrugsrådgivning (2005b), *Dyrkningsvejledning, Vårraps* (English: Cultivation guideline, Spring rapeseed). Dansk Landbrugsrådgivning Landscentret, Aarhus

Dansk Landbrugsrådgivning (2006), *Dyrkningsvejledning, Vårbyg* (English: Cultivation guideline, Spring barley). Dansk Landbrugsrådgivning Landscentret, Aarhus

Dansk Landbrugsrådgivning (2007), *Sort-info Vinterraps* (English: Species-info Winter rapeseed). Dansk Landbrugsrådgivning Landscentret and Danmarks Jordbrugsforskning, Aarhus. http://www.sortinfo.dk (Acessed June 2007)

Department of Environment (1999), *Industrial Processes & The Environment (Handbook No. 3) Crude* Palm Oil Industry. Department of Environment, Malaysia

Distances (2005), *World Ports Distances Calculator*. World News Network. http://www.distances.com (Accessed December 2006)

Ecoinvent (2004), *ecoinvent data v1.3. Final reports ecoinvent 2000 No. 1-15*. Swiss Centre for Life Cycle Inventories, Dübendorf

EFMA (2000), *Understanding Phosphorus and its use in Agriculture*. European Fertilizer Manufacturers Association, Brussels

EFMA (2003), *Understanding Potassium and its use in Agriculture*. European Fertilizer Manufacturers Association, Brussels

EFMA (2004), *Understanding Nitrogen and its use in Agriculture*. European Fertilizer Manufacturers Association, Brussels

EFMA (2006), *Fertilizer Products*. European Fertilizer Manufacturers Association, Brussels, http://www.efma.org/introduction/section02.asp (Accessed March 2006)

EDIP (1996), *EDIP life cycle inventory database*. Danish Environmental Protection Agency, Copenhagen

EDIP (2000), *EDIP life cycle inventory database – reversed version*. Danish Environmental Protection Agency, Copenhagen

EIA (2005), *International Energy Outlook 2005*. Energy Information Administration (EIA), Washington DC

Ellermann T, H V Andersen, C Monies, K Kemp, R Bossi, B Bügel Mogensen, P Løfstrøm, J Christensen and L M Frohn (2005), *Atmosfærisk deposition 2004* (English: Atmospheric deposition 2004). NOVANA. Danmarks Miljøundersøgelser. Faglig rapport fra DMU, nr.555, Danmarks Miljøundersøgelser, Miljøministeriet, Copenhagen

Elsam (2005), *Grønt regnskab 2004, Elsam Kraft A/S, Studstrupværket* (English: Green account 2004, Elsam Kraft Ltd., Studstrupværket). Elsam, Fredericia

Emmenegger, M F, N Jungbluth and T Heck (2003), *Erdgas, Teil V* (English: Natural gas, part 5). In Dones R, C Bauer, R Bolliger, B Burger, T Heck, A Röder, M F Emmenegger, R Frischknecht and N Jungbluth (2003), *Sachbilanzen von Energiesystem*, *Datenbestand v1.01 (2003)*. Final report ecoinvent 2000 No. 6-IV, Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf

Emmersen C (2006), Personal Communication with Claus Emmersen, Production director, Scanola, Aarhus, Denmark

Energi E2, Elkraft, Elfor, Elsam and Eltra (2000), *Livscyklusvurdering af dansk el og kraftvarme - Hovedrapport* (English: Life cycle assessment of Danish electricity and heat – Main report). Energi E2, Elkraft, Elfor, Elsam and Eltra

Energistyrelsen (2005), *Danmarks olie- og gasproduktion 2004* (English: Denmark’s oil and gas production 2004). Energistyrelsen, Copenhagen

Energistyrelsen (2006), Biomasseressourcer (English: Biomass resources). Energistyrelsen, Copenhagen. Only available on Energistyrelsen’s webpage: http://www.energistyrelsen.dk/sw17120.asp (Accessed April 2006)

EQ crude palm-oil regulations (2005), *Environmental Quality (Prescribed Premises) (Crude Palm –Oil) Regulations, 1977*. In: Environmental Quality Act 1974 (Act 127) & Subsidiary Legislation (As at 5th January 2005), pp 1-48. International Law Book Services, Petaling Jaya, Malaysia

EQA (2005), *Environmental Quality Act 1974 (Act 127).* In: Environmental Quality Act 1974 (Act 127) & Subsidiary Legislation (As at 5th January 2005), pp 1-48. International Law Book Services, Petaling Jaya, Malaysia

ETH-ESU (1996), *ETH-ESU life cycle inventory database*. Available in the PC software SimaPro 7.0. Background data are described in Frischknecht et al. (1996). Zurich

The European Commission (2006a), *An EU Strategy for Biofuels*. Communication from the Commission COM(2006) 34. Commission of the European Communities, Brussels

The European Commission (2006b), *Biofuels Strategy: Background memo*. MEMO/06/05. Brussels, 8 February 2006

The European Commission (2006c*), *Draft proposal relating to cadmium in fertilisers*. The Chemicals Unit of DG Enterprise, European Commission, Brussels. *Date of issue is not given. 2006 is the year of download.
http://europa.eu.int/comm/enterprise/chemicals/legislation/fertilizers/cadmium/draft_proposal.pdf (Accessed March 2006)

The European Commission (2006d), *Reference Document on Best Available Techniques for the Manufacture of Large Volume Inorganic Chemicals – Ammonia, Acids and Fertilisers*. European Commission, Brussels

The European Parliament and the Council (2003), *Regulation (EC) No 2003-2003 of the European Parliament and the Council of 13 October 2003 relating to fertilisers*. The European Parliament and the Council, Brussels

FAO (2004), *Fertilizer use by crop in Malaysia*. Food and Agriculture Organization of the United Nations (FAO), Rome. http://www.fao.org/docrep/007/y5797e/y5797e00.HTM (Accessed December 2006)

FAO (2005), *State of the World's Forests 2005*. Food and Agriculture Organization of the United Nations (FAO), Rome

FAO and IFA (2001), *Global estimates of gaseous emissions of NH3, NO and N2O from agricultural land*. Food and Agriculture Organization of the United Nations (FAO) and International Fertilizer Industry Association (IFA). Rome

FAOSTAT (2006), *FAOSTAT Agriculture Data*, Food and Agriculture Organisation of the United Nations (FAO).
http://apps.fao.org/ (Accessed December 2006)

Fee C G and M Sharma (2002), *Integrated Pest and Disease Management and Associated Impact of Pesticides*. In: Singh G, L K Huan, Leng T and D L Kow (1999), Oil Palm and the Environment – A Malaysian Perspective. Malaysian Oil Palm Growers Council, Kuala Lumpur

Frese S D, Ibsen S R, Bang J K and Andersen J (2006), *Madens globale fodaftryk* (English: Global footprint of food). WWF Denmark, Copenhagen

Frischknecht R, U Bollens, S Bosshart, M Ciot, L Ciseri, G Doka, R Dones, U Gantner, R Hischier and A Martin (1996), *Ökoinventare von Energiesystemen. Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. Auflage No. 3*. Gruppe Energie - Stoffe - Umwelt (ESU), Eidgenössische Technische Hochschule Zürich und Sektion Ganzheitliche Systemanalysen, Paul Scherrer Institute, Bern

Frischknecht R, Jungbluth N, Althaus H-J, Doka G, Dones R, Hellweg S, Hischier R, Nemecek T, Rebitzer R and Spielmann M (2003), *Overview and Methodology*. ecoinvent report No. 1, Swiss Centre for Life Cycle Inventories, Dübendorf

Frischknecht R, Althaus H-J, Bauer C, Capello C, Doka G, Dones R, Emmenegger M F, Hischier R, N Jungbluth, Margni M, Kellenberger D, Nemecek T and Spielmann M (2006), *Documentation of changes implemented in ecoinvent Data v1.2 and v1.3. Data v1.3.* ecoinvent report No. 16, Swiss Centre for Life Cycle Inventories, Dübendorf

Garrity D P, Soekardi M, van Noordwijk M, de la Cruz R, Pathak P S, HGunasena H P M, van So N, Huijun G and Majid N M (1997), *The Imperata grasslands of tropical Asia: area, distribution, and topology*. Agroforestry Systems 36, pp 3-29. Kluwer Publishers, The Netherlands

Glastra R, Wakker E and Richert W (2002), *Oil palm plantations and deforestation in Indonesia. What Role Do Europe and Germany Play?* WWF Switzerland

Goedkoop M and Spriensma R (2001), *Eco-indicator 99, A damage oriented LCA impact assessment method, Methodology report*. Third edition. Nr. 1999/36a. Pré Consultants, Amersfoort. http://www.pre.nl/download/EI99_methodology_v3.pdf (Accessed June 2006)

Gomez P and J Gurevitch (1998), *Weed Community Responses in a Corn-Soybean Intercrop*. Applied Vegetation Science, Vol. 1 No. 2, pp 281-288, Opulus Press

Hansen E et al. (2004), *Livscyklusvurdering af deponeret affald* (English: Life cycle assessment of landfill). Environmental Project No. 971. Danish Environmental Protection Agency, Copenhagen

Hansen A K (2006), Personal communication with Anders Kromand Hansen, engineer, AarhusKarlshamn Denmark, Aarhus

Haque I and Jutzi S (1984), *Nitrogen fixation by forage legumes in sub-Saharan Africa: Potential and limitations*. ILCA Buletin No. 20, October 1984, CGIAR
http://www.ilri.cgiar.org/InfoServ/Webpub/Fulldocs/Bulletin20/Nitrogen.htm#TopOfPage (Accessed December 2006)

Hauschild M and H Wenzel (1998), *Environmental Assessment of Products – Volume 2: Scientific background*. Chapman and Hall, London

Hauser S (2006), *Nitrogen fixation and balance in burned versus mulched Mucuna pruriens var. utilis and Pueraria phaseoloides relay maize cropping systems*. Proceeding presented at Tropentag 2006, International Research on Food Security, Natural Resource Management and Rural Development. October 11 - 13, 2006, University of Bonn, Bonn.
http://www.tropentag.de/2006/abstracts/full/64.pdf (Accessed December 2006)

Henson I E (2004), *Modelling Carbon Sequestration and Emissions Related to Oil Palm Cultivation and Associated Land Use Change in Malaysia*. MPOB Technology No. 27, December 2004. Kajang, Malaysia

Hischier R (2003), *Life Cycle Inventories of Packagings and Graphical Papers, Data v1.01 (2003), Part II Plastics*. ecoinvent report no. 11, Swiss Centre for Life Cycle Inventories, Dübendorf

Hirsinger F, K P Schick and M Stalmans (1995), *A Life-Cycle Inventory for the Production of Oleochemical Raw Materials*. Tenside Surf Det 32 (1995) 5, Carl Hanser Verlag, München

Husain Z, Z A Zainal, M Z Abdullah (2003), *Analysis of biomass-residue-based cogeneration system in palm oil mills*. Biomass and Bioenergy 24 (2003) 117 – 124. Elsevier

Hvid S K, B Weidema, I S Kristensen, R Dalgaard og T Bech-Larsen (2004), *Miljøvurdering af Landbrugsprodukter*. Miljøprojekt Nr. 954. Danish Environmental Protection Agency, Copenhagen

IEA (2004), *World Energy Outlook 2004*. International Energy Agency (IEA), Paris
http://www.iea.org//textbase/nppdf/free/2004/weo2004.pdf (Accessed January 2007)

IEA (2007), *IEA Statistics, Statistics by Product*. International Energy Agency
http://www.iea.org/Textbase/stats/index.asp (Accessed January 2007)

IFA (2007a), *Production and International Trade Statistics - Fertilizer Consumption Statistics*. Nitrogen fertilizer nutrient consumption. International Fertilizer Industry Association (IFA). Paris,
http://www.fertilizer.org/ifa/statistics.asp (Accessed January 2007)

IFA (2007b), *Fertilizer Indicators, The World, 1920/21 to 2000/01 - Outlook to 2030*. International Fertilizer Industry Association (IFA). Paris,
http://www.fertilizer.org/ifa/statistics/indicators/ind_cn_world.asp (Accessed January 2007)

IPCC (2000), *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. Intergovernmental Panel on Climate Change (IPCC), Geneva

IPCC (2003), *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. Intergovernmental Panel on Climate Change (IPCC), Geneva

Ishizuka S, A Iswandi, Y Nakajima, S Yonemura, S Sudo, H Tsuruta and D Murdiyarso (2005), *The variation of greenhouse gas emissions from soils of various land-use/cover types in Jambi province Indonesia*. Nutrient Cycling in Agroecosystems 2005: 71, pp 17-32. Springer

Islam M, Fartaj A and Ting D S K (2004), *Current utilization and future prospects of emerging renewable energy applications in Canada*. Renewable and Sustainable Energy Reviews 8 (2004) 493–519, Elsevier

ISO 14040 (2006), *Environmental management - Life cycle assessment – Principles and framework*. International Standard Organization (ISO), Geneve

ISO 14044 (2006), *Environmental management - Life cycle assessment – Requirements and guidelines*. International Standard Organization (ISO), Geneve

Jacobsen B H, C G Sørensen and J F Hansen (2002), *Håndtering af husdyrgødning – en teknisk-økonomisk systemanalyse* (English: Handling of animal manure in Denmark - a technical and economical system analysis). Rapport nr. 138, Fødevareøkonomisk Institut (FØI), Copenhagen

Jales M Q M, Jank M S, Yao S and Carter C A (2006), *Agriculture in Brazil and China: Challenges and Opportunities*. Institute for the Integration of Latin America and the Carribean. Buenos Aires

Jensen E B, K Jørgensen, C Haldrup, K A Nielsen, B Christensen, M Wegge, T Serup, F Udesen and J J Høy (2005), *Budgetkalkuler 2006, for de enkelte produktionsgrene, Kalenderårene 2005 og 2006* (English: Budget estimates 2006, for single production lines, Calendar years 2005 and 2006). Dansk Landbrugsrådgivning, Landscentret, Aarhus

Jolliet O, M Margni, R Charles, S Humbert, J Payet, G Rebitzer and R Rosenbaum (2003), *Impact 2002+: A New Life Cycle Impact Assessment Methodology*. International Journal of Life Cycle Assessment 8 (6) 324 – 330. Ecomed Publishers, Landsberg

Jungbluth N (2003), *Erdöl - Teil IV* (English: Natural gas, Part 4) In Dones R, C Bauer, R Bolliger, B Burger, T Heck, A Röder, M F Emmenegger, R Frischknecht and N Jungbluth (2003), *Sachbilanzen von Energiesystem*, *Datenbestand v1.01 (2003)*. Final report ecoinvent 2000 No. 6-IV, Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf

Kandiah S, M Hasan and M Yaacob (1992), *Overview of automation in a palm oil mill-the sterilisation process*. Computing and Control Engineering Journal, Volume 3, Issue 1, Jan. 1992, pp 45-52, The Institution of Engineering and Technology The Knowledge Network

Kang L J (2006), *Refinery of Palm Oil*. Webpage. ASTS Fellow, Pusat Pengajian Kejuruteraan Kimia di Universiti Sains Malaysia, Kuala Lumpur. http://www.andrew.cmu.edu/user/jitkangl/Index.htm (Accessed December 2006)

Kellenberger D, H-J Althaus, T Künniger and N Jungbluth (2003), *Life Cycle Inventories of Building Products, Data v1.01 (2003)*. ecoinvent report No. 7, EMPA Dübendorf , Swiss Centre for Life Cycle Inventories, Dübendorf

Khalid H, Zin Z Z and Anderson J M (2000), *Decomposition Processes and Nutrient Release Patterns of Oil Palm Residues*. Journal of Oil Palm Research Vol 12 No. 1, June 2000, pp 46-63. Malaysian Palm Oil Board, Kuala Lumpur

Kiese and Butterbach-Bahl (2002), *N2O and CO2 emissions from three different tropical forest sites in the wet tropics of Queensland, Australia*. Soil Biology & Biochemistry 34 (2002) pp 975-987. Elsevier

Kiese and Butterbach-Bahl (2003), *N2O and CH4 Sink and Source Strength of Tropical Rain Forest Soils in Australia: Long-term Measurements and Upscaling of Field Results with the Biogeochemical Model PNET-N-DNDC*. Geophysical Research Abstracts, Vol. 5, 05674, 2003, European Geophysical Society

Kløverpris J (2006), Inventory analysis of crop production in LCA– a pre-requisite for impact assessment of crop use. In: Milà i Canals L, Basson L, Clift R, Müller-Wenk R, Bauer C, Hansen Y and Brandão M (2006), Expert Workshop on Definition of Best Indicators for Biodiversity and Soil Quality for Life Cycle Assessment (LCA) - Proceedings and Conclusions. Centre for Environmental Strategy, University of Surrey, Guildford, Surrey

Kløverpris (2007), Ongoing Ph.D. project: Land Use and Toxicity in Life Cycle Assessment. Dept. of Manufacturing Engineering and Management, Technical University of Denmark, Lyngby

Koch S (2003), *LCA of Biodiesel in Costa Rica, An Environmental Study on the Manufacturing and Use of Palm Oil Methyl Ester*. University of Applied Sciences Northwestern Switzerland (FHNW), Muttenz, Switzerland

Korning J (2006), Personal communication with Jesper Korning, Quality Manager, AarhusKarlshamn Denmark, Aarhus

Krak (2006), *Europa ruteplan* (English: Route plan in Europe). Krak.
http://www.krak.dk/INC/EuroRoute/default.asp (Accessed December 2006)

Kromann L (1996), L*ivscyklusbaseret miljøvurdering af anvendelser af sildeafskær fra fiskeindustrien, Delrapport 2* (English: Life cycle based environmental assessment of applications of fish waste (herring) from fishing industry, report 2). Department of Planning and Development and Planning, Aalborg University, Aalborg

Kromann L, A S Madsen, J Schmidt, B V Mathiesen (2004), *Madaffald fra storkøkkener* (English: Food waste from commercial kitchens). Arbejdsrapport fra Miljøstyrelsen Nr. 1 2004. The Danish Environmental Protection Agency, Copenhagen

Kronborg L (2006), Personal Communication with Lars Kronborg, Quality Engineer, AarhusKarlshamn Denmark, Aarhus

LCA-Center (2006), *Der kommer kul ud af din stikkontakt* (English: Coal is the marginal electricity in Denmark). LCA-nyt Nr 27, Februar 2006. LCA-Center, Kgs. Lyngby, Denmark

LCA-Center (2007), *Updated version of EDIP97*. LCA-Center, Kgs. Lyngby, Denmark
http://www.lca-center.dk/cms/site.asp?p=1378 (Accessed January 2007)

Lim C H, G Singh and K H Lim (1999), *Production of Organic Fertilisers and Soil Conditioners*. In: Singh G, L K Huan, Leng T and D L Kow (1999), Oil Palm and the Environment – A Malaysian Perspective. Malaysian Oil Palm Growers Council, Kuala Lumpur

Ma A N (1999a), *Treatment of Palm Oil Mill Effluent*. In: Singh G, L K Huan, Leng T and D L Kow (1999), Oil Palm and the Environment – A Malaysian Perspective. Malaysian Oil Palm Growers Council, Kuala Lumpur

Ma A N (1999b), *Treatment Technology for Palm Oil Refinery Effluent*. In: Singh G, L K Huan, Leng T and D L Kow (1999), Oil Palm and the Environment – A Malaysian Perspective. Malaysian Oil Palm Growers Council, Kuala Lumpur

Ma A N, Y M Choo, T S Toh and N S Chua (2004), *Renewable energy from palm oil industry*. Not published. Updated version of chapter 17 in: Singh G, L K Huan, Leng T and D L Kow (1999), Oil Palm and the Environment – A Malaysian Perspective. Malaysian Oil Palm Growers Council, Kuala Lumpur

Meyer N I, Nørgård J S, Galster G and Guldbrandsen (1994), *Energi og Ressourcer – for en bæredygtig fremtid* (English: Energy and Resources – for a sustainable future). Polyteknisk Forlag, Lyngby

Mikkelsen H J, S Gyldenkærne, H D Poulsen, J E Olesen and S G Sommer (2005), *Opgørelse og beregningsmetoder for landbrugets emissioner af ammoniak og drivhusgasser 1985-2002* (English: Statement and method for calculations of agricultural emission of ammonia and green house gases 1985 - 2002). Arbejdsrapport fra DMU Nr. 204. Danish Ministry of the Environment

Miljøstyrelsen (2002), *Redegørelse om Vandområdedistrikter (VOD) i Danmark*. (English: Report on water districts in Denmark). Miljøstyrelsen, Copenhagen, www.mst.dk/vand/06020300.htm#12 (Accessed April 2006)

Miljøstyrelsen (2005), *Bekæmpelsesmiddelstatistik 2004, Salg 2002, 2003 og 2004, Behandlingshyppighed 2004* (English: Pesticides statistics 2004, Sale 2002, 2003 and 2004, Treatment frequency 2004). Orientering fra Miljøstyrelsen Nr. 6 2005. The Danish Environmental Protection Agency, Copenhagen

Ministeriet for Fødevarer, Landbrug og Fiskeri (2004), *Orienterende notat til Folketingets Europaudvalg om EU kommissionens overvejelser om regulering af cadmiumindholdet i handelsgødning* (English: Brief note to the Danish Parliament's European Affairs Committee; on the EU Commission's considerations on regulation of cadmium content in artificial fertilisers). Ministeriet for Fødevarer, Landbrug og Fiskeri, Copenhagen,
http://www.folketinget.dk/img20031/udvbilag/lib2/20031_13312/20031_13312.pdf (Accessed March 2006)

Mohamed A R and K T Lee (2006), *Energy for sustainable development in Malaysia: Energy policy and alternative energy*. Energy Policy 34 (2006) 2388–2397, Elsevier

MPOB (2005), *Review of the Malaysian Oil Palm Industry 2004*. Economics and Industry Development Division, Malaysian Palm Oil Board, Kelana Jaya

MPOB (2006), *Review of the Malaysian Oil Palm Industry 2005*. Economics and Industry Development Division, Malaysian Palm Oil Board, Kelana Jaya

Møller J, R Thøgersen, A M Kjeldsen, M R Weisberg, K Soegaard, T Hvelplund and C F Børsting (2000), *Fodermiddeltabel - Sammensætning og foderværdi af fodermidler til kvæg* (English: Feeding component table – Composition and feeding value of feeding components for cattle), Rapport nr 91 Landsudvalget for Kvæg. Foulum, Denmark

Nemecek T, A Heil, O Huguenin, S Meier, S Erzinger, S Blaser, D Dux and A Zimmermann (2003), *Life Cycle Inventories of Agricultural Production Systems, Data v1.01 (20*03). Final report ecoinvent 2000 No. 15. FAL Reckenholz, FAT Tänikon, Swiss Centre for Life Cycle Inventories, Dübendorf

Nielsen P H, A M Nielsen, B P Weidema, R Dalgaard and N Halberg N (2005), *LCA food database*. www.lcafood.dk. The database is available in the LCA pc-software SimaPro 7.0.

Pedersen C Å (2005), *Oversigt over Landsforsøgene, Forsøg og undersøgelser i de danske landøkonomiske foreninger 2005* (English: Overview of agricultural experiments, experiments and examinations in the Danish agricultural economic associations). Dansk Landbrugsrådgivning, Landscentret, Aarhus

Perelman S B, R J C León and M Oesterheld (2001), *Cross-scale vegetation patterns of Flooding Pampa grasslands*. Journal of Ecology 2001 89, 562-577. British Ecological Society

Petersen B M and J Berntsen (2002), *Omsætning i jordpuljen på forskellige bedriftstyper*. In: Kvælstofbalancer på landbrugsbedriften - status og perspektiver. DJF intern rapport 157, Tjele, Denmark.
http://www.agrsci.dk/c-tool/BMP.pdf (Accessed April 2006)

Pidwirny M (2006), *Fundamentals of Physical Geogrphy, 2nd edition*. 6th of November 2006
http://wwwphysicalgeography.net/fundamnetals/contents.html (Accessed January 2007)

Plantedirektoratet (2004), *Tilførsel af cadmium til dansk jordbrug via fosforholdig handelsgødning 1984 – 2002* (English: Inpu of cadmium to Danish agriculture from phosphate fertiliser 1984 – 2002). Miljøstyrelsen, Copenhagen.
http://www.mst.dk/kemi/02310000.htm (Accessed March 2006)

Plantedirektoratet (2005a), *Vejledning om gødsknings- og harmoniregler* (English: Guidelines on regulations of fertilising and harmony rules). Plantedirektoratet. Ministeriet for Fødevarer, Landbrug og Fiskeri, Lyngby

Plantedirektoratet (2005b), *Danmarks forbrug af handelsgødning 2004/05, 1/8 - 31/7* (Denmark's consumption of artificial fertilisers 2004/05, 1/8 - 31/7). Plantedirektoratet. Ministeriet for Fødevarer, Landbrug og Fiskeri, Lyngby

ProForest (2003), *Palm oil forests and sustainability – Discussion paper for the Round Table on Sustainable Palm Oil*. ProForest, Oxford, United Kingdom

Reijnders L and M A J Huijbregts (2006), *Palm oil and the emission of carbon-based greenhouse gases*. Journal of Cleaner Production (2006) Article in press. Elsevier

Röder A, C Bauer and R Dones (2003), *Kohle, Teil VI* (English: Coal, part 6). In Dones R, C Bauer, R Bolliger, B Burger, T Heck, A Röder, M F Emmenegger, R Frischknecht and N Jungbluth (2003), *Sachbilanzen von Energiesystem, Datenbestand v1.01 (2003)*. Final report ecoinvent 2000 No. 6-IV, Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf

RSPO (2006), *RSPO Principles and Criteria for Sustainable Palm Oil Production*. Kuala Lumpur
http://www.rspo.org/criteria.htm (Accessed January 2007)

Ruser R, H Flessa, R Schilling, F Beese and J C Munch (2001), *Effect of crop-specific field management and N fertilization on N2O emissions from a fine-loamy soil*. Nutrient Cycling in Agroecosystems 59: 177–191, 2001. Kluwer Academic Publishers, The Netherlands

Schmidt J H (2007a)[25], *Comparative Life Cycle Assessment of Rapeseed Oil and Palm Oil*. International Journal of Life Cycle Assessment (in prep.), Ecomed Publishers, Landsberg

Schmidt J H (2007b)[26], *Methodology for system delimitation in agricultural life cycle assessment*. International Journal of Life Cycle Assessment (in prep.), Ecomed Publishers, Landsberg

Schmidt J H (2007c)[27], *Development of applicable characterisation factors for land use in LCA*. Journal of Cleaner Production (in prep.), Elsevier

---

[25] Schmidt (2007a) is part of the Ph.D. thesis: 'Life assessment of rapeseed oil and palm oil' and it is published in the report 'Life assessment of rapeseed oil and palm oil. Ph.D. thesis, Part 2: Article collection'.

[26] Schmidt (2007b) is part of the Ph.D. thesis: 'Life assessment of rapeseed oil and palm oil' and it is published in the report 'Life assessment of rapeseed oil and palm oil. Ph.D. thesis, Part 2: Article collection'.

[27] Schmidt (2007c) is part of the Ph.D. thesis: 'Life assessment of rapeseed oil and palm oil' and it is published in the report 'Life assessment of rapeseed oil and palm oil. Ph.D. thesis, Part 2: Article collection'.

Schmidt J H and B Weidema (2007)[28], *Shift in the marginal supply of vegetable oil.* International Journal of Life Cycle Assessment (in prep.), Ecomed Publishers, Landsberg

Schnepf R D, Dohlman E and Bolling C (2001), *Agriculture in Brazil and Argentina: Developments and Prospects for Major Field Crops.* Agriculture and Trade Report, WRS-01-3, Market and Trade Economics Division, Economic Research Service, U.S. Department of Agriculture (USDA), Washington
http://www.ers.usda.gov/Publications/WRS013/ (Accessed January 2007)

Sharma M (2005), Personal communication with Researcher Dr. Mukesh Sharma, United Plantations Berhad, Research Department, Jendarata Estate, Teluk Intan, Malaysia

Shonfield P (2004), Personal communication with LCA Team Leader Peter Shonfield, Chemistry & Environmental Protection Department, Safety and Environmental Assurance Centre, Unilever

Singh G (1999), *The Malaysian Oil Palm Industry: Progress towards Zero Waste and Environment Excellence*. Bioresources Technology for Sustainable Agriculture, 1999, pp. 318-341. New Delhi

Singh G, D L Kow, K H Lee, K C Lim and S G Loong (1999), *Empty Fruit Bunches as Mulch.* In: Singh G, L K Huan, Leng T and D L Kow (1999), Oil Palm and the Environment – A Malaysian Perspective. Malaysian Oil Palm Growers Council, Kuala Lumpur

Singh G and T T San (2002), *United Plantation Berhad's Approach to Environment Quality Management in the Palm Oil Mill Through Optimal Utilisation of Biomass Residues. Submitted for PBEC 4th Environment Award, 2002. United Plantation Berhad, Teluk Intan, Malaysia*

Singh G (2006), Personal communication with Director of Research Dr. Gurmit Singh, United Plantations Berhad, Research Department, Jendarata Estate, Teluk Intan, Malaysia

Singh G and I NP Thorairaj (2006), *Data on Energy Use in the Oil Mill.* Data provided by research director Gurmit Singh and process engineer Ir. NP Thorairaj, United Plantations Research Department, Teluk Intan, Malaysia

Spielmann M, T Kägi, P Stadler and O Tietje (2004), *Life Cycle Inventories of Transport Services, Data v1.1 (2004).* ecoinvent report No. 14, Swiss Centre for Life Cycle Inventories, Dübendorf

Statistics Finland (2006), *Greenhouse Gas Emissions in Finland 1990-2004, National Inventory Report to the European Union.* Statistics Finland

Stehfest E and Bouwman L (2006), *N2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions*. Nutrient Cycling in Agroecosystems (2006) 74: 207 –228, Springer

Subranamiam V (2006a), Personal communication with research officer Vijaya Subramaniam, Engineering & Processing Division, Energy and Environment Unit, Malaysian Palm Oil Board (MPOB), Kajang

Subranamiam V (2006b), *Life Cycle Inventory for Palm Kernel Crushing*. Unpublished data by research officer Vijaya Subramaniam, Engineering & Processing Division, Energy and Environment Unit, Malaysian Palm Oil Board (MPOB), Kajang.

Subranamiam V, Ma A N, Choo Y M (2005), Life Cycle Inventory of the Production of CPO. Poster Presentation at PIPOC 2005, 25-29 September, Kuala Lumpur

Subranamiam V, Chow M C and Ma A N (2004), *Energy Database of the Oil Palm.* Palm Oil Engineering Bulletin, Volume EB70, Malaysian Palm Oil Board (MPOB), Kajang

Swart P H D and Diest A V (1987), *The rock-phosphate solubilizing capacity of Pueraria javanica as affected by soil pH, superphosphate priming effect and symbiotic N2 fixation*. Plant and Soil 100, pp 135-147 (1987), Martinus Nijhoff Publishers, Dordrecht, the Netherlands

Tian H, Melillo J M, Kicklighter D W, McGuire A D, Helfrich J, Moore B and Vörösmarty C J (2000), *Climatic and biotic controls on annual carbon storage in Amazonian ecosystems*. Global Ecology & Biogeography (2000) 9, 315–335, Blackwell Science

---

[28] Schmidt and Weidema (2007) is part of the Ph.D. thesis: 'Life assessment of rapeseed oil and palm oil' and it is published in the report 'Life assessment of rapeseed oil and palm oil. Ph.D. thesis, Part 2: Article collection'.

Tinker P B H and Smilde K W (1963), *Dry-matter Production and Nutrient Content of Plantation Oil Palms in Nigeria*. Plant and Soil XIX, no. 3, pp 350-363

Trebs I, Lara L L, Zeri L M, Moura M A, Gatti L V, Artaxo P, Slanina J, Andreae M O and Meixner F X (2004), *Dry and Wet Deposition of Atmospheric Inorganic Nitrogen in a Tropical Environment* (Rondônia, Brazil, 10.deg45.44S, 62.deg21.27W). American Geophysical Union, Fall Meeting 2004, abstract #B12A-04

UNFCCC (2006), *Methane recovery and utilisation project at United Plantations Berhad, Jendarata Palm Oil Mill, Malaysia*. Clean Development Mechanism Project Design Document Form (CDM-PDD), version 03 – in effect as of: 28 July 2006. UNFCCC

UNFCCC (2007), Beluran Biomass Project. Validated CDM project activity hosted by Malaysia. United Nations Framework Convention on Climate Change, UNFCCC's database of CDM projects (under validation and validated projects):
http://cdm.unfccc.int/Projects/Validation/index.html (Accessed May 2007)

UNFCCC (date of issue not given), *Tool to determine methane emissions avoided from dumping waste at a solid waste disposal site*. CDM Executive Board, Meeting report, Annex 14, United Nations Framework Convention on Climate Change, UNFCCC
http://cdm.unfccc.int/EB/026/eb26_repan14.pdf (Accessed May 2007)

Unilever (1990), LCI datasheets for palm oil, palm kernel oil and coconut oil (not published). The LCI data are collected by Unilever during 1990. Provided by Peter Shonfield 2004. LCA Team Leader, Chemistry & Environmental Protection Department, Safety and Environmental Assurance Centre, Unilever

United Plantations Berhad (2005), *Report on Stack Flue Gas Monitoring for Ulu Bernam Palm Oil Mill*. United Plantations Berhad, Teluk Intan, Malaysia

United Plantations Berhad (2006), *Annual Report 2005*. United Plantations Berhad, Teluk Intan, Malaysia

UPRD (2004), Environmental Impact Assessment of Oil Palm Cultivation & Processing in United Plantations Berhad. United Plantations Research Department, United Plantations Berhad, Teluk Intan, Malaysia

USDA (1997), *World Agricultural Production, Part Two*. Production Estimates and Crop Assessment Division, **Foreign Agricultural Service (FAS),** United States Department of Agriculture (USDA), Washington
http://www.fas.usda.gov/WAP/circular/1997/97-07/jul97wap2.html (Accessed January 2007)

USDA (2006), *Argentina's Soybean Complex Competitiveness*. Internation Trade Report, April 14 2006. Commodity & Marketing Programs. Foreign Agricultural Service, USDA, Washington
http://www.fas.usda.gov/oilseeds/highlights/06-04/ArgentinaCompetitiveness.pdf (Accessed January 2007)

Vinther F P and Hansen S (2004), *SimDen – en simpel model til kvantificering af N_2O-emission og denitrifikation* (English: SimDen – a simple model for quantification of N_2O-emission and denitrification). DJF rapport. Markbrug nr. 104. Danmarks Jordbrugsforskning, Ministeriet for Fødevarer, Landbrug og Økonomi, Tjele, Denmark

Wakker E (2004), *Greasy Palms - The social and ecological impacts of large-scale oil palm plantation development in Southeast Asia*. Friends of the Earth, United Kingdom

Weng C K (1999), *Biomass production in the Oil Palm Industry.* In: Singh G, L K Huan, Leng T and D L Kow (1999), Oil Palm and the Environment – A Malaysian Perspective. Malaysian Oil Palm Growers Council, Kuala Lumpur

Weidema, B (2003), *Market Information in life cycle assessment*, Environmental Project No. 863. Danish Environmental Protection Agency, Copenhagen

Weidema B and Wesnæs M (2006), *Marginal production routes and co-product allocation for alcohol etoxylate from palm oil and palm kernel oil*. 2.-0 LCA consultants, Copenhagen

Wenzel H, M Hauschild and L Alting (1997), *Environmental Assessment of Products – Volume 1: Methodology, tools and case studies in product development*. Chapman and Hall, London

Werner C, Zheng X, Tang J, Xie B, Liu C, Kiese R and Butterbach-Bahl K (2006), *N2O, CH4 and CO2 emissions from seasonal tropical rainforests and a rubber plantation in Southwest China*. Plant Soil (2006) 289, pp 335–353. Springer

Wetlands International (2007), *Factsheet on palmoil and tropical peatlands*. Wetland International, Wageningen, the Netherlands.

http://www.wetlands.org/publication.aspx?ID=40938c7b-d689-4b17-87dc-9f65def5bfaa (Accessed March 2007)

Wiggers L, M Thorsen and K H Nilsson (2005), *Jordpuljen – en joker i udvaskningsberegninger* (English: The soil pool – a joker in leaching calculations). Van dog Jord. 12. årgang/December 2005, pp 147-149. Nepper & Stagehøj, Copenhagen

Wood S M and Layzell D B (2003), *A Canadian Biomass Inventory: Feedstocks for a Bio-based Economy*. BIOCAP Canada Foundation, Queen's University, Kingston, Canada

WSDA (2006), *Fertilizer product database*. Available online. Washington State Department of Agriculture. Olympia, Washington State. http://agr.wa.gov/PestFert/Fertilizers/ProductDatabase.htm (Accessed March 2006)

Yacob S, M A Hassan, Y Shirai, M Wakisaka and S Subash (2006), *Baseline study of methane emission from anaerobic ponds of palm oil mill effluent treatment*. Science of the Total Environment 366 (2006), pp 187– 196. Elsevier

Yusof B and Weng C K (2004), *The Oil Palm and its Sustainability*. Journal of Palm Oil Research, Vol. 16, No. 1, June 2004, p 1-10. Malaysian Palm Oil Board, Kajang, Malaysia

Yusoff S (2006), *Renewable energy from palm oil – innovation on effective utilization of waste*. Journal of Cleaner Production 14 (2006), pp. 87-93. Elsevier

Yusoff S and S B Hansen (2007), *Feasibility Study of Performing an Life Cycle Assessment on Crude Palm Oil Production in Malaysia*. International Journal of Life Cycle Assessment 12 (1) 50-58 (2007), Ecomed Publishers, Landsberg

Zah R and Hischier R (2003), *Life Cycle Inventories of Detergents, Data v1.01 (2003)*. ecoinvent report No. 12, Swiss Centre for Life Cycle Inventories, Dübendorf

Østergaard H S (2000), *Typetal for nitratudvaskning* (English: General values for nitrate leaching). Arbejdsrapport fra Miljøstyrelsen Nr. 11 2000. Miljøstyrelsen, Copenhagen

Århus Kommunale Værker (2005), *Varmeplan Århus* (English: Heat plan Århus). Århus Kommunale Værker, Aarhus

Århus Kommune (2004), *Århus Kommune, Lokalplan nr. 685 – Erhvervsområde mellem Sydhavnsgade og Oliehavnsvej, Århus Havn* (English: Municipality of Aarhus, District plan no 685 – Industrial district between Sydhavnsgade and Oliehavnsvej, Habour of Aarhus). The municipality of Aarhus

Appendix 1: Data on fuels

Fuel	Density	Energy content	
Fuelolie, heavy	0.95 tonne/m^3	40.6 MJ/kg	38.6 MJ/litre
Diesel	0.87 tonne/m^3	41.9 MJ/kg	36.4 MJ/litre
Petrol	0.72 tonne/m^3	42.7 MJ/kg	30.8 MJ/litre
Methane	0.000717 kg/ m^3		

Table A1.1: Density and lower calorific values for different fuels (Andersen et al., 1981, p 218)
methane at 0.717 g/litre (Andersen et al. 1981, p 119)

Appendix 2: Rapeseed production in Europe in 2004

Major rapeseed producing countries in Europe	Rapeseed production in 2004 (1000 tonne)	Rapeseed production 2004 (winter + spring) (1000 tonne)	Spring rapeseed's share of total rapeseed 2004
Source	(FAOSTAT 2006)	(Eurostat 2006)	(Eurostat 2006)
Germany	5,277	5,277	0.8%
France	3,969	3,995	0.5%
Poland	1,633	1,633	5.3%
United Kingdom	1,609	-	-
Czech Republic	935	-	-
Denmark	468	468	0.8%
Hungary	287	-	-
Russian Fed	276	-	-
Slovakia	263	263	2.3%
Sweden	228	211	39.0%
Lithuania	205	205	68.0%
Ukraine	149	-	-
Belarus	143	-	-
Austria	121	121	0.5%
Latvia	104	104	59.4%
Other <100,000 tonne	432	-	-
Total	**16,096**	**12,275**	**3.6%**

Table A2.1: Production of rapeseed in major rapeseed producing countries in Europe. In cases with no data available the cell is marked with a '-'. When production data from FAOSTAT are compared with data from Eurostat, it appears that there is good consistency.

Major rapeseed producing countries in Europe	Yield , average 2002-2004 (tonne/ha)				Spring rapeseed in relation to winter rapeseed
	Rapeseed	Rapeseed	Winter rapeseed	Spring rapeseed	
Source	(FAOSTAT 2006)	(Eurostat 2006)			
Germany	3.32	3.32	3.35	1.97	-41%
France	3.28	3.29	3.29	2.72	-17%
Poland	2.35	2.35	2.43	1.69	-31%
United Kingdom	3.18	3.23	-	-	-
Czech Republic	2.47	2.47	-	-	-
Denmark	3.25	3.25	3.29	2.39	-28%
Hungary	1.96	1.98	-	-	-
Russian Fed	1.04	-	-	-	-
Slovakia	1.99	1.96	1.96	1.63	-17%
Sweden	2.43	2.59	3.07	2.09	-32%
Lithuania	1.86	1.86	2.18	1.73	-20%
Ukraine	1.07	-	-	-	
Belarus	0.90	-	-	-	
Austria	2.50	2.50	2.51	1.73	-31%
Latvia	1.71	1.71	2.03	1.54	-24%
Other <100,000 tonne	1.65	-	-	-	-
Total	**2.78**	**2.58**	**2.68**	**1.94**	**-27%**

Table A2.2: Yields (average of 2002-2004) of rapeseed (winter + spring), winter rapeseed and spring rapeseed in major rapeseed producing countries in Europe. In cases with no data available the cell is marked with a '-'.

Appendix 3: Soil types and adjustments to different sources

Several inventory data are related to different soil types. However, the data sources of these inventory data do not apply the same terminology for soil types. Therefore, this appendix adjusts the different terminologies to a common set, defined in **Table A3.1**.

The share of different soil types under Danish agriculture is shown in **Table A3.1**. The column to the right shows a rough classification of the soil types into sand and clay.

Adjustment of data from DJF (Danish Institute for Agricultural Science, 2005)				
DJF no.	**Soil type**	**Area, km^2**	**Share of agricultural soils**	**Sand/clay**
1	Coarse sandy soil	10,548	26%	Sand
2	Grinding sand	4,233	10%	Sand
3	Sandy soil with clay	11,523	28%	Clay
4	Clay soil with sand	9,817	24%	Clay
5	Clay soil	2,390	6%	Clay
6	Heavy clay soil	303	1%	Clay
7	Humus soil	2,090	5%	Sand
8	Calcareous soil	87	0%	Sand
9	City	1,704	-	-
Total		**42,694**	**100%**	**Sand (41%)/clay (59%)**

Table A3.1: Distribution of soil types in Denmark.

Soil types used in Plantedirektoratet (2005a) and conversion to soil types given in **Table A3.1** are shown in **Table A3.2**. Data from Plantedirektoratet (2005a) are used for determination of fertiliser application. Firstly, the data from Plantedirektoratet (2005a) are adjusted in order to avoid distinguishing between irrigated and non-irrigated soils. The assumption that 50% is irrigated is applied. This adjustment is shown in the third column. Secondly, the adjusted soil types from Plantedirektoratet (2005a) are converted to soil types matching the data given in **Table A3.1**. This is shown in the fourth column.

Adjustment of data from PDIR (Plantedirektoratet, 2005a)					
PDIR no.	**Types**	**Adjusted PDIR no.**	**Conversion og soil type: DJF no.**	**Share**	**Sand/clay**
1	Non-irrigated coarse sandy soil (JB 1+3)	Average of 1 and 3	1	26%	Sand
2	Non-irrigated grinding sand (JB 2+4 and 10-12)	Average of 1 and 3	2+7+8	16%	Sand
3	Irrigated sandy soil (JB 1-4)	-	-	-	-
4	Mixed sand and clay soil (JB 5-6)	4	3+4	52%	Clay
5	Clay soil (JB 7-9)	5	5+6	7%	Clay

Table A3.2: Adjustment of soil types in Plantedirektoratet (2005a) to fit into the types given in **Table A3.1**.

Soil types used in Vinther and Hansen (2004) and conversion to soil types given in **Table A3.1** are shown in **Table A3.3**. Data from Vinther and Hansen (2004) are used for determination of denitrification. Firstly, the data from Vinther and Hansen (2004) are adjusted in order to fit into the categories defined by **Table A3.1** – in some cases more than one soil in Vinther and Hansen (2004) fit into each type in **Table A3.1**. This adjustment is shown in the second column. Secondly, the adjusted soil types from Vinther and Hansen (2004) are converted to soil types matching the data given in **Table A3.1**. This is shown in the third column.

Adjust of data from SimDen (Vinther and Hansen 2004)				
SimDen no.	**Adjusted SimDen no.**	**Conversion of soil type: DJF no.**	**Share**	**Sand/clay**
JB1	Average of JB1 and JB3	1	26%	Sand
JB2	Average of JB2 and JB4	2+7+8	16%	Sand
JB3	-	-	-	-
JB4	-	3+4	52%	Clay
JB5-6	JB5-6	5+6	7%	Clay
JB7-8	JB7-8			

Table A3.3: Adjustment of soil types in Vinther and Hansen (2004) to fit into the types given in **Table A3.1**.

Appendix 4: Characterisation factors for land use in Brazil and Canada

Schmidt (2007c) provides characterisation factors covering Denmark/N-Europe and Malaysia/Indonesia only. Since this study also include cultivation in Brazil (the Cerrado savannah and the Amazon tropical forests) and Canada (prairie grassland), characterisation factors for these regions are developed in this appendix. The method for calculation of characterisation factors is described in detail in Schmidt (2007c).

Species richness: For Brazil, only the average species richness of a single-sized sample plots have been available. Therefore, S_{100} of these land use types has been calculated assuming a value for the species accumulation rate. Perelman et al. (2001) have calculated $z = 0.14$ for the pampas in Argentina. Thus, this value is applied to the Cerrado as well as to soybean fields in Brazil. The data and results of these land use types are shown in **Table A4.1**. The species richness of agriculture in Canada is assumed to be equal to that of N-Europe and the species richness of prairie grassland is assumed to be equal to imperata grassland in SE-Asia.

Land use type	S_{100}	Comments to calculation of S_{100} in this study…
Brazil		
1 Arable, cereals/annuals, soybean, intensive	16	one entry: 7.15 species on 0.4 m^2 (Gomez and Gurevitch 1998)
5 Nature, forest (Amazon forest)	98	Assumed value as in SE-Asia, obtained from Schmidt (2007c)
7 Nature, grassland (Cerrado savannah)	24	one entriy: 430 species on 90,000 km^2 (Perelman et al. 2001)
Canada		
1 Arable, cereals/annuals, intensive	10	Assumed value as in N-Europe, obtained from Schmidt (2007c)
7 Nature, grassland	12	Assumed value as in SE-Asia, obtained from Schmidt (2007c)

Table A4.1: Species richness of vascular plants in a standardised area of 100 m^2 for relevant land use types in Brazil and Canada.

Ecosystem vulnerability: For the Brazil Cerrado, z is assumed to be represented by $z = 0.14$ for the Argentine Pampas given in Perelman et al. (2001), and for Canada, z is assumed to be represented by the same value as in N-Europe, i.e. $z = 0.22$ (Schmidt 2007c). The factors for ecosystem vulnerability are calculated in **Table A4.2**.

	Brazil	Canada
High intensity land		
Arable	590,000	456,600
Permanent crop	76,000	64,550
Built-up, roads, barren land	1,046,440	4,397,610
Low-intensity land		
Permanent pasture	1,970,000	153,900
Forest and woodland	4,776,980	4,020,850
Total land area	**8,459,420**	**9,093,510**
LI	0.80	0.46
Z	0.14	0.22
Factor for ecosystem vulnerability: z/LI	**0.18**	**0.48**

Table A4.2: Land cover by land use types in km^2. The values are used for determining LI. LI and z are used for calculating the factor for ecosystem vulnerability. Data for all land use types except forest and woodland are from 2003 (FAOSTAT 2006). Data for forest and woodland are from 2005 (FAO 2006).

Characterisation factors: Table A4.3 summarise the determining factors for calculating the characterisation factors as well as the calculated characterisation factors. The renaturalisation times for natural grassland and forests are all based on 500 years for the nature types in mid-Europe (Schmidt 2007c) corrected for the latitude using factors obtained from Schmidt (2007c). Characterisation factors for occupation impacts are calculated for two different areas in Brazil, i.e. the Amazon forests and the Cerrado savannah. This is because the renaturalisation potential (species richness) differs in the two regions.

Land use type	**S_{100}**	**z/LI**	**$S_{100} \cdot$ z/LI**	**Renaturalisation time**	**Characterisation factors (wS100)**		
					Occ.	**Trans. from…**	**Trans. to…**
Brazil, Amazon region							
1 Arable, cereals/annuals, soy, intensive	16	0.18	3	1	15	1	-1
7 Nature, forest, Amazon*	98*	0.18	4	355	0*	3,131*	-3,131*
Brazil, Cerrado region							
1 Arable, cereals/annuals, soy, intensive	16	0.18	3	1	1	1	-1
7 Nature, grassland, Cerrado*	24*	0.18	4	430	0*	929*	-929*
Canada							
1 Arable, cereals/annuals, intensive	10	0.48	5	1	1	2	-2
5 Nature, grassland*	12*	0.48	6	500	0*	1,440*	-1,440*

Table A4.3: Characterisation factors given in units of weighted species richness on a standard area of 100 m^2, wS100. Reference states for natural relaxation in each region are marked with *.

Abbreviations

A.i.	Active ingredients in pesticides
Alang-alang	Grassland in Indonesia is often reffered to as alang-alang. Often covered by the grass species; imperata.
BL	Barley
BR	Brazil
CAN	Canada
CDM projects	Cleaner Development project. Project within the Kyoto framework aiming at reducing greenhouse gas emissions.
CPO	Crude palm oil
DK	Denmark
Dry climate	<1000 mm annual precipitation, same definition as in IPCC (2003)
EFB	Empty fruit bunches
FFA	Free fatty acid
FFB	Fresh fruit bunches
ha y	Hectare years
IN	Indonesia
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
Moist climate	1000-2000 mm annual precipitation, same definition as in IPCC (2003)
MPOB	Malaysian Palm Oil Board
MY	Malaysia
MY&IN	Malaysia and Indonesia
NBD	Neutralised, Bleached and Deodorised (i.e. the processes in refining of vegetable oil)
PKC	Palm kernel cake
PKO	Palm kernel oil
PO	Palm oil
PO+PKO	Total output of vegetable oils from palm oil industry, i.e. PO from FFB and PKO from kernels
POME	Palm oil mill effluent
RSO	Rapeseed oil
RSM	Rapeseed meal
RSPO	Round Table on Sustainable Palm Oil
SM	Soybean meal
SO	Soybean oil
Wet climate	>2000 mm annual precipitation, same definition as in IPCC (2003)