Calculation of GHG emissions caused by direct land use change and cultivation on peat soil for palm kernel oil based precursors of surfactants

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List of Acronyms

AGB	Above-ground biomass
BGB	Below-ground biomass
CML	Centre of Environmental Science at Leiden
CEFIC	European Chemical Industry Council
CPO	Crude palm oil
CPKO	Crude palm kernel oil
dLUC	Direct land use change
EFB	Empty fruit bunches
ERASM	Environmental Risk Assessment and Management
FAOSTAT	Food and Agriculture Organization of the United Nations
FFB	Fresh fruit bunches
GHG	Greenhouse Gas
GWP	Global Warming Potential
ILCD	International Cycle Data System
iLUC	Indirect land use change
IPCC	Intergovernmental Panel for Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LUC	Land Use Change
POME	Palm oil mill effluent
RSPO	Roundtable on Sustainable Palm Oil
SLE	Surfactant Life Cycle and Ecofootprinting

Executive Summary

This publication describes a practical approach to generate Life Cycle Inventory (LCI) data for the global, averaged production of crude palm kernel oil (CPKO) used as surfactant precursor. The key methodology development is the inclusion of land use change (LUC) impacts using geospatial techniques to identify types of land cover and land use along with soil type, in particular peat. The study has been an integral part of the ERASM Surfactant Life Cycle and Ecofootprinting Project (Schowanek et al. 2017).

The geographical coverage of this LCI study represents the cradle-to-gate production of 'world market' palm kernel oil. The two most important global producer countries of palm kernel oil, Indonesia and Malaysia with around 85% of global supply, are used as representative of the global average. This assessment includes greenhouse gas (GHG) emissions from cultivation including use of peat soil, processing in palm oil mill and direct land use change. The calculation of direct land use change (dLUC) emissions by identification of land cover (previous and current use) along with soil type was based on geospatial techniques which are believed to be unique for this application in a life cycle assessment context. The framework of the LCI results aligns with ISO standards 14044 and 14040.

The calculated global average cradle-to-gate GHG value for CPKO is 3.07 t CO_2e/ton, including carbon uptake during cultivation. Of this total, 52% is due to cultivation on peat soils and a further 28% is due to dLUC. The analysis of satellite image based information and literature sources (Hooijer 2010) show that the percentage of cultivation on peat soil is 16% in Malaysia and 22% in Indonesia. These satellite images also indicate that the conversion rate of cultivation area for Indonesia is 20% higher than for Malaysia.

The presented approach shows that the use of geospatial technology to assist in calculating GHG emissions caused by dLUC and peat soil oxidation for a crop at a regional or country scale is feasible. The dLUC- and peat-related emissions are a significant part of the carbon footprint for palm kernel oil based products. The outcomes can be used in LCA-based studies for oil kernel palm based products. The calculation approach has the potential to be applied for calculation of dLUC of agricultural products in general.

1. Introduction

The working group Environmental Risk Assessment and Management (ERASM)[1], together with the European Chemical Industry Council (CEFIC)[2], recently completed the "The ERASM Surfactant Life Cycle and Ecofoot-printing (SLE) project". The project was performed by thinkstep AG in partnership with 14 industrial companies and analysed the environmental profile, on a life cycle inventory basis, for petro- and oleo-based surfactants. Life cycle inventories (LCIs) have been generated for 15 surfactants and 17 surfactant precursors. Some of these precursors are based on crude and refined palm and palm kernel oil, as well as their respective methyl esters and fatty alcohols. These precursors are also used for a broad range of applications in several other industries. The detailed findings of the ERASM SLE project are published in Schowanek et al. 2017. The study builds on a similar project executed by CEFIC-Franklin (1994) and summarised by Stalmans et al. (1995). At the time of this previous study, research and methods about the quantification of GHG caused by land use change were missing and hence were a significant limitation. The new surfactants LCI data are intended to support the increasing use of life cycle assessment (LCA) in industry as well as in various policy initiatives. They represent industry-agreed, market average data for surfactants in Europe for

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[1] ERASM is a research partnership of the Detergents and Surfactants Industries in Europe which was created in 1991 as a response of the involved industries to the ongoing risk assessment activities in Europe. ERASM initiates and co-ordinates joint industry activities for improving and enlarging the basis for and the knowledge about the risk assessment of detergent-based surfactants in environmental compartments. More information under http://www.erasm.org/index.htm

[2] CEFIC is the Brussels-based organization representing national chemical federation and chemical companies of Europe. CEFIC represents about 40,000 companies in Europe which employ 2 million people and account for more than 30% of the world's chemical production. CEFIC is the recognized lobby organization which assists member federations and companies to defend their interests at the EU Commission, Council and Parliament

the reference year 2011. In contrast to the previous study, the ERASM SLE study considers and quantifies land use change effects on GHG emissions.

Oil palms are cultivated in tropical areas in South America, Africa and Asia. Oil palm is, on average, the most efficient oilseed crop in the world although regional yields per hectare can vary significantly. The highest agricultural yields per country are obtained in Malaysia which obtains around 20 t fresh fruit bunches (FFB) x ha^{-1} yr^{-1}. The world average for 2011-2013 was 15 t FFB x ha^{-1} yr^{-1} (FAOSTAT 2014). In 2013 Indonesia and Malaysia were responsible for 82% of the globally harvested amount of FFB (FAOSTAT 2014) and are thus the most important producer countries of palm oil and palm kernel oil.

Changing the cultivated crop on existing agricultural land or transferring non-agricultural land into agricultural land is defined as land use change (LUC). To quantify the environmental impact of LUC in terms of greenhouse gases, the change in soil carbon stock is used as indicator according to GHG Protocol. Generally, land use change can be addressed with two different approaches in life cycle assessment (LCA):

(1) Direct land use change (dLUC), that can be defined as change in human use or management of land within the boundaries of the product system being assessed,

(2) Indirect Land Use Change (iLUC), that refers to a “change in the use or management of land which is a consequence of direct land use change, but which occurs outside of the product system assessed” (ISO/TS 14067:2013).

iLUC is an element of consequential LCA modelling (ILCD handbook, p.173) and is not included within existing LCA or Carbon Footprint standards such as e.g. ISO/TS 14067:2013, WRI GHG Protocol, PAS 2050 or PEF Guidelines. Therefore, this publication provides a calculation approach considering dLUC to address global warming impacts of land conversion.

Global demand for food, biofuels and bio-based materials are major driver for deforestation in tropical areas. Expansion of oil palm cultivation contributes to deforestation in South East Asia, including Malaysia and Indonesia (Koh et al. 2010) and the affiliated environmental aspects such as emissions of greenhouse gases. Between 2000 and 2010, between 4.6 - 8.1% of global annual GHG emissions were estimated to be attributable to land use change and forestry (WRI 2014).

Cultivation on peat soil is another important source of GHG emissions. Peat soils are the predominant soil type in large areas of Southeast Asia with approximately 2.15 Mha in Malaysia and Indonesia (Miettinen et al. [1] 2012). Oil palm plantations can be found on both mineral soil and peat soil (Page et al. 2011; Hooijer et al. 2010; Miettinen et al. [1] 2012; Hergoualc'h et al. 2011). A regional land cover assessment of large-scale agriculture on peat soil on the Malaysia peninsular and on the islands of Sumatra and Borneo showed that the predominant use of these peat soils was for palm oil plantations (Miettinen et al. [1] 2012). Cultivation of oil palm on peat soil requires ongoing drainage of the area which causes peat shrinkage and biological oxidation with a resultant loss of carbon stock (Miettinen et al. [1] 2012) and additional greenhouse gas emissions.

Historically, different approaches have been used to calculate the environmental burdens, particular GHG emissions, due to dLUC. The objective of this publication is to present a LCA based modelling approach at a country level which includes land use data based on geospatial techniques along with emissions derived from cultivation on peat soil. The production of crude palm kernel oil, a renewable precursor for the surfactant industry, is used to exemplify the approach. Results and conclusions can be transferred to other oil palm based precursors such as refined oils, methyl esters and fatty alcohols. The dLUC GHG emissions plus the GHG emissions from cultivation on peat soils are presented as overall country averages for the two global major cultivation areas, Malaysia and Indonesia.

2. Methods

2.1. LCA for Crude Palm Kernel Oil

2.1.1. Product System & System Boundary

The production of crude palm kernel oil is discussed here as this is the primary oleo-chemical feedstock used in surfactant production. Attributional LCA models for palm kernel oil production were developed for Malaysia and Indonesia using the LCA software GaBi 6 and are based on the GaBi databases 2012. The system boundaries include the agricultural production system and the extraction and processing to crude palm kernel oil (Table 1). The production of crude palm oil (CPO) and crude palm kernel oil (CPKO) are necessarily coupled. The fresh fruit bunches contain the fruit (for palm oil) and the kernels (for palm kernel oil). This study focuses on CO_2 emissions induced by LUC and cultivation on peatland. Hence, the LCA description explains the most important choices and findings, but does not represent a full documentation of the underlying assessment.

Table 1: LCA System boundaries production of palm kernel oil.

Included	Excluded
✓ Oil palm plantation (see Annex A:)	× Palm oil nursery
✓ Direct land use change effects (as described in chapter 3 and 4)	× Equipment
✓ Processes (including material and energy inputs) of the palm oil mill	× Capital goods
✓ Processes (including material and energy inputs) of the palm kernel oil mill	
✓ Transport from the field to the palm oil mill	
✓ Transport from the palm oil mill to the palm kernel oil mill	

The **geographical coverage** of this study represents the cradle-to-gate production of crude palm kernel oil available on the world market. A mixture, based on the production share of 2010 (FAOSTAT) of Malaysian and Indonesian (47% and 53%) palm kernel oil has been used as global average.

GHG emissions of agricultural products are highly influenced by **yield**, which can vary due to age, location and management practices on plantations. A discussion of the different yields is available in the Annex A: Table 12. The Malaysian Statistical Yearbook (Statistics Yearbook Malaysia (2011)) has been used as the reference source for yields as it provides the most reliable value for a national average. A five years' (2007-2011) average has been used as a basis in order to avoid displaying a single, potentially extreme production year. The deviation for different time averages (e.g. 10, 15 or 20 years) is smaller than 2.6% (checked for Malaysia; data not shown). In this study an average yield of 18.9 t FFB x ha^{-1} yr^{-1} has been used for Malaysia. This value does not include the unproductive first years of cultivation. If the unproductive phase is included, the yield would decrease by 14% to 16.3 t FFB x ha^{-1} yr^{-1}.

Contrary to Malaysia, the availability of sources for yield information in Indonesia was not very satisfying, thus yield was calculated backwards from the palm oil extraction value based on information from the Indonesian Statistical Yearbook (Statistical Yearbook of Indonesia (2011)). For the years 2007-2011 the oil yield per hectare reported was on average 2.63 t CPO x ha^{-1} yr^{-1}. Based on the oil extraction efficiency, the average yield of palm oil plantations was calculated assuming the same processing efficiencies as in Malaysia being 5.1 t FFB/t CPO (average for 2006-2010, compare Table 13) which results in an average yield of 13.4 t FFB/ha/yr. This value is lower than the average value of 16.9 given by FAOSTAT for the years 2007 to 2011. An explanation for the discrepancy could be that the published values in FAOSTAT most likely do not consider immature plantations. Under that prerequisite the difference is explainable, as there is a strong growth of area for oil palm cultivation in Indonesia. The same difference can be seen for Malaysia where the FFB yield per hectare values reported in FAOSTAT are higher than the values provided by the Malaysian Palm Oil Board or the Malaysian Statistical Yearbook. Taking a conservative assumption, an average yield of 13.4 t FFB x ha^{-1} yr^{-1} for Indonesia is applied in this study.

Data collection for the LCI is based on different literature sources. The availability of secondary data for palm oil production is much higher for Malaysia than for Indonesia.

The most relevant literature sources for this study are Choo et al. (2011), Rettenmaier et al. (2007), Schmidt (2007), Subramaniam et al. [1] (2010) and Subramaniam et al. [2] (2010).

Input data for agricultural modelling and sources are provided in Table 2. The basis for the agricultural modeling is described in Liedke et al. (2014).

Field emissions related to fertilizer application, such as nitrous oxide, have been calculated based on the emission factors from the Intergovernmental Panel for Climate Change (IPCC 2006) considering the share of soil type, for example for the cultivation on peat land.

Table 2: Annual input parameters for agricultural modelling for oil palm cultivation in Malaysia and Indonesia.

Fertilizer	Malaysia	Indonesia*	Unit	Additional comment	Values calculated / estimated based on
N, total nitrogen applied and formed by applying:	71	50	kg/ha*yr		Choo et al. 2011
Ammonium sulphate	188	133	kg/ha*yr		Choo et al. 2011
Urea	8	5	kg/ha*yr		Choo et al. 2011
Ammonium nitrate	14	10	kg/ha*yr		Choo et al. 2011
Rock phosphate	136	96	kg/ha*yr	Values originally provided as P_2O_5	Choo et al. 2011
Potassium chloride (KCl)	304	216	kg/ha*yr	Value originally provided as K_2O	Choo et al. 2011
Magnesium oxide (MgO)	36	36	kg/ha*yr	Applied as $MgSO_4$	Schmidt 2007
Non-fertilizer N input					
Atmospheric N deposition	17.5	17.5	kg/ha*yr		Schmidt 2007
N from biomass left in field/plantation	5.2	5.2	kg/ha*yr	Pruned fronds remain on the plantation during harvesting	Schmidt 2007
N from biomass previous plantation	22.8	22.8	kg/ha*yr	Felled stems from cutting down former plantations	Schmidt 2007
N fixation	11.5	11.5	kg/ha*yr	with legumes during the first 4 years of the plantation	Schmidt 2007
Pesticides					
Herbicide (glyphosate, sulfonylurea, bipyridylium, dimethylamine salt)	11.7	8.3	kg a.i./ha*yr	0.62 kg a.i /t FFB	Choo et al. 2011
Insecticide (pyretroid, carbofuran)	1.1	0.8	kg a.i./ha*yr	0.06 kg a.i /t FFB	Choo et al. 2011
Other					
Diesel	2.4	2.4	L/t FFB		Choo et al. 2011, Chen 2008

In accordance with IPCC 2006 and Rettenmaier et al. (2007) it is assumed that a share of 50% of land use change from primary and logged-over forest took place with fire clearance. This assumption was considered in the LCA model (50% of the carbon stock is incinerated) and affects the calculation since not only CO_2 is released (which is the assumption for the share of biomass not burned), but also other greenhouse gases and other air emissions.

2.1.2. Allocation

The production of crude palm kernel oil is a multi-output process. Following the rules of ISO 14044 several allocations by mass have been applied in this study:

Palm oil mill: Allocation has been applied between the product crude palm oil and the co-product palm kernel. Additional co-products are not allocated as they are used internally and are modelled further: shells and fibres are used for energy production, EFB (empty fruit bunches) are returned to the field as mulch, and palm oil mill effluent (POME) is partly used for the biogas generation and partly treated in open ponds before being returned to the field.

Palm kernel oil mill: Allocation is applied between the product crude palm kernel oil and the co-product palm kernel cake.

Further information on LCA-related information for palm oil processing to crude palm kernel oil (routes, efficiencies, treatment of waste products, assumptions, transport) is provided in the Annex A: .

2.1.3. Life Cycle Impact Assessment

The impact assessment in this publication focuses on greenhouse gases (GHG). The global warming potential (GWP) summarises and characterises GHG emissions and their effect on global warming (contributing to anthropogenic climate change). This indicator is calculated according to IPCC (2007) and Guinée (2001). For the indicator GHG to air, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) contribute to more than 99.9% (CML 2001-Nov 2010) of dLUC impacts for both countries. The results are provided both as GWP excluding biogenic carbon and including biogenic carbon. The latter considers the carbon uptake of crops during cultivation and so results in lower values compared to the GWP excluding biogenic carbon.

3. Theoretical background for GHG-emissions calculation related to direct land use change and cultivation on peat soil

This study covers GHG-emissions from direct land use change as well as from the cultivation on peatland.

3.1. Direct land use change

The difference in carbon stock before and after the occurrence of land use change is the basis for the calculation of dLUC-related GHG emissions. Carbon stock describes the carbon bound in above-ground biomass (AGB) and below-ground biomass (BGB) (see Figure 1). Those changes in carbon stock, as well as GHG-emissions related to the preparation of peatland (fire clearance of peat soil) for oil palm plantations, are considered as dLUC related emissions in this study.

The emissions caused by the conversion of land to oil palm plantations depend on the carbon stock of the previous type of land. Soil organic matter is a generic term for all organic compounds in the soil that are not living roots or animals (Watson et al. 2000).

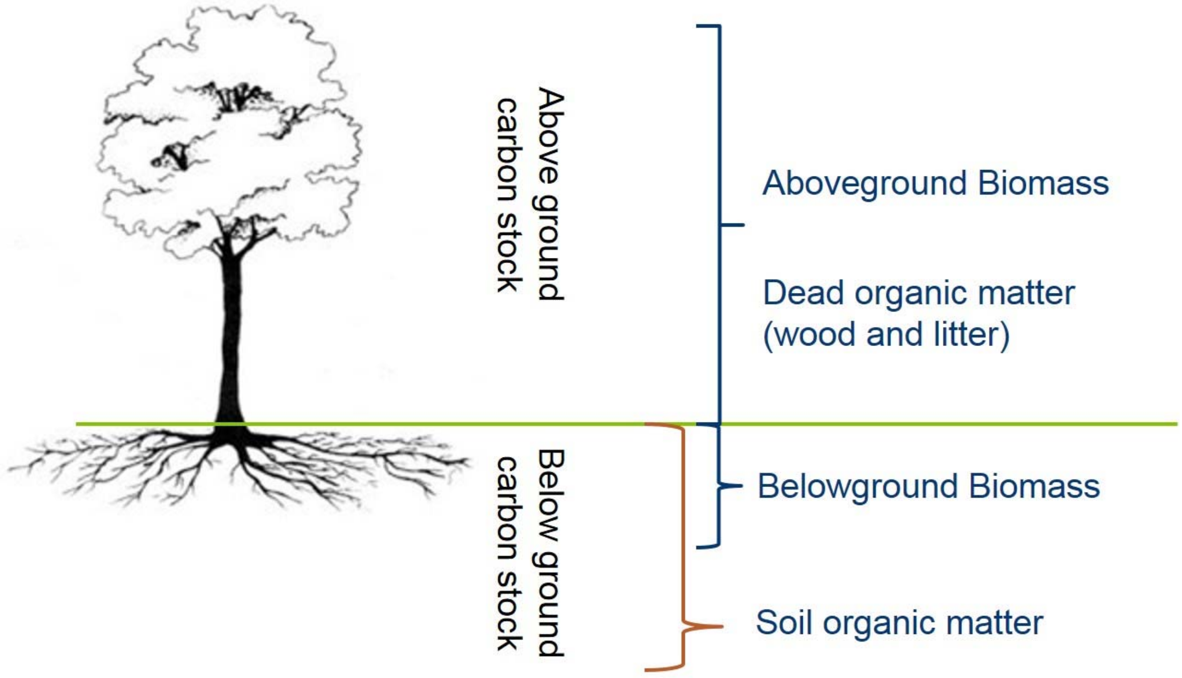


Figure 1: Above- and below-ground carbon stocks based on IPCC 2006

When assessing changes in carbon stocks, it is important to distinguish between the soil type on which the oil palms are cultivated. The carbon stock is different for different soil types. The two major soil types assessed for oil palm plantations are mineral and organic soils (the latter refers to peatland in this study). However there are large uncertainties associated with determining the changes of the soil organic carbon stocks when shifting from different land use categories to oil palm plantations on mineral soil. Rettenmaier et al. (2007), Agus et al. [1] (2013) and Agus et al. [2] (2013) state, "emissions from mineral soils, including those linked to changes in below ground biomass and soil organic matter are discussed, but their incorporation into emissions estimates is not recommended due to inadequate data and subsequent high levels of uncertainty". Due to the high uncertainty, soil organic carbon was not included in the calculations of land use change for mineral soils in this study. During the preparation of plantations on peat land, the above-ground biomass is incinerated (cleared) by human intervention. While clearing, a layer of peat soil is oxidized to a depth of 5-15 cm (depending on the previous land use type, e.g. grassland or forest) and the emissions are released suddenly during this process. Further details are described in chapter 4.3.

3.2. Cultivation on peat soil

Cultivation on peat requires the drainage of the peat soils, which leads to an oxidation of the stored carbon with resultant CO_2 emissions. These emissions are continuous throughout the lifetime of all plantations that operate on partially drained peat soils. The amount of emissions from cultivation on peat soil mainly depend on the depth of the drainage. The calculation of emissions from oil palm cultivation on peat soil is explained in detail in chapter 4.4.

3.3. Allocation to palm kernel oil

According to the Greenhouse Gas Protocol – Product Life Cycle Accounting and Reporting Standard, direct land-use change needs to be assessed if "the carbon stock change was caused by human intervention with the intent of creating a product" and "the carbon stock change occurred within the assessment period – 20 years or a single harvest period from the extraction (e.g. harvesting) of a biogenic product or product component, whichever timeframe is longer" (GHG Protocol 2011).

The GHG protocol standard requires companies to quantify and report the total inventory results in CO_2e per unit of analysis, which includes all emissions and removals included in the boundary from biogenic sources, non-biogenic sources and, separately, land-use change impacts.

ILCD (2010) specifies two different kinds of carbon stock changes. Firstly, inventory emissions that occur over a longer period than one year, and that eventually reach a new equilibrium (e.g. CO_2 emissions from loss of soil organic carbon due to biodegradation of e.g. humus). In this case the “entire inventory can be allocated to the total amount of the crop, independently of the specific year when the crop has been harvested; i.e. each kg [crop] has the same inventory”. Secondly, inventory items that occur in direct context of the transformation and not longer than one year afterwards (e.g. machine use during conversion and peak emissions e.g. from biomass burning). Furthermore, “the total amount of uses over which the "production" inventory of the land transformation is to be shared shall be 20 years” or in cases where the minimum use is longer, “one plantation/use cycle shall be used.”

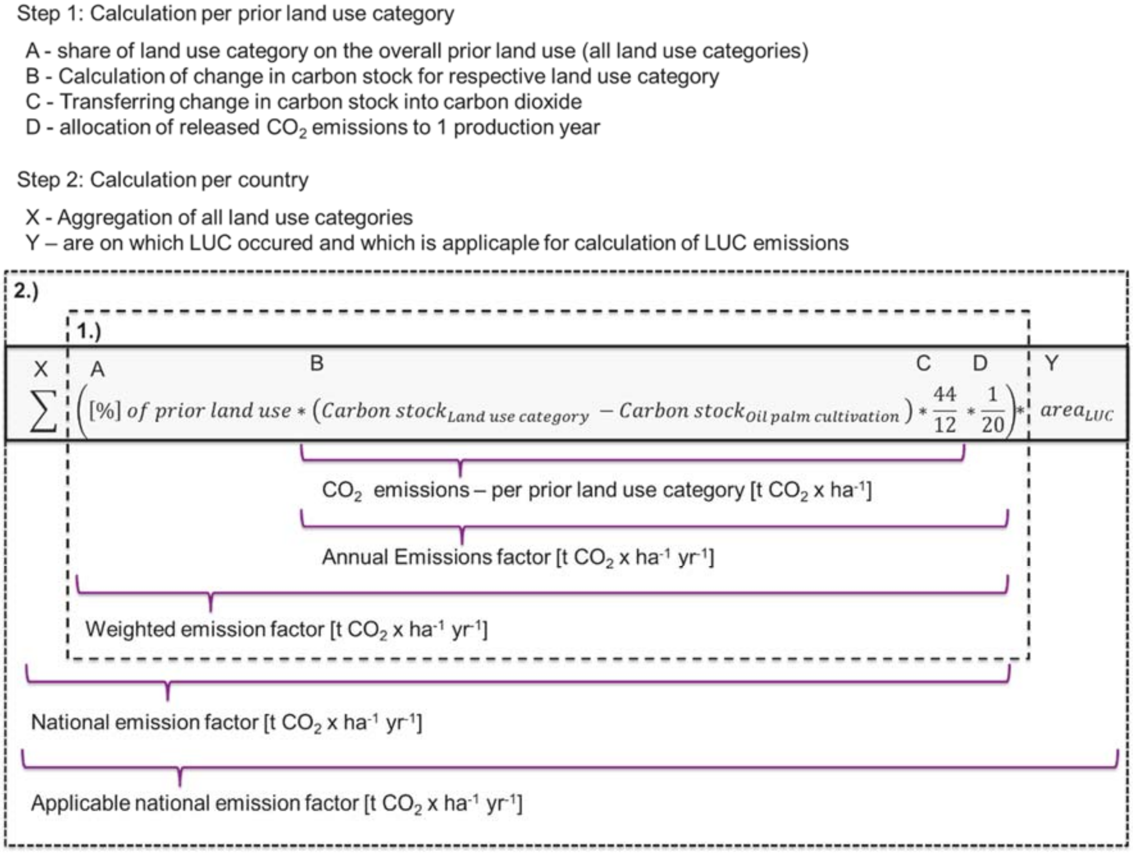
In this study, the assessment year was 2010: The entire transformation that happened in the last 20 years (1990 to 2010) is allocated to 1/20 of the averaged emissions to the inventory.

4. Practical calculation of greenhouse gas emissions

According to ILCD (2010), “CO_2 emissions shall be calculated using the most recent Intergovernmental Panel for Climate Change (IPCC) factors [carbon stock values] per default, unless more accurate, specific data are available.” Other LCA or carbon footprint standards, in which the calculation of direct land use change emissions are specified, also contain similar statements (e.g. ISO/TS 14067:2013, WRI GHG protocol, PEF guidelines 2012) – only PAS 2050: 2012-1 requires the use of predefined values from IPCC.

In this study, more specific carbon stock values, which are derived from a literature review, have been applied.

Figure 2 provides an overview of the approach used to calculate GHG-emissions from direct land use change. Each factor of the equation depicted in Figure 2 can be found in the chapter 4.1. and Table 4. This approach is used for the calculation of GHG emissions from above- and below-ground biomass as described in chapter 4.1 and 4.2. This approach contains two elements. Firstly, GHG emissions are calculated according to the prior used land type and secondly, these emissions are aggregated at a country level by summing the results for all prior land use types and considering the share of applicable LUC.



Step 1: Calculation per prior land use category

A - share of land use category on the overall prior land use (all land use categories)
B - Calculation of change in carbon stock for respective land use category
C - Transferring change in carbon stock into carbon dioxide
D - allocation of released CO_2 emissions to 1 production year

Step 2: Calculation per country

X - Aggregation of all land use categories
Y – are on which LUC occured and which is applicaple for calculation of LUC emissions

$$\sum \left([\%]\ of\ prior\ land\ use * \left(Carbon\ stock_{Land\ use\ category} - Carbon\ stock_{Oil\ palm\ cultivation} \right) * \frac{44}{12} * \frac{1}{20} \right) * area_{LUC}$$

Figure 2: Formula for calculation of dLUC emissions

When an area of land is converted into an oil palm plantation, the long-term net carbon stock change is the release of all carbon previously stored minus the carbon stored in the oil palm plantation. The change of carbon stock is reported in units of CO_2 emissions, obtained by multiplying the stoichiometric carbon value by 44 (the molecular mass of CO_2) and dividing by 12 (the atomic mass of carbon). This equals the “total CO_2 emissions” as given in Figure 2 and Table 4). The share of the respective prior type of land that was converted is taken into account as the carbon stock change is dependent on the prior land use type. CO_2 emissions occurring due to LUC are allocated to 20 years, which results in an “annual emission factor”. A “national emission factor” for Malaysia and Indonesia has then been calculated by summing up the annual emission factors of each land use type. This national emission factor is given in the second last line from the bottom of Table 4. Finally, the “national emission factors” have to be multiplied with the area applicable for LUC, the ratio of oil palm plantation area that has been established in the time period between 1990 and 2010. The result is an “applicable national emission factor” which represents the emissions which have to be taken into account in the LCI-model for palm oil and palm kernel oil. The presented emission factors are calculated for the cultivation of oil palms only.

4.1. Calculation of GHG emissions from above ground biomass

4.1.1. Determination of factor “Y” – share of area where dLUC has to be applied

The increase of the area under oil palm cultivation is displayed in Figure 3. The area applicable for the calculation of emissions from dLUC is the increase of the total area under cultivation in the observed time frame from 1990 to 2010. The values used in this study are 3.3 Mha for Malaysia and a value of 6.4 Mha for Indonesia (Agus et al 2013).

Based on the absolute values of land coverage the area on which LUC occurred between 1990 and 2010 can be calculated: for Malaysia 38.9% of the area currently under oil palm cultivation in 2010 was already under oil palm cultivation in 1990. Accordingly, 61.1% of the area under cultivation in 2010 was used differently before undergoing a land use change. The value applicable for LUC for Indonesia is 82.7%.

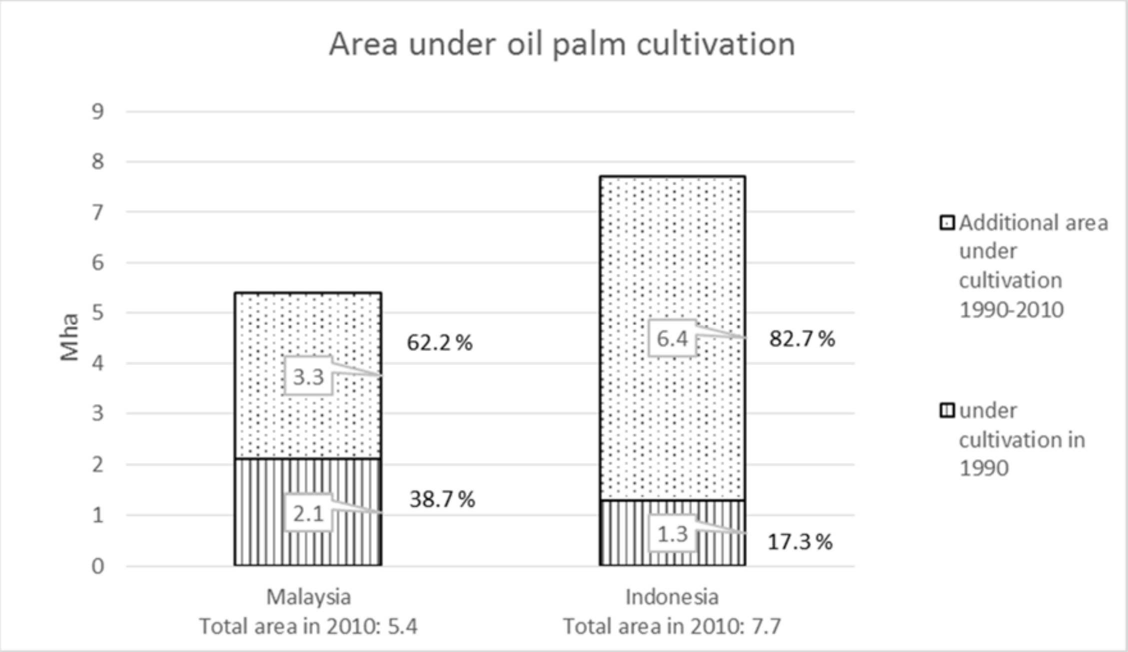


Figure 3: Development of area under oil palm cultivation between 1990 and 2010 in Malaysia and Indonesia. Additional area refers to new established plantations. The percentages of the area under cultivation in 1990 and the newly established area until 2010 are provided next to the bars.

4.1.2. Prior type of land before transformation to oil palm

The area that underwent land use change is analysed in detail: Agus et al. (2013) performed an analysis of historical land-use data. The extent and temporal expansion of oil palm plantations were based on on-screen visual interpretation of Landsat TM images for 1990, 2000, 2005 and 2010 for both countries. They determined the percentage of area converted to oil palm plantations within the last 20 years in discrete time steps of 5 or 10 years (1990-2000, 2000-2005, 2005-2010). The specific type of land converted to oil palm plantations within each discrete time step was analysed to determine previous land use.

In contrast to the recommendations of the GHG Protocol, but due to data availability, the period from 1990 to 2010 was used as period of consideration, although oil palm plantations are normally established for 25 years in average. For both countries, detailed information about the prior land use of all new plantations established in Malaysia and Indonesia in the time period of 1990-2010 are provided in Table 3 and are applied in Table 4.

Table 3: Prior land use of all new oil palm plantations (in 1000 ha) established between 1990 and 2010 (according to Agus et al. [1] 2013).

Aggregate Class	Malaysia		Indonesia	
	1000 ha	%	1000 ha	%
Undisturbed upland forest	0	0	13.0	0.2
Disturbed upland forest	1,239	38.1	1,207	18.9
Shrubs and grassland	15	0.5	1,268	19.9
Undisturbed swamp forest	0.5	0.0	384	6.0
Disturbed swamp forest	126	3.9	539	8.4
Open swamp	4.9	0.2	411	6.4
Agroforest and plantation	1,119	34.4	2,176	34.1
Agriculture	8.5	0.3	212	3.3
Bare land	731	22.5	74	1.2
Other	7.3	0.3	98	1.6
Total new plantations	**3,252**	**100**	**6,387**	**100**

4.1.3. Calculation of the applicable national emission factor

The carbon stock values of the above ground biomass of different land use types are based on a literature review of Gunarso et al. (2013). Gunarso et al. and Agus et al. provide a detailed analysis of land use types and corresponding carbon stocks based on satellite images. The carbon stock values of the land use types are provided in Table 4. The carbon stocks and, accordingly, the emissions released per land use type converted (see Table 4) are assumed to be the same in Indonesia and in Malaysia.

Oil palm plantations store 36 t C/ha on average in above ground biomass. A conversion of shrub land and agricultural land into palm oil plantations results in a net carbon uptake due to lower carbon stock values for both compared to oil palm plantations.

The applicable national emissions factor of the assessed period results in a value of 3.7 t CO_2e x ha^{-1} yr^{-1} for Malaysia and in a value of 4.1 t CO_2e x ha^{-1} yr^{-1} for Indonesia (see Table 4).

The assumed carbon stock for oil palm plantations are in average 36 t C/ha.

Table 4: Emission factors per ha and year for conversion of different land use types to oil palm plantations in Malaysia and Indonesia (Agus et al.[1] 2013; Agus et al. [2] 2013)

Land Use Type in Malaysia	Prior land use 1990-2010 [%] "A"	Carbon stock [t / ha] "B" (prior land use)	Total CO_2 emissions – change to oil palm Plantation [t CO_2/ha] "B*D"	Annual emissions factor (allocation to 20 years) – change to oil palm Plantation [t CO_2 x ha^{-1} yr^{-1}] "B*C*D"	Weighted emission factor [t CO_2 x ha^{-1} yr^{-1}] "A*B*C*D"
Undisturbed upland forest	0.0	189	561	28.1	0
Disturbed upland forest	38.1	104	249	12.5	4.8
Shrubs and grassland	0.5	30	-22	-1.1	-0.0
Undisturbed swamp forest	0.0	162	462	23.1	0
Disturbed swamp forest	3.9	84	176	8.8	0.3
Open swamp	0.2	28	-29	-1.5	-0.0
Agroforest and plantation	34.4	51**	55	2.8	0.9
Agriculture	0.3	11	-92	-4.6	-0.0
Bare land *	22.5	36	-****	-****	0
Other	0.2	37	4	0.2	0.0
National Malaysian emission factor					**6.0**
Applicable national Malaysian emission factor ***					**3.7**

Land Use Type in Indonesia	Prior land use 1990-2010 [%] "A"	Carbon stock [t/ha] "B" (prior land use)	Total CO_2 emissions – change to Palm Oil Plantation [t CO_2/ha] "B*D"	Annual emissions factor (allocation to 20 years) – change to Palm Oil Plantation [t CO_2 x ha^{-1} yr^{-1}] "B*C*D"	Weighted emission factor [t CO_2 x ha^{-1} yr^{-1}] "A*B*C*D"
Undisturbed upland forest	0.2	189	561	28.1	0.1
Disturbed upland forest	18.9	104	249	12.5	2.4
Shrubs and grassland	19.9	30	-22	-1.1	-0.2
Undisturbed swamp forest	6.0	162	462	23.1	1.4
Disturbed swamp forest	8.4	84	176	8.8	0.7
Open swamp	6.4	28	-29	-1.5	-0.1
Agroforest and plantation	34.1	51**	55	2.8	0.9
Agriculture	3.3	11	-92	-4.6	-0.2
Bare land *	1.2	36	-****	-****	0
Other*****	1.5	37	4	0.2	0.0
National Indonesia emission factor					**5.0**
Applicable national Indonesian emission factor ***					**4.1**

* Bare land is defined as area with little or no woody vegetation (i.e. also newly planted palm oil plantations, etc.). The type bare land refers to a carbon stock of 36 t C/ha due to the precautionary principle used in LCA to avoid underestimation of occurring GHG emissions.

** weighted average of carbon stock values for agro-forests (54 t C/ha), timber plantations (44 t C/ha) and rubber plantations (55 t C/ha)

*** This emission factor is used to account for the increase of land used for oil palm cultivation.
**** no data available

***** Other land use categories, which are not further specified.

4.2. Calculation of GHG emissions from below ground biomass

For the calculation of below-ground biomass, information from Rettenmaier et al. (2007) was used as this information was not provided by Agus et al. (2013). Rettenmaier et al. (2007) conclude a below-ground carbon stock of 13 t C/ha (average over 25 years) in below-ground biomass of oil palm plantations. In shrub- and grassland they assume carbon stocks of 4.7 t C/ha, in secondary forest an average of 25 t C/ha (8-51 t C/ha), and in natural forest an average of 54 t C/ha (26-96 t C/ha). Similar to the calculations described in section 4.1 the emissions from below-ground biomass were calculated (see Table 5).

Accordingly, for the dLUC of below-ground biomass an applicable national emission factor of 0.54 t CO_2 x ha^{-1} yr^{-1} for Malaysia and 0.52 t CO_2 x ha^{-1} yr^{-1} for Indonesia are used in the model for palm and palm kernel oil.

Table 5: Calculation of emissions from LUC from below-ground biomass per ha and year in Indonesia and Malaysia - adopted (matching and grouping of land use type information) from Agus et al. (2013)

Land Use Type	t C/ha for Oil Palm	Delta t C/ha (conversion to palm plantation)	Annual Emissions t CO_2 x ha^{-1} yr^{-1}	Share of prior land cover Malaysia	Weighted emission factor in Malaysia t CO_2e x ha^{-1} yr^{-1}	Share of prior land cover Indonesia	Weighted emission factor in Indonesia t CO_2e x ha^{-1} yr^{-1}
Undisturbed upland forest + undisturbed swamp forest	54*	41	7.5	0.00	0.00	0.06	0.47
Disturbed upland forest + disturbed swamp forest	25**	12	2.2	0.42	0.92	0.27	0.60
Shrubs- and grassland + open swamp + agriculture	5***	-8	-1.5	0.01	-0.01	0.30	-0.43
Agroforest and plantation + bare land + other	13****	0	0	0.57	0	0.37	0
National Emission factor [t CO_2 x ha^{-1} yr^{-1}]					**0.91**		**0.63**
Applicable National Emission factor [t CO_2 x ha^{-1} yr^{-1}]					**0.54**		**0.52**

* primary forest; ** secondary forest; *** shrubland; **** oil palm plantation

4.3. Calculation of GHG emissions from preparation of peat soil (peat fire emission)

Emissions from preparation of peat soils are emissions generated while establishing a new plantation. The top layer of soil is assumed to be incinerated by human intervention. As described in Agus et al. [2] (2013), the depth of the burnt peat can vary significantly. It is recommended in Agus et al. [2] (2013) to assume a burnt depth of 15 cm for “swamp forest” and 5 cm for “swamp shrub”. The average carbon density (carbon content) of both is 60 kg/m^3. (Agus et al. [2] 2013). Due to the assumed difference in burning depth, 1 ha of prepared area swamp forest or swamp shrub releases 330 or 110 t CO_2/ha, respectively. As it is common practice to incinerate peat soils, this practice is assumed to occur for 100% of all peat area converted into oil palm cultivation area. The calculations in Table 6 follow the same logic as described in Figure 2.

Table 6: Emission factors per ha and year from preparation (fire clearance) of peat soils for plantations in Malaysia and Indonesia

Land Use Type Malaysia	Prior land use (see Table 4) 1990-2010 [1000 ha]	Emission factor [t CO_2/ha]	Total CO_2 emissions – change to oil palm plantation [1000 t CO_2]	Annual emissions factor (allocation to 20 years) – change to oil palm plantation [1000 t CO_2/yr]
Undisturbed Swamp Forest	0.5	330	165	8.3
Disturbed Swamp Forest	126	330	41,580	2,079.0
Swamp Shrub & Grasslands	5	110	550	27.5
Sum			42,295	2,114.8
Total area under oil palm plantation in Malaysia in 2010 [1000 ha]				**5,225**
Applicable national Malaysian emission factor [t CO_2 x ha^{-1} yr^{-1}]				**0.4**
Land Use Type Indonesia	**Prior land use (see Table 4) 1990-2010** [1000 ha]	**Emission factor** [t CO_2/ha]	**Total CO_2 emissions – change to oil palm plantation** [1000 t CO_2]	**Annual emissions factor (allocation to 20 years) – change to oil palm plantation** [1000 t CO_2/yr]
Undisturbed Swamp Forest	384	330	126,720	6,336.0
Disturbed Swamp Forest	539	330	177,870	8,893.5
Swamp Shrub & Grasslands	411	110	45,210	2,260.5
Sum			349,800	17,490
Total area under oil palm plantation in Indonesia in 2010 [1000 ha]				**7,724**
Applicable national Indonesian emission factor [t CO_2 x ha^{-1} yr^{-1}]				**2.3**

4.4. Calculation of emissions from cultivation on peat soil

Cultivation on peat requires the drainage of the peat soils, which leads to an oxidation of the stored carbon with resultant CO_2 emissions. These emissions are continuous throughout the lifetime of all plantations that operate on partially drained peat soils. Other emissions besides CO_2 either do not have a high significance or cannot be quantified due to lack of reliable calculation models. CO_2 is the most important emission in terms of GHG emissions from soil. Methane from peat soil is “insignificant, both in terms of the mass of carbon lost and overall climatic impact” (Page et al. 2011). Methane emissions from the plantation drainage may be significant but have not yet been quantified sufficiently (Page et al. 2011; Agus et al. [1] 2013; Agus et al. [2] 2013; Melling and Henson 2011). Hence the long-term methane emissions from peat soils are not considered in this study. Nitrous oxide (N_2O)

fluxes in oil palm plantations are also considered uncertain and are excluded for this reason (Page et al. 2011).

The quantity of oxidation-initiated emissions depends on the water drainage level. The drainage depth in turn depends on the land use type (large croplands including plantations, mixed cropland including small scale agriculture and shrub land). The lowest ground-water levels can be found on plantations, where normally 100% of the area is drained (Hooijer et al. 2010). Typical oil palm plantations require a minimum drainage depth of 0.6 m to 0.85 m but many exceed 1 m (Page et al. 2011). In an earlier study, an average ground water level of 0.95 m (with a range between 0.8 and 1.1 m) was given (Hooijer et al. 2010). The same research group reported the common practice to keep average water tables below 0.7 m, but that they can be as deep as 1.2 m (Hooijer et al. 2008). The documentation of the "Roundtable on Sustainable Palm Oil" (RSPO) GHG calculator suggests a range of 0.6-0.8 m drainage depth as default values (www.rspo.org/file/RSPO_PalmGHG Beta version 1.pdf). In recent literature, 0.75 m is described as a drainage depth "representative for actual conditions in most relatively well managed plantations" (5 or more years after drainage) (Miettinen et al. [2] 2012). This value was confirmed by personal communication with experts. In this study a drainage depth of 0.75 m has been used.

Hooijer et al. developed a literature-based formula to calculate CO_2 emissions from drained peat soil. This approach covers two different causes for CO_2 emissions; CO_2 emissions in relation to drainage depth and CO_2 emissions from peat subsidence in drained peat soils (considering peat carbon content and bulk density measurements to separate the contribution of compaction from the total subsidence rate). (Hooijer et al. 2006; Hooijer et al. 2010).

The result is a linear relation:

$$CO_2 \text{ emissions } [t \times ha\text{-}1\ yr\text{-}1] = 91 * \text{drainage depth } [m]$$

Agus et al. [1] (2013) reviewed studies which assess emissions from plantations on peat soil. Based on their gained experience the authors recommend the usage of this relationship for calculating the emissions from cultivation on peat soil. Agus et al. [1] (2013) and Agus et al. [2] (2013) assume an average drainage depth of 0.6 m (which varies between 0.5 and 0.7 m), but corrected the formula by a factor 0.79 for the exclusion of root-related emissions.

The reasoning for including this factor is based on the results of Jauhiainen et al. (2012), Agus et al. [1] (2013) and Agus et al. [2] (2013):

$$CO_2 \text{ emissions } [t \times ha\text{-}1\ yr\text{-}1] = 91 * 0.79 * \text{drainage depth } [m]$$

Emissions are calculated based on the formula by Agus et al. [1] (2013) and Agus et al. [2] (2013). Applying a drainage depth of 0.75 m, this results in a general emission factor of 53.9 t CO_2 x ha^{-1} peat soil a^{-1} for cultivation of oil palm plantations on peat soil.

According to Miettinen et al [1] (2012) in 2010 the plantation area on peat soil in Malaysia was 843,000 ha. This area represents 16% of the entire cultivation area in 2010 (calculated for the entire area used based on Agus et al. [1] (2013) and Agus et al. [2] (2013)). In contrast, Agus et al. state that 570,000 ha of the area of palm oil plantations are grown on peat soil. This area represents approximately 11% of the entire area. The value of 843,000 ha (16% of the area) was applied in this study. With this value an applicable national emission factor of 8.6 t CO_2e/ha*year has been calculated for Malaysia.

RSPO (2012) communicated a percentage of 22% of the area used for oil palm plantations being cultivated on peat soil for Indonesia. Agus et al. [1] (2013) also report a number of 22%. Miettinen et al. (2011) provide an estimation of 1,311,000 ha of oil palm plantations on peat soil in Indonesia soil, but excluding the region of Papua. According to two sources (Agus et al. [1] (2013) and Agus et al. [2] (2013)) either 24% or 37% of peat soil area in Indonesia are located in Papua. Correcting the value of Miettinen et al. (2011) by these shares (assuming that the usage of peat soil for oil palm plantation in Papua is comparable to the usage in Borneo and Sumatra) an area of oil palm plantations on peat soil of 1,725,000 – 2,081,000 ha can be calculated for Indonesia in total. This leads to a share of 22-27% of the total area under cultivation in Indonesia in 2010. Due to the incompleteness of the source Miettinen et al. (2011), a share of 22% has been used for Indonesia, as provided by Agus et al.[1] (2013). With this value an applicable national emission factor of 11.9 t CO_2e/ha*year has been calculated for Indonesia.

Based on the estimated proportion of palm cultivated on peat soils in Malaysia, the contribution of peat oxidation to average Malaysian palm oil plantations is 8.6 t CO_2e/ha*year. For Indonesia, the value is 11.9 t CO_2e/ha*year.

IPCC 2013 suggests using a Tier 1 emission factor of 11 t CO_2e/ha*year for all drained oil palm plantations. Tier 1 emissions are described as follows: “At Tier 1, there is no transition period for CO_2 emissions from drained organic soils because the land immediately switches to the methods for the new land use type. High carbon loss from drained organic soils can occur after natural vegetation is converted to another land use, e.g. after converting tropical Forest Land to palm plantations, or converting Grassland to Cropland, and in particular, immediately after initial drainage of organic soils (Stephens et al.,1984; Wösten et al.,1997; Hooijer et al.,2012). These CO_2-C on-site emissions in the transition phase are not captured by the Tier 1 default emission factors shown in Table 2.1, which were derived from data representing long-term land uses present for decades in the boreal and temperate climate zones, and land uses drained for more than six years in the tropical climate zone. A transitional phase is not captured by Tier 1 methodology due to lack of scientific data for deriving default emission factors. After initial drainage of organic soils and if a transitional phase occurs, this should be addressed using higher tier methods.”

Further IPCC 2013 recommends using a tier 2 or tier 3 approach if more detailed information about peatland management i.e. drainage depth is available. Following this recommendation, the authors of this study used a more detailed approach as described above.

5. Results

The applicable national emission factors for Malaysia and Indonesia for oil palm cultivation as calculated by applying the approach described above are shown in Table 7. Indonesia has a slightly higher emission profile per hectare for aboveground biomass than Malaysia. As the share of cultivation on peat soil is higher in Indonesia, the Indonesian weighted national emission factors for preparation of peat soil for plantation and cultivation on peat soil are much higher.

Table 7: Overview of all applicable national emission factors for Malaysia and Indonesia for oil palm cultivation in t CO_2 per ha per year

Emission category	Emission source	Applicable national emission factor for dLUC from [t CO_2 x ha^{-1} yr^{-1}]	
		Oil palm cultivation in Malaysia	Oil palm cultivation in Indonesia
dLUC	From above-ground biomass	3.7	4.1
	From below-ground biomass	0.5	0.5
	From preparation of peat soil	0.4	2.3
Cultivation on peat soil	From cultivation on peat	8.6	11.9
Sum		13.2	18.8
Global share for CPKO production		47%	53%

These applicable national emission factors are then further used to calculate global warming potential (GWP) results for CPKO in accordance with the LCA model described above (Table 12).

The detailed stage-by-stage GWP results for Malaysian and Indonesian CPKO production are given in Table 8 and Table 9. Different emission flows are quantified and shown for the product life cycle phase in which they occur. Fossil CO_2 emissions refer to carbon released from fossil fuels or that occur due to land use change and peat oxidation. Hence, for better visibility, the overall fossil CO_2 flow has been separated into CO_2 (fossil), CO_2 (land use change) and CO_2 (peat oxidation). The second last column shows the global warming potential of all listed flows (characterisation factors according to CML 2001-Nov 2010).

Table 8: LCI results for Malaysia (in kg emission/t CPKO) for different product life cycle phases.

Greenhouse gas	Above ground biomass LUC	Below ground biomass LUC	Peat Preparation	Cultivation on Peat soil	Cultivation	Processing	Sum	Weighted sum to be used in global average (47% Malaysian CPKO)
CO_2 (fossil)	0	0	0	0	172	113	285	134.0
CO_2 (fossil - land use change)	758	114	85	0	0	0	957	449.8
CO_2 (fossil - peat oxidation)	0	0	0	1820	0	0	1820	855.4
Nitrous oxide (N_2O)	0	0	0	0.44	0.23	0	0.67	0.3
Methane (CH_4)	2.1	0	0	0	1.7	30.1	34	16.0
GWP (CML 2001-Nov 2010) excl. biogenic CO_2 [kg CO_2e]	**812**	**114**	**85**	**1952**	**281**	**867**	**4111**	**1932.2**
GWP (CML 2001-Nov 2010) incl. biogenic CO_2 [kg CO_2e]	**624**	**114**	**85**	**1952**	**-3330**	**2003**	**1448**	**680.6**

Summarising the last two lines of Table 8 and Table 9, the global average cradle-to-gate GHG results in 5.73 t CO_2e/t CPKO (GWP excl. biogenic carbon), respectively 3.07 t CO_2e/t CPKO (GWP incl. biogenic carbon).

Emissions from above-ground biomass and on-going emissions from cultivation peat soil are the largest contributors to the results. Likewise, these are then reflected in their significant contribution to the CPKO results. Overall, emissions per tonne CPKO are higher in Indonesia than in Malaysia due to the higher level of plantings on peat soils and the lower yields.

Table 9: LCI results for Indonesia (in kg/t CPKO) for different product life cycle phases.

Greenhouse gas	Above ground biomass LUC	Below ground biomass LUC	Peat Preparation	Cultivation on Peat soil	Cultivation	Processing	Sum	Weighted sum to be used in global average (53% Indonesian CPKO)
CO_2 (fossil)	0	0	0	0	191	134	325	172.3
CO_2 (fossil - land use change)	1185	155	676	0	0	0	2016	1068.5
CO_2 (fossil - peat oxidation)	0	0	0	3552	0	0	3552	1882.6
Nitrous oxide (N_2O)	0	0	0	1.08	0.22	0.01	1	0.5
Methane (CH_4)	3.3	0	0	0	2.2	30.1	36	19.1
GWP (CML 2001-Nov 2010) excl. biogenic CO_2 [kg CO_2e]	**1269**	**155**	**676**	**3875**	**311**	**888**	**7174**	**3802.2**
GWP (CML 2001-Nov 2010) incl. biogenic CO_2 [kg CO_2e]	**1010**	**155**	**676**	**3875**	**-3301**	2024	**4439**	**2352.7**

The third most significant contributor to the GHG footprint for CPKO is the processing step. In particular, this is due to the treatment of palm oil mill effluent (POME) which releases methane during its treatment and disposal.

Figure 4 shows the GWP results as displayed in Table 8 and Table 9. Emissions from LUC (AGB, BGB and preparation of peat soil) sum up to 28% of the total GWP whereas 52% are caused by permanent CO_2 emission of drained peat soil for the global average on crude palm kernel oil. Even though the area planted on peat is relatively small it has a disproportionately high contribution to the overall carbon footprint. The data in Figure 4 are based on a drainage depth for peat soils of 0.75 m.

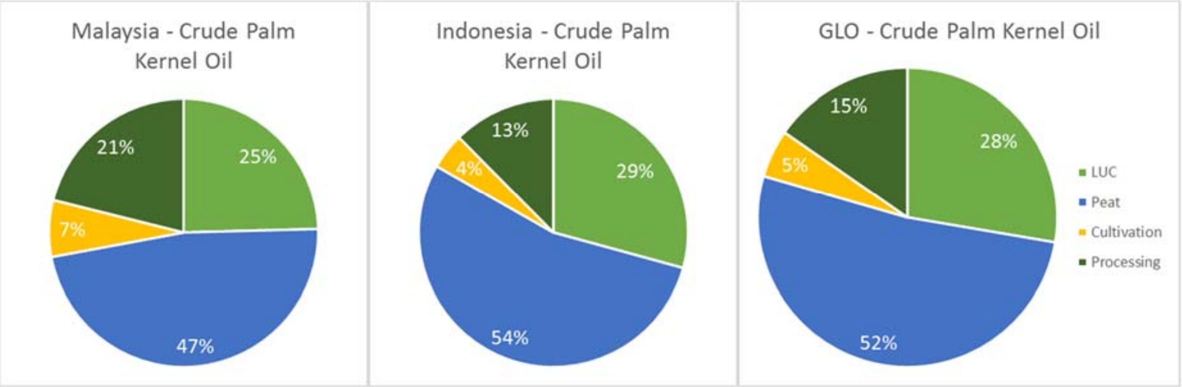


Figure 4: Share of different life cycle phases of crude palm kernel oil (CPKO) to the GWP (CML2001 - Nov. 2010, Global Warming Potential, excl. biogenic carbon (GWP 100 years)) for Malaysia, Indonesia and global average (as described above).

Sensitivity analysis: Varying the drainage depth by 20% from 0.6 m to 0.9 m has a direct influence on the GWP as shown in Table 10 and Figure 5.

Table 10: Sensitivity analysis on drainage depth (+/- 20%) due to potential differences in cultivation

GWP excl. biogenic carbon (t CO_2 eq./t CPKO	LUC	Peat (90 cm drainage depth)	Peat (60 cm drainage depth)	Cultivation	Processing
Malaysia	1.01	2.34	1.56	0.28	0.87
Indonesia	2.10	4.65	3.10	0.31	0.89
Global average (47% Malaysia + 53% Indonesia)	**1.59**	**3.57**	**2.38**	**0.30**	**0.88**

This sensitivity shows that drainage depth has a significant effect on GHG gases from cultivation on peat soil.

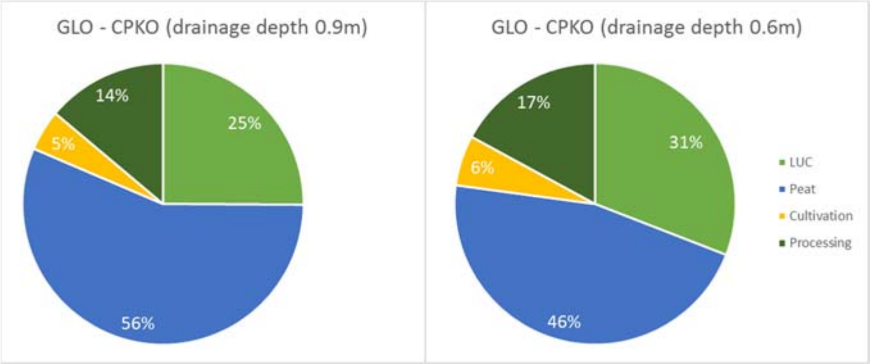


Figure 5: Share of different life cycle phases of crude palm kernel oil (CPKO) to the GWP (CML2001 - Nov. 2010, Global Warming Potential, excl. biogenic carbon (GWP 100 years)) for the global average. Two different drainage depths of cultivation on peat soil are displayed.

The results shown in Table 8and Table 9 are used in the LCI model for CPKO as described in Schowanek et al. 2017. Due to the influence on GHG emissions caused by dLUC and cultivation on peat soil the presented approach was a crucial part of the ERASM Surfactant Life Cycle and Ecofootprinting Project.

6. Discussion

This study focusses on two countries: Malaysia and Indonesia as the major producing countries for CPKO with 85% of world CPKO supply. The development of LCI data sets for CPKO are based on average agricultural production data in both countries with additional dLUC impacts calculated based on satellite imaging techniques obtained from the stated sources in section 4.1.

6.1. Data sources and modelling assumptions for calculation of dLUC

To calculate dLUC emissions information on the area under investigation the “additional area under cultivation between 1990-2010” (or total area converted) and the “carbon stock” assumed for each respective land use type are needed. FAOSTAT reports an area under cultivation for Malaysia in 2010 of 4.1 Mha (of which 2.4 Mha were added as new plantations since 1990, when 1.8 Mha were under oil palm cultivation). The last official data for both countries available at FAOSTAT are from 1998 with the subsequent years flagged as “unofficial data”. Malaysian Statistical Yearbook 2011, which most likely can be seen as official source, reports a value of 4.9 Mha under cultivation (including smallholders) for 2010.

As described above, for Malaysia an increase in area, from 2.1 Mha in 1990 to 5.4 Mha in 2010 (3.3 Mha) was used as basis for calculation. Similarly, for Indonesia FAOSTAT reports an area under cultivation of 5.8 Mha in 2010 (of which 5.1 Mha were newly added plantations since 1990, when 0.7 Mha were under oil palm cultivation). As previously described the area under cultivation in Indonesia increased from 1.3 Mha in 1990 to 7.7 Mha in 2010 (6.4 Mha). The values for cultivation of oil palms applied in this study are higher than statistical data report. The discrepancies in these values highlights the uncertainty in the statistical data sources. The use of specific data such as satellite images are to be preferred over the use of statistical data.

The land use types applied for calculation of dLUC emissions is also essential. In Malaysia, conversion from disturbed upland forest for palm oil production contributes around 80% to the absolute emissions of the national emission factors for oil palm cultivation. For Indonesia, undisturbed upland forest contributes around 50% to the absolute emissions of the national emission factors. The highest greenhouse gas emissions per converted land use type occur for changes from undisturbed upland forest area to oil palm plantations due to the highest change in carbon stock.

6.2. Emissions from cultivation on peat soil

As can be seen from the results, inclusion of emissions from peat oxidation is highly important for any Carbon Footprint or LCA study for crops cultivated on peat soil and is highly recommended to be considered in all forthcoming studies. Unless more specific information on drainage depth is available, the values calculated in this study could be used for oil palm plantations.

For the calculation method applied, the drainage depth and the share of cultivation on peat soil are the main determining factors of product-related GHG emissions from peat soil on national scales. The drainage depth influences the GHG emissions according to a linear relationship; the deeper the drainage depth, the higher the emissions. From an environmental perspective, a lower drainage depth is beneficial over deeper drainage depths. As shown in a sensitivity analysis, this factor is the single most crucial factor for the overall results.

The total area of peat soils, as well as the share of the total area for oil palm cultivation is much larger in Indonesia than in Malaysia. The accuracy of the results could be improved if better data on share of area were available.

6.3. Comparison of dLUC results

The use of purely statistical data for land conversion from FAOSTAT and the Global Forest Resource Assessment of the FAO and using default carbon stock values from IPCC results in greenhouse gas emissions that are significantly different from the results obtained in this study (see Table 11). The comparison was calculated using the “Direct Land Use Change Assessment Tool” (Blonk 2013). The approach presented here aims to close these data gaps and prove its fundamental importance for dLUC calculation in LCA. The absolute value of the emission factors from peat soil underline their importance.

Calculated dLUC emissions can vary: With the calculation approach presented in this article, significantly reduced emission factors are obtained in comparison to generic data (see Table 11). Higher quality data sources based on detailed satellite imaging approaches and a detailed understanding of land type prior to conversion and the underlying soil type provide a more accurate and realistic picture. Overall, if values from dLUC and emissions from peat soil are summed up, they exceed other published results for crude palm kernel oil.

Table 11: Comparison of dLUC results

Crop	Location	Emission in t CO_{2e} per hectare and year		
		This study (dLUC without emissions from peat soil)	This study (dLUC incl. emissions from peat soil)	Generic data dLUC (FAO Forest/ IPCC/ FAOSTAT) *
Oil palm cultivation	Malaysia	4.8	13.4	5.3*
	Indonesia	6.9	19.8	11.4*

*The results displayed show the weighted average GHG results for the tool setting "country known" and "land use unkown". Recurring emissions from peat soil are not considered: "It should be noted … that the calculation in the "Direct Land Use Change Assessment Tool" does not take (emissions from organic) peat soils into account, which is a limitation related to data availability."

All land use change and associated emissions are directly related to the crop yield. This parameter is of importance in agricultural LCA studies and is particularly relevant if cultivation on peat soil and emissions from dLUC are taken into account. This is also true for all other factors which influence the input of precursor products from the field, such as processing efficiencies and allocations. The assumption of yield in this study is therefore crucial.

Other important parameters are the prior land use, its stored carbon stock and the carbon stock of oil palm plantations influencing the above-ground emissions. Carlson et. al (2012) describes above-ground dLUC effects for Kalimantan solely, which makes 40% of entire Indonesia analysed in the current study. Taking into account the findings of Carlson et. al, the above-ground results for Kalimantan could be approximately three times higher compared to this study. Applying the findings of Carlson et al could lead to above-ground emissions of 11.1 t CO_2 x ha-1 yr-1 compared to 4.1 t CO_2 x ha-1 yr-1 as found by this study. In this study above-ground emissions contribute 22% of the total dLUC and peat soil emissions.

6.4. Discussion of LCA results

The largest share of CO_2 emissions result from cultivation on peat soil. The second biggest contributor to CO_2 emissions arise from direct land use change. Cultivation and processing contribute most of the methane emissions. Processing emits around 82-84% of the methane, mainly from POME treatment. Other methane emissions occur on the plantation. Nitrous oxide emissions occur predominantly during cultivation. Cultivation on organic soil leads to higher nitrous oxide emissions than cultivation on mineral soils, as the emission factor of nitrous oxide is higher for organic than for mineral soils. Although the share of plantations cultivated on peat soil is smaller than those cultivated on mineral soils, the overall emissions of nitrous oxides from peat soil cultivation exceed that from mineral soils by a factor of 3.4.

During POME treatment, methane capture and the subsequent use of occurring biogas instead of releasing these emissions to air reduces overall methane emissions of the processing life cycle stage by around 15%. Other emissions are reduced as well as the energy requirements from the electricity grid are slightly reduced by increasing the amount of methane captured and used for electricity production.

7. Conclusions

This study provides a practical example of the development of global LCI data sets for CPKO based on global market share and average production at a scale level (country). It includes dLUC impacts based on satellite imaging techniques to identify land cover, previous and current land use, and soil type – peat in particular. With this new approach a more detailed quantification of the GWP impacts of oil palm cultivation can be obtained and used in future LCA based studies. A similar methodology was applied for other oleo-chemical precursors covered in the ERASM SLE study.

Further, the study clearly finds that emissions from land use change are of major relevance for global warming potential for all products based on renewable raw materials like crude palm kernel oil. Cultivation on peat soil contributes significantly to the greenhouse gas emissions of oil palm cultivation. Impacts from mineral soils were not included in the assessment due to a lack of consensus about how to account for soil organic carbon in these soils; this is a limitation of the study and is identified as an area for further research.

Drainage depth on the existing oil palm plantations on peat soil is the most direct management factor applicable on existing plantation and should also be kept on the lowest drainage depth possible to reduce GHG emissions. RSPO provides a guidance document on how to manage existing plantations on peat soil. For existing plantations, increasing yields of FFB per hectare will result in fewer GHG emissions per tonne oil produced.

In addition to information about drainage depth, studies like the present one could be improved by reliable and consistent data for cultivation (e.g. cultivation area, fertilizer and water use, practises on land clearance, yields etc.) and averaged information for processing in oil mills.

8. Access to the data

The LCI data from the SLE project can be obtained free of charge in one of the following data formats: EcoSpold, ILCD and GaBi. They can be downloaded from the following locations: www.erasm.org. It is also available to GaBi software users. In addition, Environmental Fact Sheets per surfactant, which contain more specific information on the process, PED (Primary Energy Demand) and GWP (Global Warming Potential), will be made available via www.erasm.org.

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10. References

Agus F, Gunarso P, Sahardjo BH, Harris N, van Noordwijk M, Killeen TJ [1] (2013) Historical CO_2 emissions from land use and land cover change from the oil palm industry in Indonesia, Malaysia and Papua New Guinea. RSPO http://www.tropenbos.org/publications/historical+co2+emissions+from+land+use+and+land+use+change+from+the+oil+palm+industry+in+indonesia,+malaysia+and+papua+new+guinea

Agus F, Henson IE, Sahardjo BH, Harris N, van Noordwijk M, Killeen TJ [2] (2013) Review of emission factors for assessment of CO_2 emission factors for assessment of CO_2 emission from land use change to oil palm in South-east Asia. RSPO http://worldagroforestry.org/sea/Publications/files/report/RP0305-15.pdf

Direct Land Use Change Assessment Tool, Version 2013.1, Blonk Consultants, Gouda, 2013.

Carlson KM, Curran LM, Asner GP, McDonald Pittman A, Trigg SN, Adeney JM (2012) Carbon emissions from forest conversion by Kalimantan oil palm plantations. Nature Climate Change 3, 283–287

CEFIC-Franklin (1994). Resource and environmental profile analyis of petrochemical and oleochemical surfactants produced in Europe. Phase II Final Report (and related reports), Franklin Associates, LTD.

Chen SS (2008) The LCA approach to illustrate palm oil’s sustainability advantage. International Palm Oil Sustainability Conference

Choo YM, Muhamad H, Zulkfili Hashim Z, Subramaniam V, Puah CW, Tan YA (2011) Determination of GHG contributions by subsystems in the oil palm supply chain using the LCA approach. Int J Life Cycle Assess 16:669–681

FAO (2010) Global Forest Resources Assessment http://www.fao.org/forestry/fra/fra2010/en/ accessed 2014

FAOSTAT (2012) http://faostat.fao.org/. Accessed 2012

FAOSTAT (2013) http://faostat.fao.org/. Accessed 2013

FAOSTAT (2014) http://faostat.fao.org/. Accessed 2014

GEA Westfalia Separator group (2013) Raffination von Palmöl. http://www.westfaliaseparator.com/de/anwen dungen/nachwachsenderohstoffe/palmoelverarbeitung.html. Accessed 2014

Germer J, Sauerborn J (2008) Estimation of the impact of oil palm plantation establishment on greenhouse gas balance. Environmental Development Sustainability 10:697-716

GHG Protocol, WRI and WBCSD (2011) The Greenhouse Gas Protocol: Product Life Cycle Accounting and Reporting Standard. World Resources Institute and World Business Council for Sustainable Development, www.ghgprotocol.org. Accessed 2014

Guinée J (2001) Editorial: Announcing a new LCA guide. Handbook on Life Cycle Assessment - Operational guide to the ISO standards. http://rd.springer.com/content/pdf/10.1007%2FBF02978784.pdf

Gunarso P, Hartoyo ME, Agus F, Killeen TJ (2013) Oil palm and land use change in Indonesia, Malaysia and Papua New Guinea. RSPO

Hansen SB, Olsen SI, Ujang Z (2011) Greenhouse gas reductions through enhanced use of residues in the life cycle of Malaysian Palm Oil derived biodiesel. Bioresource technology 104:358-366

Hassan MNA, Jaramillo P, Griffin WM (2011) Life Cycle GHG emissions from Malaysian oil palm bioenergy development: The impact on transportation sector’s energy security. Energy Policy 39:2615–2625

Hergoualc'h K, Verchot LV (2011) Stocks and fluxes of carbon associated with land use change in Southeast Asian tropical peatlands: A review. Glob Biogeochem Cycles Vol: 25, Article Number: GB2001. doi:10.1029/2009GB003718

Hirsinger F, Schlick KP (1995) A Life Cycle Inventory for the production of oleochemical raw materials. European LCI for detergent surfactant production. Tenside Surf. Det 32

Hooijer A, Page S, Canadell JG, Silvius M, Kwadijk J, Wösten H, Jauhiainen J (2010) Current and future CO_2 emissions from drained peatlands in southeast Asia. Biogeosciences 7:1505-1514. doi:10.5194/bg-7-1505-2010

Hooijer A, Page S, Jauhiainen J, Lee WA, Lu XX, Idris A, Anshari G (2012) Subsidence and carbon loss in drained tropical peatlands. Biogeosciences 9:1053–1071

Hooijer A, Silvius M, Wösten H, Page S (2006) Peat-CO_2 Assessment of CO_2 emissions from drained peatlands in Southeast Asia. Delft Hydraulics

IPCC 2014, 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands". Chapter 2 - DRAINED INLAND ORGANIC SOILS, Table 2.1, http://www.ipcc-nggip.iges.or.jp/public/wetlands/pdf/Wetlands_separate_files/WS_Chp2_Drained_Inland_Organic_Soils.pdf

ISO/TS 14067 (2013) Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification and communication.

Jauhiainen, J.,. Hooijer A., Page, S. E. (2012) Carbon dioxide emissions from an Acacia plantation on peatland in Sumatra, Indonesia; Biogeosciences, 9, 617–630, 2012 (doi:10.5194/bg-9-617-2012)

Koh LP, Miettinen J, Liew SC, Ghazoul J (2010) Remotely sensed evidence of tropical peatland conversion to oil palm. http://www.pnas.org/content/108/12/5127.short. Accessed 2014

Liedke A, Deimling S, Rehl T, Bos U, Brandstetter P, Baitz M (2014) Feed and Food Databases in LCA – an example of implementation. Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector

Malaysian Palm Oil Board (MOPB) [1] (2013) http://www.mpob.gov.my. Accessed 2014

Manfredi S, Allacker K, Chomkhamsri K, Pelletier N, de Souza DM (2012) Product Environmental Footprint (PEF) Guide. JRC Reference Reports, Luxembourg

Melling L, Henson IE (2011) Greenhouse Gas Exchange of Tropical Peatlands – a Review. J Oil Palm Res 23:1087-1095

Miettinen J, Hooijer A, Shi C, Tollenaar D, Vernimmen R, Liew SC, Malins C, Page SE [1] (2012) Extent of industrial plantations on southeast asian peatlands in 2010 with analysis of historical expansion and future projections. Glob Chang Biol 4, 908–918

Miettinen J, Hooijer A, Tollenaar D, Page S, Malins C, Vernimmen R, Shi C, Liew SC [2] (2012) Historical analysis and projection of oil palm plantation expansion on peatland in Southeast Asia. White Paper Number 17, ICCT

Miettinen J, Shi C, Liew SC (2011) Deforestation rates in insular Southeast Asia between 2000 and 2010. Global Change Biology 17:2261–2270

Murty D, Kirschbaum MUF, Mcmurtrie RE, Mcgilvray H (2002) Does Conversion of forest to agricultural land change soil carbon and nitrogen? A Review of the Literature. Global Change Biology, Volume 8, Issue 2, 105–123

Page SE, Morrison R, Malins C, Hooijer A, Rieley JO, Jauhiainen J (2011) Review of peat surface Green-house Gas Emissions from oil palm plantations in southeast Asia. White Paper Number 15, Indirect Effects of Biofuel Production Series

Panapanaan V, Helin T, Kujanpää M, Soukka R, Heinimö JJ, Linnanen L (2009) Sustainability of palm oil production and opportunities for finnish technology and know-how transfer. Lappeenranta University of Technology, Research Report 1, pp 13 - 61.

Rettenmaier N, Reinhardt G, Münch J, Gärtner S (2007) Datenprojekt „Nachwachsende Rohstoffe“. Report for environmental agency of Germany

Roundtable on Sustainable Palm Oil RSPO (2012) RSPO-Principles and criteria for sustainable palm oil production. http://www.rspo.org. Accessed 2014

Schmidt JH (2007) Life Cycle Assessment of rapeseed oil and palm oil. Dissertation, Part 3: Life Cycle Inventory of rapeseed oil and palm oil. Department of Development and Planning, Aalborg University

Schowanek D et al (2017) New and Updated Life Cycle Inventories for Surfactants used in European Detergents: Summary of the ERASM Surfactant Life Cycle and Ecofootprinting Project. Int. J. LCA, DOI 10.1007/s11367-017-1384-x

Smith P, Bustamante M, Ahammad H et al (2014) Agriculture, forestry and other land use (AFOLU). In: Edenhofer O, Pichs-Madruga R, Sokona Y et al IPCC Climate Change 2014: Mitigation of climate change. Cambridge University Press, Cambridge, United Kingdom and New York, USA, AR5 chapter 11

Stalmans M, Berenbold H, Berna JL, Cavalli L, Dillarstone A, Franke M, Hirsinger F, Janzen D, Kosswig K, Postlethwaite D, Rappert Th, Renta C, Scharer D, Schick K-P, Schul W, Thomas H, Van Sloten R (1995). European Life-Cycle Inventory for Detergent Surfactants Production. Tenside Surf. Det. 32, 84-109.

Statistics Yearbook Malaysia (2011) Department of Statistics, Malaysia; Statistics Yearbook Malaysia 2011, September 2012

Statistical Yearbook of Indonesia (2011), BPS - Statistics Indonesia, Statistical Yearbook of Indonesia 2011, ISSN: 0126-2912

Stichnothe H, Schuchardt F (2011) Life Cycle Assessment of two palm oil production systems. Biomass and Bioenergy 35: 3976-3984

Subramaniam V, Choo MY, Muhamad H, Hashim Z, Tan YA, Wei PC [1] (2010) Life Cycle Assessment of production of crude palm oil (Part 3). J Oil Palm Res 22:895-903

Subramaniam V, Choo MY, Muhamad H, Hashim Z, Tan YA, Wei PC [2] (2010) Life Cycle Assessment of production of crude palm kernel oil (Part 3a). J Oil Palm Res 22:904-912

The International Reference Life Cycle data System (ILCD) (2010) International Reference Life Cycle Data Sys-tem (ILCD) Handbook – General guide for Life Cycle Assessment - Detailed guidance. JRC Reference Reports, Luxembourg

The International Reference Life Cycle data System (ILCD) (2010) International Reference Life Cycle Data Sys-tem (ILCD) Handbook – General guide for Life Cycle Assessment - Detailed guidance. JRC Reference Reports, Luxembourg

Watson RT, Noble IR, Bolin B, Ravindranath NH, Verardo DJ, Dokken DJ (2000) Land Use, Land-Use Change and Forestry. IPCC Cambridge University Press, UK, pp 375

Wicke B, Sikkema R, Dornburg IV, Junginger M, Faaij A (2008) Drivers of land use change and the role of palm oil production in Indonesia and Malaysia-overview of past developments and future projections. Utrecht University

Wijbrans RA, Van Zuthen JM (2011) LCA GHG emissions in production and combustion of Malaysian palm oil biodiesel. Journal of Oil Palm & The Environment 2:86-92. An official publication of the Malaysian Palm Oil Council (MPOC)

WRI, CAIT 2.0. (2014) Climate Analysis Indicators Tool: WRI’s Climate Data Explorer. Washington, DC: World Resources Institute. http://cait2.wri.org. Accessed 2010

Zulkifli H, Halimah M, Chan KW, Choo YM, Mohd Basri W (2010) Life Cycle Assessment of oil palm fresh fruit bunch production from continued land use for oil palm planted on mineral soil (Part 2). J Oil Palm Res 22:887-894

Annex A: Oil Palm Cultivation

For oil palm cultivation in Malaysia, the values for yield described in literature vary in general between 18.9 and 20.7 t FFB x ha-1 yr-1 (Choo et al. 2011; Zulkifli et al. 2010; Schmidt 2007; Stichnothe and Schuchard 2011; Panapanaan et al. 2009; Rettenmaier et al. 2007; Chen 2008; Hassan et al. 2011). Other literature sources report even higher numbers, i.e. Wicke et al. (2008) gives yields of 31 t FFB x ha-1 yr-1. Those numbers may occur locally and during specific growing seasons but do not represent the regional overall average. In addition, three official sources – FAOSTAT, Malaysian palm oil board (MPOB) and Malaysian statistical yearbook (MSY 2011) report yields (see Table 2). Out of these, the Malaysian Statistical Yearbook is the only source which specifies the consideration of mature and immature plantations. Both other sources do not give explanation on this aspect. In this study mature and immature cultivation area is taken into account. Data from the Malaysian Statistical Yearbook [MSY 2011] are used within this study to best display the national average production.

Table 12: Different yields reported by Malaysian official sources (numbers in t FFB x ha-1 yr-1).

Source / Year	2007	2008	2009	2010	2011	Average
FAOSTAT 2013	21.1	22.7	21.9	21.9	21.9	21.9
MPOB [1] 2013	19.0	20.2	19.2	18.0	19.7	19.2
Malaysia - Statistics yearbook - MSY 2011	18.8	19.8	18.8	17.7	19.5	18.9

Hirsinger and Schlick (1995) and Gea (2013) state that the mechanical **palm oil extraction** is the most commonly applied method. Same argument is exposed by Schmidt (2007), since no use of a solvent in special hexane is reported in his study. This study assumes in the inventory the mechanical palm oil extraction path.

The mass balances are given in Table 13. The water use, energy input and diesel requirements in the palm mill were modeled according to Subramaniam et al. [1] (2010) and Subramaniam et al. [2] (2010) (Table 13). Data from Schmidt (2007) are used to supplement data gaps in the publications of the MPOB.

The palm oil mills are self-sufficient of energy supply. Emissions to air are modeled by estimating the incineration of all shells (116 kg/t FFB) and fibres (104 kg/t FFB) using a wood combustion process. No credit is given for energy recovered from these processes. The mass balance is closed assuming evaporation during the processing (water vapour to air). The carbon, water and heavy metals content is taken into account according to Stichnothe and Schuchhardt (2011).

Table 13: Inventory- Palm Oil mill per 1 kg CPO according to Subramaniam et al. [1] (2010)

Inputs	Quantity	Unit	Outputs	Quantity	Unit
Oil Palm FFB	5.08	kg	Crude palm oil	1.00	kg
			Palm kernel*	0.27	kg
			EFB	1.16	kg
			Palm shells**	0.38	kg
			POME	3.05	kg
			Boiler ash	0.02	kg
Utilities	Quantity	Unit			
Diesel	164.5	MJ	Steam to air***	5.2	kg
Electricity	2.90E-03	MJ			
Boiler water consumption	2.6	kg			
Water for processing	3.6	kg			

* Value taken from Schmidt (2007) ** The fibre and shells which are used as fuel in the boiler are not included in the mass balance. Excess shells are incinerated. No credit is given; *** The steam emission was calculated as the sum of steam input to turbine plus steam input for sterilization (considered within the process)

Currently most **palm oil mill effluent** (POME) is treated in open ponds. Methane emissions, which have a higher GWP impact than CO_2, are released from those open ponds. For this study it is assumed, that 95% of all POME is treated in open pond. 5% of the POME biogas is collected (Hansen et al. 2011) and subsequent incinerated. 1 t POME produces 16-55 m^3 of biogas. More frequently numbers between 23-28 m^3 biogas are given (Rettenmaier et al. 2007; Schmidt 2007; Wicke et al. 2008; Subramanian et al. 2010; Wijbrans and van Zuthen 2011; see Annex A: Table 15). Open ponds release methane as emission, due to the fact that biogas is not captured. For open ponds the share of methane is 35-65% of the biogas. In this study, after consultation with experts, values are taken and calculated based on Schmidt (2007): 27.8 m^3 biogas with 65% methane for open ponds. Besides methane, other open pond emissions were taken into account based on Schmidt (2007) (N_2O 1.5 g/t POME; NH_3 58 g/t POME; H_2S 86.2 g/t POME, NH_3 58 g/t POME). When collected, the biogas is captured in digester tanks. For digester tanks the share of methane is 55-65%. 5% of the methane is assumed to be captured and used as fuel in a biogas power plant, a credit is given for the electricity generated (average Malaysian and Indonesian grid mix respectively). This credit is used within the system boundaries (electricity input for palm oil mill and palm oil refinery).

Mulching is the currently most commonly used treatment option for **empty fruit bunches.** 100% mulching is assumed for this study. The EFBs are brought back to the field and used as organic fertilizer. This leads to a reduced mineral fertilizer demand, which is already accounted for with reduced mineral fertilizer input (see Table 13).

The palm kernel oil can be obtained by mechanical or solvent extraction. Schmidt (2007) state that the oil can be extracted using solvent - however, only one of Malaysia's 41 palm kernel oil mills was using this technology in 2005. This study assumes the mechanical extraction method. The palm kernel oil mill is modelled according to Subramaniam et al. [1] (2010) and Subramaniam et al. [2] (2010). The mass balance is provided in Table 14. Inventory data are calculated considering the weight allocation between the CPKO and the Palm Kernel cake.

Table 14: Inventory- palm kernel oil mill per 1 kg CKPO according to Subramaniam et al. [2] (2010).

Inputs	Quantity	Unit	Outputs	Quantity	Unit
Palm kernel*	2.13	kg	Crude palm kernel oil	1.00	kg
			Palm kernel cake	1.12	kg
Utilities	**Quantity**	**Unit**			
Electricity	0.89	MJ	Wastewater	0.40	kg
Water**	0.40	kg			

* Value scaled up based on weight allocation; ** Value is taken from Schmidt 2007. It is assumed that the water used in the mill is released as wastewater

Transport distances are provided in Table 16. Kernel-crushing plant location near ports is assumed to be standard scenario, since 5 out of 6 investigated palm kernel oil mills are located close to the sea.

Table 15: Emissions from different POME treatments given in literature (values were partly given in different units and calculated to the respective units m3 biogas/ m3 POME and kg CH4/t CPO).

Source	Biogas yield [m^3 biogas/m^3 POME]	Methane Emissions [kg CH_4/t CPO]	Share methane	Type of pond
Rettenmaier et al. 2007	23.3	27.6	0.55	closed
Rettenmaier et al. 2007	23.3	17.6	0.35	open
Schmidt 2007	27.8	43.6	0.65	Not specified
Wicke et al. 2008	Min: 16.3	14.0	0.4	open
Wicke et al. 2008	Max: 55.2	47.5	0.4	open
Wicke et al. 2008	Average: 27.5	23.7	0.4	open
Subramanian et al. [1] 2010	28.0	36.4	0.38	open
Wijbrans and van Zuthen 2011	28.0	39.2	0.65	closed

Table 16: Applied transport distances

Commodity	transport distances	km	source
FFB	field to palm oil mill	50	Subramaniam et al. [1] (2010) and Subramaniam et al. [2] (2010)
EFB	palm oil mill to field	50	Subramaniam et al. [1] (2010) and Subramaniam et al. [2] (2010)
PK	palm oil mill to palm kernel oil mill	318	Subramaniam et al. [1] (2010) and Subramaniam et al. [2] (2010)