Journal of Cleaner Production 277 (2020) 124045

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Certified palm oil reduces greenhouse gas emissions compared to non-certified

Jannick Schmidt*, Michele De Rosa

Aalborg University, Rendsburggade, 14 9000, Aalborg, Denmark

ARTICLE INFO

Article history:
Received 25 November 2019
Received in revised form
28 July 2020
Accepted 29 August 2020
Available online 3 September 2020

Handling editor. Yutao Wang

Keywords:
Palm oil
Carbon footprint
Biodiversity
RSPO certified
GHG emissions

ABSTRACT

Consumers are increasingly demanding products containing palm oil produced without harm to the environment. The industry response to this demand has been the creation of the Roundtable on Sustainable Palm Oil (RSPO) and the development of a certification system to ensure sustainable palm oil production. However, currently there is no scientific evidence of the benefit gained through the RSPO certification schema. This paper quantifies the environmental impacts of RSPO certified and non-certified through a detailed Life Cycle Assessment (LCA) of 1 kg of RBD palm oil to factory gate, produced in Indonesia and Malaysia in 2016, to identify potential benefits and trade-offs of RSPO certification. The ISO 14040/14044 compliant LCA is carried out following both a consequential and an attributional LCA approach. The inventory model presents a high level of detail. Primary inventory data describing the certified production system are obtained from RSPO assessment reports, covering 73% (634 estates) of the certified estate, including 111 smallholders, and 58% (165 oil mills) of the certified mills. Data for the total industrial production are drawn from national statistics and scientific literature. The non-certified flows are derived by subtracting the certified flows from the total industry flows. The consequential results show that RSPO certified oil reduces GHG emission by 35% compared to non-certified i.e. 3.41 (2.61–4.48) kg CO_2 eq./kg for certified vs 5.34 (3.34–8.16) kg CO_2 eq./kg for non-certified. Based on a thorough data quality assessment and uncertainty analysis, this result is deemed sufficiently robust and thus conclusive. Certified production achieves the largest GHG emissions reduction because of higher yields, i.e. less land use per unit of product, less oil palm cultivated on peat soil and higher share of palm oil mill effluents treated with biogas capture technologies. We also found that nature occupation is reduced by 20% in certified production while respiratory inorganic is slightly higher (3%) in certified production, due to the larger use of fertilisers. For other impact categories, results are associated with a larger uncertainty and therefore shall be considered as indicative. Similar results are found in attributional modelling.

1. Introduction

Palm oil is an agricultural commodity produced at large scale, consumed and traded globally. In the last decades, the oil palm harvested area showed an outstanding growth, particularly in Indonesia and Malaysia, which in 2016 together accounted for more than 82% of the global production of fresh fruit bunches (FFB, FAOSTAT, 2018). From 1990 to 2016, the oil palm area harvested increased from 0.7 to 9.3 million ha in Indonesia and from 1.7 to 5.0 million ha in Malaysia (FAOSTAT, 2018).

Palm is not a land-use intensive product compared to the alternative vegetable oils (Schmidt et al., 2015a). Nevertheless, oil palm plantations are spurring debates, especially in Europe, due to the environmental effects caused by land-use changes (LUC) from natural forest and peat swamps to plantations in tropical areas and due to the related social implications (Wicke et al., 2011). The main environmental concerns are the emissions of greenhouse gasses (GHG) and loss of biodiversity caused by forest fires or logging, changes in carbon stocks of soil and biomass triggered by drainage of peatland. Tropical peatland stores a large share of the global carbon stock (IPCC, 2014a) and the drainage of peatland for agricultural purposes exposes the organic matter to oxygen, accelerating its decomposition and the emission of CO_2. Social concerns are human health issues, such as respiratory diseases caused by

* Corresponding author.
E-mail address: jannick@plan.aau.dk (J. Schmidt).

https://doi.org/10.1016/j.jclepro.2020.124045

forest fires, land tenure and human right conflicts caused by illegal land occupation or forced displacement of local population (Wicke et al., 2011).

In response to these concerns, in 2004 a group of various organizations including palm oil producers, traders, consumer goods manufacturers, investors and NGOs, established the Roundtable on Sustainable Palm Oil (RSPO). RSPO promotes the production of sustainable palm oil by setting credible global standards included in the RSPO principles and criteria. In 2008, RSPO developed a voluntary certification schema and released the first certification. In 2017, certified production accounted for 12.1 million tons (RSPO, 2018), 19% of the 2014 global palm oil and palm kernel oil production of 63.9 million tons (FAOSTAT, 2018).

The awareness of sustainable palm oil production rose further in 2015 in conjunction with the European legislation on the provision of food information to consumers. From December 2014, the EU (law No 1169/2011) requires that nutrition labels of products specify information on the origin of refined vegetable oils and fats (e.g. "palm oil" instead of "vegetable oil"), making palm oil visible to consumers (Gassler and Spiller, 2018). Because of the increased public attention, the need for a verifiable and efficient certification schema has become even more urgent.

This paper compares the performances of RSPO certified and non-certified palm oil to quantify the difference between the two production systems. Life Cycle Assessment (LCA) is a commonly used framework particularly suitable for comparing the environmental performances of alternative products or production systems. Since 2007, a few LCAs of palm oil have been published in literature (e.g. Yusoff and Hansen, 2007; Schmidt, 2007; Vijaya et al., 2008; Tan et al., 2010; Saswattecha et al., 2015; Morgans et al., 2018) including simplified LCAs accounting only for GHG emissions (Choo et al., 2011; Puah et al., 2013). The first ISO compliant (i.e. review by an independent panel) LCA of palm oil was a comprehensive LCA of Palm Oil at United Plantations (Schmidt, 2008). Comparative LCAs allow the comparison of the potential environmental impacts of palm oil with substitutable products in the same economic sector. Examples of comparative LCAs of vegetable oils exist, e.g. Arvidsson et al., (2013), Schmidt (2015a). LCAs have been performed to compare the performances of palm oil with rapeseed oil (Schmidt, 2010), or among palm oil, soybean oil, rapeseed oil, sunflower oil and peanut oil (Schmidt, 2015a). Comparative LCA has also been performed in the biodiesel sector, e.g. comparing palm oil with jatropha oil (Lam et al., 2009), and with rapeseed biodiesel (Yee et al., 2009). These studies focused on comparing palm oil with competing (i.e. substitutable) products, but none of them assess the environmental effects of RSPO certification.

Previous works assessed the effectiveness of specific aspects of the certification such as: the impact of palm oil certifications on small holders in Indonesia (Brandi et al., 2013; Hutabarat et al., 2018); the effect of RSPO certification in reducing forest fire in Sumatra and Kalimantan (Cattau et al., 2016); the impact of certification on deforestation and fire Carlson et al. (2017). Bessou et al. (2014) performed a simplified LCA of RSPO certified palm oil produced by nine RSPO member companies, focusing exclusively on global warming potential (i.e. a carbon footprinting). More recently, Meijide et al. (2020) carried out a life-cycle carbon footprinting of palm oil biodiesel, distinguishing between mature and immature Indonesian plantations. Yet, a comprehensive LCA comparing the environmental effects of RSPO certification against non-certified palm oil production is currently missing in the scientific literature. Therefore, the potential environmental benefits of the RSPO's certification have yet to be demonstrated.

This work intends to fill this gap by performing a detailed and comprehensive LCA, comparing the performance of average RSPO certified versus non-certified production of palm oil. The certified and non-certified palm oil are both assumed as produced in Indonesia and Malaysia, the two largest palm oil producing countries in the world. The objective is to identify the potential environmental benefits of the certification and the possible trade-offs between the two production systems. This requires the quantification of the GHG emissions of the two production systems and other relevant impacts in palm oil production, such as nature occupation (biodiversity) and respiratory impacts. Other less relevant impacts for palm oil production are also assessed, e.g. eutrophication, toxicity etc.The comparison between these two palm oil production systems allows the identification of the most promising and the less obvious improvement options. The results also provide useful insights to several stakeholders: palm oil consumers, to highlight the benefits of choosing certified palm oil; palm oil suppliers, to define further requirements to producers, based on environmental performances; palm oil producers, to prioritise options to improve the palm oil product system. Therefore, this work addresses a pressing and currently unanswered question: what are the environmental benefits and trade-offs of RSPO certified palm oil production compared to non-certified production?

2. Materials and methods

2.1. Functional unit and system boundaries

The functional unit (FU) of the LCA is 1 kg of refined, bleached and deodorized (RBD) palm oil at refinery gate in 2016, produced in Indonesia and Malaysia. The formulation of the FU as refined oil instead of crude palm oil (CPO) is because CPO contain impurities and free fatty acids typically removed at refinery stage, making CPO not substitutable in a one-to-one ratio.

Palm kernels are a by-product of the palm oil mill sent to a palm-kernel crusher plant, where they are processed into crude palm kernel oil (CPKO) and palm kernel cake (PKC). After the CPKO is refined, the output falls under the definition of the functional unit. We include the production stages of oil palm cultivation, palm oil mill and palm oil refinery. The downstream life cycle stages, i.e. the use stage and the product's end-of-life, are excluded from the assessment. Product packaging is also outside the model's system boundaries, because most oils are traded as bulk oils in trucks or ships.

2.2. Modelling approach

The LCA is performed according to attributional and consequential modelling approaches, described in Schmidt and Dalgaard (2012), Weidema (2003) and Weidema et al. (2009). The consequential approach follows a causal model, seeking to describe the consequences of a change in demand of the functional unit and it treats by-products by modelling their product's substitution effect. In consequential modelling, the inputs to a system are assumed as provided by the marginal suppliers of that input in the market. The attributional modelling instead follows a normative approach: it assumes the inputs to a system are the average of the products supplied in the market; by-products are allocated based on one of their properties, e.g. the mass in the case of this study.

The background database used for the consequential model is the latest version of the global hybrid environmentally extended multi-regional input-output (EEMRIO) database EXIOBASE (version 3.3.13), described in Merciai and Schmidt (2017a) and Stadler et al. (2018). The databases operates with no cut-off criteria, and thus it is significantly more complete in terms of product flows and industries. It also includes emissions from the production of more capital goods and services than any traditional processed-based

LCA databases. EXIOBASE distinguishes among 164 activities/products (equivalent to LCA processes in a conventional LCA database), 43 countries and 5 Rest-Of-the-World (ROW) regions, representing the remaining countries for the reference year 2011. The database also distinguishes between 34 emissions, 22 resources, including water, and 5 land use types. In this study, both direct land use change (dLUC) and indirect land use change (iLUC) are modelled. The land use change (LUC) model follows the framework described Schmidt et al. (2015) and it is integrated in EXIOBASE. This is further described by section 2.4.1.

The attributional approach follows, as close as possible, the modelling assumptions of 'Palm GHG', a GHG accounting tool commissioned by RSPO, described in Chase et al. (2012). PalmGHG is chosen as a guiding principle for the attributional model, because it is a tool and method provided by RSPO and because it is widely used by certified palm oil producers. However, the emission calculations and the background database in this study are different compared to PalmGHG. PalmGHG operates with a FU of 1 kg crude palm oil (CPO). To compare results calculated with the PalmGHG calculator and this LCA, the contribution from the refining stage shall be subtracted from the results of the current study. As in PalmGHG, the attributional model in the current LCA uses mass as a property of the products to allocate the impacts (mass allocation) among by-products and it includes only direct land use changes. This is consistent with the PAS 2050 (2011) specification. The direct LUC in the attributional model is calculated following a normative approach also used by PAS2050. The GHG emissions from land conversion are amortized (i.e. allocated) over an arbitrarily defined period, in this case 25 years. Thus, only the LUC emissions occurred during the last 25 years are included. Although common in LCAs, this approach does not reflect a cause-effect relationship. Allocating historical land use change impacts to current oil palm cultivation implies a causality that goes backwards in time (e.g. current demand for oil palm caused deforestation 25 years ago). The changes in carbon stock associated with the land cover changes during the last 25 years are identified based on historical land cover data. The calculated carbon stock changes are then annualized (i.e. divided by 25), as further explained in section 6 of the Supplemental Information (SI) provided with this paper.

Similarly, for consistency with the PAS 2050 (2011) guidelines, the attributional model does not include capital goods in the foreground system. The background database applied to the attributional model is ecoinvent v3.4. (ecoinvent 2017) with system model 'Allocation at the Point Of Substitution' (APOS). In accordance to the 'Palm GHG' modelling approach, iLUC is not included in the attributional model.

The Life Cycle Impact Assessment (LCIA) method applied is Stepwise 2006 version 1.7. The method is described and documented in the Annex II of Weidema et al. (2008). The weighting module is documented in Weidema (2009). The most recent updates for the impact 'nature occupation' are described in Schmidt and de Saxcé (2016). The characterization module of Stepwise is based on a combination of the Impact 2002+ method (Jolliet et al., 2003) and the EDIP 2003 method (Hauschild and Potting, 2005). The indicators in the Stepwise method are explained in the SI, section 8. The full environmental impact of palm oil production is captured by considering a comprehensive set of environmental impact categories:

- Global warming
- Nature occupation
- Respiratory inorganics
- Respiratory organics
- Human toxicity, carcinogens
- Human toxicity, non-carc.
- Ecotoxicity, aquatic
- Ecotoxicity, terrestrial
- Acidification
- Eutrophication, aquatic
- Eutrophication, terrestrial
- Photochemical ozone, vegetat.
- Non-renewable energy
- Mineral extraction

2.3. Data collection approach

The inventory data for RSPO certified production and total industrial production in Indonesia and Malaysia in 2016 are drawn from different data sources. These are described in section 2.3.1 and section 2.3.2 below, respectively. Data for the non-certified production are obtained by subtracting the RSPO certified flows from the total industry flows. Summary inventory tables for the total industry, RSPO certified and non-certified production are available in section 3 of the SI. The summary inventory tables cover all the production stages of palm oil production: oil palm cultivation, palm oil mil processing and kernel crusher plant, palm oil refining. The tables present inventory data for the consequential and attributional model separately (see SI, section 3).

The consequential model draws fuel combustion emissions for the whole product system from consistent emission factors found in the EXIOBASE database. The marginal electricity mix is estimated based on the expansion of the national electricity supply in the period 2006–2011. The attributional model draws fuel combustion emission factors and average electricity mixes from the ecoinvent database (ecoinvent 2017).

2.3.1. RSPO certified production

The inventory data collection for certified production is based on a bottom-up approach, i.e. estate-by-estate and oil mill-by-oil mill from the annual surveillance assessment reports, provided by RSPO member estates and mills for 2016 (RSPO, 2017). In order to obtain data coverage for at least 50% of all certified FFB production and 50% of all certified Crude Palm Oil (CPO) production, data have been collected from 165 RSPO annual assessment reports. The data describe 634 estates (of which 111 are smallholders), covering around 73% of the total certified oil palm planted area in Indonesia (381 estates) and Malaysia (253 estates). Palm oil mills data have been collected for 165 mills in Indonesia (101 mills) and Malaysia (64 mills), producing 58% of the certified palm oil in Indonesia and Malaysia. The thorough inventory data collected describe the RSPO certified and the non-certified palm oil production systems with an unprecedented level of detail. For statistics describing the data collected, see the SI, section 2.

The RSPO's annual assessment reports provide data on several product flows and land use needed for the LCA. The assessment reports show data per oil mill, including the estates in its supply base. When the assessment report for an oil mill includes aggregated data for several estates (e.g. data on land use for nursery and land set-aside for nature conservation aggregated for the mill's supply-base), data have been allocated to the estates proportionally to the share of the total planted area occupied by each estate.

2.3.2. Total industrial production

While the data collection for the RSPO certified flows followed a bottom-up approach, the inventory data collection for the foreground system of the total industry flows follows a top-down approach, when statistical data are available for this purpose. Alternatively, representative coefficients drawn from literature are used, e.g. diesel use per hectare oil palm estate and water use per tonne processed FFB in palm oil mills. The next sections describe how data have been obtained for three production stages: oil palm cultivation, palm oil milling and palm oil refining.

2.4. Oil palm cultivation stage

Table 1 shows selected key performance indicators describing the oil palm cultivation stage. The yields have large impact on the results. In order to make the results for 2016 significant and comparable with other years, the FFB yields are adjusted to take into account the particularly disadvantageous conditions that occurred in 2016, due to a severe drought attributed to El Niño–Southern Oscillation (ENSO) in the central and eastern tropical Pacific. In 2016, weather changes in Southeast Asia caused by El Niño lowered the Malaysian yield of approximately 14%. (MPOB, 2018). The FFB yields reported in this study refer to the area occupied by mature (producing) and immature (developing) oil palms to reflect the actual land occupation. Typically, yields are reported referring only to mature area. In this study, they are converted to total planted area assuming an average rotation time of 25 years: 2.5 years to develop the crop and 22.5 years of harvesting (Woittiez et al., 2017). Further details on the data applied for the calculation of yields are available in the SI, section 4.

The model includes emissions occurring in the estates, regarding to fertiliser and crop residue inputs. This includes emissions relating to the N-turnover, P and heavy metals from contaminants in fertilisers calculated through a detailed N and P balance, respectively, using the IPCC (2014a) approach. The balances account for: 1) net inputs, 2) release from decomposition of crop residues, 3) uptake of nutrients from the soil in living biomass and 4) harvested biomass. Emissions from peat oxidation (CO_2 and N_2O), from anaerobic conditions in draining ditches (CH_4) and from the use of fire for replanting (NO_x and particulates) are also modelled.

The model accounts for carbon dioxide emissions from peat oxidation as fossil emissions and includes methane emissions from draining ditches. We estimate that 18% of the industry-average planted area in Indonesia and Malaysia is on peatland. For RSO certified planted area, we estimate that 11% of the planted area is on peatland. These percentages are based on data available in the scientific literature and on GIS elaborations performed for this study. The data and the calculations are described in the SI, section 5.

Emissions of substances containing carbon, e.g. biogenic CO_2, are not based on a field balance. Instead, we conservatively assume that the CO_2 uptake in biomass during growth is also released as CO_2 when the biomass decomposes. The CO_2 contained in the final product, the so-called biogenic CO_2, is included in the emissions account, because the functional unit is expressed at refinery gate, where the carbon content of the oil is not yet converted to emissions. This is not a problem when comparing palm oil with other bio-based alternative oils. However, if bio-based feed stocks are compared with fossil-based alternatives on a cradle-to-gate assessment, the biogenic emissions shall be subtracted from the results, in order to avoid penalising the bio-based oil incorrectly.

2.4.1. Land use change and nature conservation modelling

CO_2 emissions from land use changes are responsible for 11% of global GHG emissions (IPCC, 2014b). In the consequential model, iLUC is modelled as described in Schmidt et al. (2015). This approach is applicable to all crops (also forestland, rangeland, build areas etc.) in all regions in the world and avoids the arbitrary allocation/amortization of transformation impacts. The iLUC model reflects cause-effect relationships consistent with the LCA modelling in the consequential approach. The iLUC model has been used extensively in LCA, carbon footprints and it ranks as the best performing approach in comparison with six major LUC models (De Rosa et al., 2016) with respect to completeness, impact assessment relevance, scientific robustness, and transparency. We use version 4.3 of the iLUC model, which is integrated in the multiregional hybrid input-output model EXIOBASE v3.3.13 (Merciai and Schmidt, 2017b; Schmidt and De Rosa, 2018).

Certified oil palm plantations may reserve part of the land bank for nature conservation. We accounted for both the dLUC and the iLUC impact of nature conservation according to Schmidt (2015b, 2016; 2017).

The nature conservation dLUC (on-site) effects from avoided transformation of conserved land is modelled as one-year delay of the effects from transformation from non-productive land (i.e. the preserved land) to productive land (i.e. the land use cover, which is avoided by the conservation). The nature conservation effect is calculated on an annual basis (ha*year): the effect of preserving a conservation area for one year is a one-year delay of the change in carbon stock from nature conservation area to oil palm plantation. This is in line with the approach of the iLUC model (Schmidt et al., 2015).

The nature conservation iLUC (remote) effects are modelled as avoided transformation of conserved land in the iLUC model. The area of the nature conservation reserve is adjusted with a productivity factor to calculate the ha*year equivalents of land, which will be occupied elsewhere to compensate for the land occupied by the nature conservation area. The effect of this further land occupation is accounted by the iLUC model described by Schmidt et al. (2015).

The attributional model follows PalmGHG's LUC accounting approach, which means that iLUC is excluded. Note that the PalmGHG approach only refers to LUC impact in terms of global warming (GHG emissions) and it does not provide guidance on how to model nature occupation impacts, i.e. impacts on biodiversity from land use changes. In the LCIA method Stepwise 2006 version

Table 1
Key performance indicators for oil palm cultivation.

Flows	Unit	Total industry (ID & MY)	RSPO-certified	Non-certified
Total planted area	million ha	14.4	2.44	12.0
Share of oil palm on peat	%	18%	11%	19%
Drainage depth (DD) of peat	cm	73	57	75
FFB yield, mature	t/ha	18.9	21.1	18.5
Fuel use	MJ/ha	2940	2940	2940
Applied mineral N	kg N/ha	82	170	64
Applied organic N	kg N/ha	21	24	21
Applied mineral P_2O_5	kg P_2O_5/ha	41	103	28
Applied organic P_2O_5	kg P_2O_5/ha	28	31	27
Applied mineral K_2O	kg K_2O	156	245	138
Applied organic K_2O	kg K_2O	138	153	135

1.7 (Weidema, 2009), used for this LCA, the methodology to account for the nature occupation impact is aligned with the concept of accelerated denaturalisation, i.e. avoiding amortization of land transformation (Schmidt, 2015). The PalmGHG land use change approach instead aims to account for the land transformation in absolute terms. Therefore, the PalmGHG approach to LUC is not suitable for capturing the nature occupation impact with the Stepwise LCIA method. To overcome this issue in the attributional model, the nature occupation impact from the occupation of 1 ha*year by the oil palm estate is calculated by applying the same proportion between iLUC GHG and iLUC nature occupation in the consequential model to the LUC GHG emissions to the attributional model.

2.5. Palm oil milling stage

Table 2 shows the key performance indicators selected for palm oil mill (POM) processing. Fig. 1 shows the main palm oil mill and the involved activities in the palm oil mill life cycle stage included in this study.

Palm oil mills produces empty fruit bunches (EFB) and palm oil mill effluents (POME). The POME treatment activity is a major contributor to GHG emissions, and the POME treatment method is a crucial difference between RSPO certified and non-certified palm oil. We implemented a state-of-the-art model to determine the methane emissions from POME treatment with or without biogas capture facilities at the POM. The model calculates emissions based on the fate of the captured methane, i.e. whether it is flared (distinguishing between open or enclosed flaring), used in POM boilers or in biogas engines for electricity generation. The calculations of POME treatment emissions for these technologies are described in the SI, section 7.

The amount of POME from a conventional palm oil mill, without a decanter and an Empty Fruit Bunches (EFB) press, has been found to be 675 kg/t FFB (Ma et al., 2007); yet, estimations from UPRD (2007) shows that this amount might be low, and that 700 kg/t FFB may better reflect actual measurements. A decanter reduces the effluents by 35 kg/t FFB, while an EFB press increases them by 118 kg/t FFB. The EFB press also produces 120 kg EFB liquor. Based on these data, the POME produced for each palm oil mill is calculated depending on whether the mill has an EFB press and decanter. When no information is available, the default assumption is that mills do not have EFB an press and decanter.

The EFB are either burned in oil mill boilers or used as mulch. POME is often applied to land. In the consequential model, the EFB and POME used as fertiliser reduces the fertiliser applied to the field by a corresponding amount. The substituted fertiliser is assumed to be urea. The substitution efficiencies of nutrients in EFB and POME applied to land are 50% and 100%, respectively. Knowing the nutrient content, the moisture content and the substitution efficiencies, the amount of substituted fertiliser is determined.

2.6. Palm kernel crusher and palm oil refining stage

Kernel crusher plants process palm kernels into crude palm kernel oil (CPKO) and kernel meal (PKM). There is no distinction in inventory data between certified and non-certified kernel crusher plants, because the certification schema does not demand specific requirements concerning kernel crushing. The inventory data are obtained from Schmidt (2015a). The consequential approach models the kernels as material for treatment, jointly produced with the reference flow of the oil milling activity, CPO. CPKO and PKM are both modelled as material for treatment. The attributional model applied, instead, mass allocation between these two outputs. The inventory data applied for the consequential and attributional models are documented in the SI, section 3.

Palm oil refineries remove palm fatty acid distillate (PFAD), palm kernel fatty acid distillate (PKFAD) and other impurities from CPO and CPKO, respectively. There is no distinction in inventory data between certified and non-certified refining because the certification schema does not demand specific requirements concerning refining. The inventory data are obtained from Schmidt (2015a). The refined CPO produces the reference product RBD palm oil, the reference flow of the LCA. The refined palm kernel oil (PKO) is traded on the market for vegetable oil. In the consequential model, RPD PKO substitute the marginal sources of edible oils, i.e. RBD palm oil.

PKM from the palm kernel crusher plant, the PFAD and PKFAD are by-product of the palm kernel crushing and refining processes. These by-products are used as animal feed. In consequential modelling, the by-products are modelled applying substitution. Details about the modelling of the by-product and their substitution effect on the global market are described in the SI, section 3. The attributional model applies mass allocation between RBD palm oil and PFAD/PKFAD.

3. Results and discussion

Table 3 shows the characterised results of the comparative LCA of RSPO certified and non-certified palm oil according to the consequential and attributional model, respectively, for the FU of 1 kg RBD palm oil produced in 2016. In Table 3, the lower score between certified and non-certified is marked in bold, for both consequential and attributional results. The Life Cycle Impact Assessment (LCIA) method used is Stepwise 2006, version 1.7 (see section 2.2). The impact categories are also included in Table 3. Results from Ionizing radiation and Ozone layer depletion impact categories were only available for attributional model. For the consequential model, there are no contributions to these impacts, neither from the foreground system nor from the background database (EXIOBASE, does not include any elementary flows contributing to these impact categories).

In the consequential results, an abnormal contribution from the use of Uranium to the non-renewable energy impact is observed. The cause may be poor data quality in the background database on the use of uranium in Malaysian electricity, represented by ‘Rest of the World, Asia’ in Exiobase. Therefore, the consequential results for this impact category are considered non-reliable and are excluded. The consequential results show that RSPO certified performs better than non-certified in 8 out of 13 impact categories. The attributional results show that RSPO certified performs better than non-certified in 4 out of 16 impact categories. However, not all impacts have the same severity. Moreover, the differences between results may not be sufficient for drawing conclusions.

Table 2
Key performance indicators for palm oil mills.

Flows	Unit	Total industry (ID & MY)	RSPO certified	Non-certified
OER	%	20.2%	21.9%	19.8%
KER	%	5.4%	5.6%	5.4%
Share of POME treated with biogas capture	%	5.0%	16%	2.4%
Share of land bank in supply base set-aside as HCV	%	0.6%	3.1%	0%

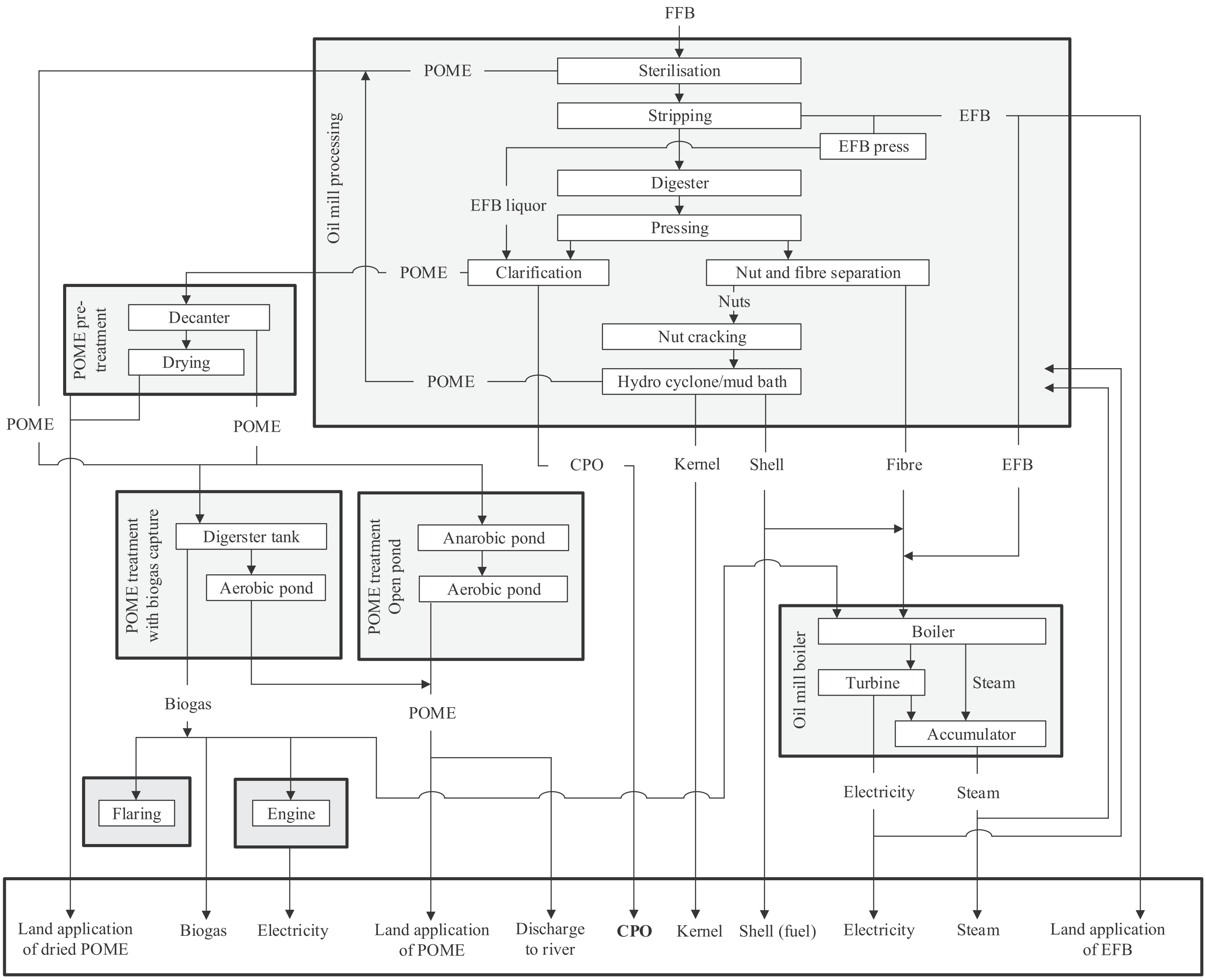

Fig. 1. Overview of the processes and flows in the palm oil mill stage.

Table 3
Characterised results: RSPO certified and non-certified palm oil in Indonesia and Malaysia. The LCIA method applied is Stepwise 2006, version 1.7 (Weidema, 2009). The lower score between certified and non-certified is marked in bold, for both the consequential and attributional results.

Impact category	Unit	Consequential results		Attributional results	
		RSPO certified	Non-certified	RSPO certified	Non-certified
Global warming	kg CO_2-eq	**3.41**	5.34	**3.42**	5.32
Nature occupation	PDF*m^2a	**1.63**	2.04	**1.64**	2.03
Respiratory inorganics	g PM2.5-eq	2.58	**2.50**	0.98	**0.67**
Respiratory organics	milli pers*ppm*h	**2.46**	2.73	**1.58**	1.78
Human toxicity, carcinogens	g C_2H_3Cl-eq	**13.3**	13.5	4.92	**2.73**
Human toxicity, non-carc.	g C_2H_3Cl-eq	35.5	**21.8**	30.0	**17.2**
Ecotoxicity, aquatic	kg TEG-eq w	106	**46.2**	93.5	**42.2**
Ecotoxicity, terrestrial	kg TEG-eq s	**3.16**	3.18	1.21	**0.96**
Acidification	m^2 UES	0.352	**0.341**	0.180	**0.135**
Eutrophication, aquatic	kg NO_3-eq	**0.159**	0.160	0.106	**0.099**
Eutrophication, terrestrial	m^2 UES	1.42	**1.35**	0.73	**0.51**
Photochemical ozone, vegetat.	m^2*ppm*hours	**22.0**	24.2	**14.6**	15.8
Non-renewable energy	MJ primary	n.a.	n.a.	3.79	**2.85**
Mineral extraction	KJ extra	**1.47**	1.56	12.2	**9.80**
Ionizing radiation	Bq C-14-eq	n.a.	n.a.	1.65	**1.33**
Ozone layer depletion	kg CFC-11-eq	n.a.	n.a.	0.044	**0.038**

Weighting the results is an optional step in LCA according to ISO 14044 (ISO, 2006), because the value-choices of the weighting method introduce a bias. However, weighting the results makes possible to express the results for all the impact categories with a common aggregated indicator (a single score) and, thus, to identify the most severe impacts, i.e. the impacts with the largest contribution to the aggregated result. In order to focus on the most relevant impact categories, the characterised results, presented in Table 3, are ranked using the weighting method Stepwise (see section 2.2). The weighted results are presented as monetarised impacts (Weidema, 2009). The results were also weighted against two other LCIA methods (ReCiPe Endpoint (H) V1.13 and IMPACT 2002+ V2.143) to ensure that the ranking is not biased by value-choices applicable only to one method. The three weighting methods show unanimously that global warming, nature occupation and respiratory inorganic are the main impacts, contributing to more than 90% of the total impact expressed as a single score, in both certified and non-certified production. The results of the three weighting methods are shown in the SI, section 9. GHG emissions and nature occupation are also the impacts causing the highest concern in the public debate on palm oil industry and its environmental effects.

In order to compare the consequential results for the three main impact categories of RSPO certified and non-certified palm oil, an uncertainty analysis was performed (Fig. 2). The uncertainty analysis concerns only the foreground system and is obtained through a Monte Carlo simulation, performed with the LCA software SimaPro version 8.4. The procedure to obtain data's uncertainty values is described in the SI, section 10.2. The uncertainty range in Fig. 2 represents the 97.5% and 2.5% percentile. The largest uncertainty ranges are observed for global warming and respiratory inorganic results, because nature occupation uncertainties are almost entirely related to the FFB yields. The uncertainty for non-certified is higher because several data point are dependent on both certified and non-certified uncertainty values. This is because data for the non-certified production are obtained by subtracting the RSPO certified flows from the total industry flows (see section 2.3).

Fig. 2 shows that RSPO certified RBD oil emits 35% less GHG emissions than non-certified, i.e. 3.41 (2.61–4.48) kg CO_2 eq./kg RBD for certified versus 5.34 (3.34–8.16) kg CO_2 eq./kg for non-certified. Global warming is largely caused by CO_2 emissions occurring during oil palm cultivations. The majority of emissions during cultivations are due to drainage of peatland and from LUCs. The remaining emissions are almost entirely caused by methane from POME treatment and from nitrous oxide emissions, occurring as field emissions during the application of nitrogen fertiliser. Sections 3.2 and 3.3 below provide a detailed analysis of the sources of GHG emissions contributing to global warming.

Nature occupation impact is measured in potentially disappeared fraction (PDF) per square meter of land occupied in a year, per kg of product, i.e. PDF m^2*year/kg. Nature occupation is 20% lower for RSPO certified palm oil than non-certified, i.e. 1.63 (1.30–2.05) PDF m^2*year/kg for certified versus 2.04 (1.12–3.34) PDF m^2*year/kg for non-certified. Nature occupation impacts are mainly caused by land occupation from oil palm plantations and, to a lesser extent, from roads, nurseries, housing in the estates, palm oil mills, POME treatment facilities, workshops, and refineries. The land occupation triggers the iLUC model accounting for the accelerated deforestation effect. The consequential model also accounts for the avoided land occupation for wheat, corn and soybean in Brazil, US, Argentina, and Ukraine, as by-products of palm kernel meals and PFAD/PKFAD substitute feeds in the global market for animal feeds (SI section 3).

Results for respiratory inorganics are similar for certified and non-certified in both consequential and attributional modelling. RSPO certified palm oil respiratory inorganics is slightly higher (3%) than the non-certified production: 2.58 (1.93–4.17) $gPM_{2.5}$ eq./kg RBD oil versus 2.50 (1.51–4.22) $gPM_{2.5}$ eq./kg RBD oil for non-certified. The main contributing substances are ammonia, particulates and NO_X, with a minor contribution from sulphur dioxide (SO_2). Ammonia emissions originate largely from oil palm cultivation in estates, while particulates are emitted from the oil mill boilers.

The uncertainty ranges in Fig. 2 for certified and non-certified production overlap for all three impact categories. This means that it is not possible to formulate a conclusive comparative assertion based on these uncertainty ranges. Therefore, data quality and uncertainties were further examined to verify whether a robust comparative assertion could be formulated for any of the impact categories.

3.1. Data quality and uncertainty analysis

A qualitative assessment was performed for the data found for the main elementary flows contributing to each impact category

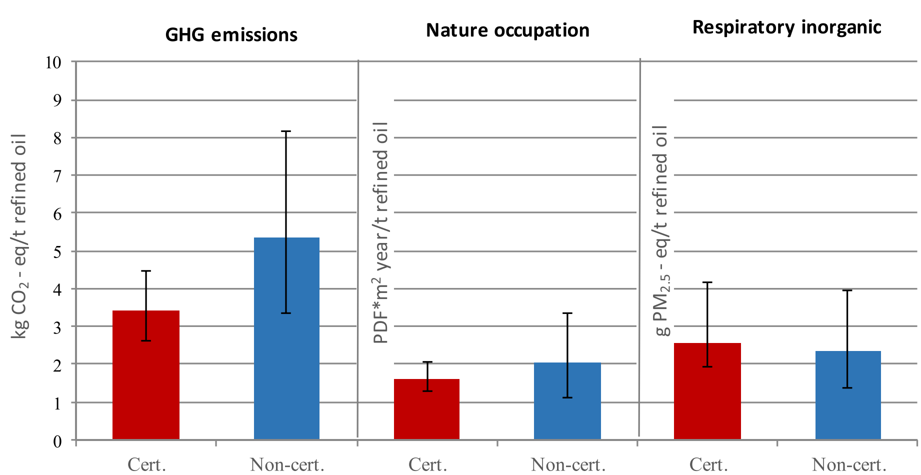

Fig. 2. Result of Monte Carlo uncertainty analysis for the three most relevant impact categories. The error bars in the figure show the 97.5% and 2.5% percentile, respectively. **Consequential model**.

(see SI section 10.1). Impact categories based on not-sufficiently reliable inventory data (SI Table 20) were excluded. The results of the qualitative test are reported in Table 4 (3rd column). Then, a discernibility analysis was performed to examine whether the results for certified and non-certified are confirmed in at least 95% of the Monte Carlo simulations (SI, Fig. 6). The results of the discernibility analysis are also reported in Table 4 (4th column). Finally, a Null Hypothesis Significance Test (NHST) was performed to test whether the means of the relative impacts of the two alternatives are significantly different (see SI Table 21). The results of the discernibility analysis are summarised in the 1st and 2nd column in Table 4. Two significance levels (alpha) were considered to evaluate the p-value. The details of the data quality and uncertainty analysis are reported in the SI, section 10. Table 4 summarizes the results of the NHST test, the qualitative test and the discernibility analysis described in section 10 of the SI. From the results presented in Table 4, it was possible to conclude that a robust comparative assertion can only be formulated for global warming. The comparison concerning the impact categories where only the NHST and the qualitative test provide a positive outcome (indicated with ‘yes’ in Table 4) shall, instead, only be considered as indicative. Conclusions cannot be drawn for the other impact categories.

The following section presents a detailed contribution analysis for global warming in consequential and attributional models.

3.2. Contribution analysis: global warming (consequential)

Table 5 shows the contribution analysis for global warming in consequential modelling. The cultivation stage is the major source of GHG emissions, with 75.6% and 83.5% of the emissions for certified and non-certified, respectively. The palm oil milling stage is the second major source of GHG emissions, contributing to 24.9% and 16.7% of the emissions for certified and non-certified, respectively. The refinery stage only contributes a small share of net negative GHG emissions. The negative values indicate that emissions are avoided in the refinery stage for both certified and non-certified production, respectively, due to the use of by-products.

In palm oil cultivation, GHG emissions are mostly caused by peat drainage and LUC emissions. Peat drainage emissions are 1.59 kg CO_2 eq. lower in RSPO certified production compared to non-certified. This alone correspond to a 30% reduction of the non-certified emissions. Field GHG emissions, mostly nitrous oxide emissions, are related to the nutrient cycle. They occur when nitrogen fertiliser is applied to the crops. Field emissions are 22% lower in certified production compared to non-certified (0.72 and 0.92 kg CO_2 eq., respectively (Table 5), corresponding to a reduction of 3.7% of the total non-certified emissions. However, the higher use of fertiliser in certified production also causes higher GHG emissions associated with material use in the cultivation stage. Table 5 shows that the iLUC contribution is significant, accounting for approximately 11% of the GHG emissions in certified production and 9% of the emissions in non-certified production. The iLUC GHG emissions in certified palm oil are 20% lower than the non-certified emissions (0.49 and 0.62 kg CO_2 eq. respectively), due to the higher average yields found in RSPO certified oil palm cultivation (Table 1). The remaining contributions to the oil crop cultivation stage are not significantly different in the two production systems (Table 5).

In Palm Oil Mills (POMs), methane emissions occur almost entirely during treatment of POME. In RSPO certified production, GHG emissions from POME treatment are 21% lower than non-certified (1.19 and 1.51 kg CO_2 eq., respectively). The certified production performs better than the non-certified because the share of POME treatment with biogas capture is higher in certified production (16% and 2.4% respectively, in Fig. 2). A large GHG emission reduction can be associated to kernels, as the impacts from its crushing process by-products, i.e. kernel oil and kernel meal, are allocated as palm oil and animal feed, respectively. The outputs of kernel oil and meal substitute palm oil and animal feed. All these effects are aggregated in the contribution related to the kernels in Table 5. The table shows that the substitution for certified palm oil mills is much smaller than for non-certified palm oil mills. This is because the kernels in the certified palm oil mills substitute only certified palm oil while this is not the case for non-certified, because the certified and non-certified product systems are modelled as two separate systems. The smaller avoided impact related to the kernels for the certified oil mills does not mean that the certified oil mills performs worse in that respect. Instead, it means that part of the cultivation stage is substituted by a by-product in the oil mill stage. Hence, the difference in performance must be assessed for the whole functional unit, rather than for the oil mill stage alone.

The palm oil refinery shows a minor contribution to the global warming result. This is also valid for nature occupation and respiratory inorganic, in both consequential and attributional modelling. Palm oil refining contributes −0.0 l kg CO_2 eq./kg RBD palm to the total 3.41 kg CO_2 eq./kg RBD in both RSPO certified and non-certified production. This corresponds to a reduction of less than −0.3% and −0.2% of the total GHG emissions in certified and non-certified production, respectively. The negative value represents a net GHG emission reduction, due to the by-product Palm

Table 4
Summary of the uncertainty analyses. “Yes” indicates when the uncertainty analysis supports reliable results and/or when a significant difference between certified and non-certified is supported.

Impact category	Null Hypothesis Significance Testing (NHST)		Qualitative test	Discernibility analysis
	Sign. Diff compared to alpha?	Sign. Diff compared to alpha-b?	Reliable data?	Reliable?
Global warming, fossil	**yes**	**yes**	**yes**	**yes**
Nature occupation	**yes**	**yes**	**yes**	no
Respiratory inorganics	**yes**	**yes**	**yes**	no
Respiratory organics	**yes**	**yes**	**yes**	no
Photochemical ozone, vegetat.	**yes**	**yes**	**yes**	no
Eutrophication, aquatic	no	no	**yes**	no
Eutrophication, terrestrial	**yes**	**yes**	**yes**	no
Acidification	yes	no	**yes**	no
Ecotoxicity, aquatic	**yes**	**yes**	no	**yes**
Ecotoxicity, terrestrial	no	no	no	no
Human toxicity, non-carc.	**yes**	**yes**	no	no
Human toxicity, carcinogens	no	no	no	no
Mineral extraction	**yes**	**yes**	no	no
Non-renewable energy	**yes**	**yes**	no	no

Table 5
Contribution analysis: GHG emissions in kg CO_2 eq. for 1 kg RBD palm oil in 2016 for the consequential model. The total results are shown with and without the iLUC contribution at the bottom of the table. HCV: High Conservation Value.

Life Cycle Stage	Contribution	RSPO Certified	Non-certified
Oil crop cultivation			
	Field emissions (related to nutrient cycle)	0.72	0.92
	Field emissions (related to peat drainage)	0.77	2.36
	Indirect Land Use Changes (iLUC)	0.49	0.62
	Material inputs: fertiliser, pesticides, capital goods etc.	0.33	0.21
	Energy	0.07	0.08
	Other (transport, waste treatment, assets and services)	0.20	0.27
	Total crop cultivation stage	**2.58**	**4.46**
Palm oil mill			
	POME treatment	1.19	1.51
	Energy inputs	−0.03	−0.06
	Other (transport, waste treatment, assets and services)	0.17	0.18
	By-product: kernel	−0.43	−0.70
	By-product: energy and EFB to field application	−0.04	−0.04
	HCV nature conservation	−0.01	0.00
	Total palm oil mill stage	**0.85**	**0.89**
Refinery			
	Materials: chemicals, water etc.	0.02	0.02
	Energy	0.03	0.03
	Other (transport, waste treatment, assets and services)	0.02	0.02
	By-products: PFAD/PKFAD	−0.08	−0.08
	Total refinery stage	**−0.01**	**−0.01**
All stages			
Total Result with iLUC (default)		**3.41**	**5.34**
Total Result without iLUC		**3.03**	**4.84**

Fatty Acid Distillate (PFAD) and Palm Kernel Fatty Acid Distillate (PKFAD). The major cause of GHG emissions in palm oil refining is energy use.

3.3. Contribution analysis: global warming (attributional)

Table 6 shows the contribution analysis for global warming in attributional modelling, including the LUC emissions. As for the consequential results, the attributional results show that the cultivation stage is the major source of GHG emissions, followed by the palm oil milling stage. In the cultivation stage, the largest source of GHG emissions is peatland drainage for non-certified and LUC emissions for RSPO certified. The cultivation stage is where the largest share of emission reduction can be observed, also in the attributional results. In particular, lower GHG emissions are achieved by certified production due to lower share of oil palm on peat soil and lower LUC emissions. However, in the attributional model the lower LUC emissions are not due to higher certified yields, rather due to the historical uses of the land currently under oil palm cultivation, as described in section 2.2.

The contribution to the palm oil milling stage is largely due to methane emissions occurring during the treatment of POME, for the consequential model. However, in the attributional results there is no-negative contribution from the by-products, because

Table 6
Contribution analysis: GHG emissions in kg CO_2 eq. for 1 kg RBD palm oil in 2016 for the attributional model. The total results are shown with and without the LUC contribution at the bottom of the table.

Life Cycle Stage	Contribution	RSPO Certified	Non-certified
Oil crop cultivation			
	Field emissions (related to nutrient cycle)	0.48	0.49
	Field emissions (related to peat drainage)	0.65	1.98
	Land use changes CO_2	1.15	1.55
	Materials: Fertilisers, chemicals and packaging	0.13	0.08
	Energy	0.05	0.06
	Other (transport, waste treatment, assets and services)	0.00	0.01
	Total crop cultivation stage	**2.47**	**4.16**
Palm oil mill			
	POME treatment	0.91	1.13
	Energy	−0.03	−0.05
	Other (transport, waste treatment, assets and services)	0.05	0.05
	By-product: energy and EFB to field application	−0.01	−0.01
	Total palm oil mill stage	**0.92**	**1.13**
Refinery			
	Materials: chemicals and water	0.01	0.01
	Energy	0.03	0.03
	Other (transport, waste treatment, assets and services)	0.00	0.00
	Total refinery stage	0.04	0.04
All stages			
Total Result with iLUC (default)		**3.42**	5.32
Total Result without iLUC		**2.27**	**3.77**

the effect of by-products is not modelled as an avoided production. Instead, a share of the impact is allocated to the by-product, based on the product property used for allocation (mass allocation, in this case, as described in section 2.3). The palm oil refinery stage shows a small negative contribution to global warming due to the by-product PFAD/PKFAD. The largest contribution to GHG emission in the refinery stage is energy use. No-difference can be detected between certified and non-certified palm oil refining. This is also valid for nature occupation and respiratory inorganic results in the attributional models.

3.4. Summary of the results

Overall, the results indicate that the largest benefit of certified production is a significant reduction in terms of global warming and nature occupation impacts. A slightly higher impact is found for respiratory inorganics in RSPO certified, although in this case the difference between the two production systems is much smaller. The impact categories global warming, nature occupation and respiratory inorganic account for more than 90% of the single score result (Fig. 3 in SI, section 9), in both the consequential and attributional LCA model. The single score expresses the results with an aggregated indicator, a monetary value in Stepwise v1.7 (Weidema, 2009).

The environmental benefits of RSPO certified production are mainly due to four factors:

1) Higher yields: lower production inputs (fertilisers, fossil fuel etc.) and especially lower land use resources, and LUC effects, per unit of product
2) Lower share of cultivated peatland: avoiding palm cultivation in peatlands prevents CO_2 emission from peat drainage
3) Nature conservation: setting-aside high conservation value (HCV) land reduces GHG emissions and nature occupation
4) Higher share of biogas capture in POME treatment facilities: it reduces methane emissions from POME

Three out of four major benefits are related to the oil palm cultivation. The palm oil refinery stage shows a minor contribution to the results and it does not show significant differences between the two production systems under study. Since three impact categories account for more than 90% of the single score, it can be concluded that the certified production performs significantly better than the non-certified, in particular with respect to global warming. The nature occupation of certified production is also lower, but this result is associated with higher uncertainty. Although the global warming comparison is confirmed by thorough uncertainty analyses, such analyses do not test the sensitivity of the result to key modelling assumptions and value choices. Thus, a sensitivity analysis was also performed, described in section 3.5 below. The analysis confirmed the robustness of the comparative assertion formulated regarding global warming.

3.5. Sensitivity analysis

We evaluated the sensitivity of the LCA results to several methodological and value choices. The following issues, related to key data applied to the model, have been identified throughout the study:

- Carbon stock in land set-aside for nature conservation
- Share of nature conservation on waterlogged peat
- Peat soil's CO_2 emission factor
- Peat drainage depth for certified estates

Table 7 presents the result of the sensitivity analysis concerning the bullet points above. Overall, the table shows that the conclusion of the study does not change by modifying the analysed parameters, i.e. RSPO certified palm oil still perform better than non-certified palm oil in term of GHG emissions (kg CO_2 eq.). Doubling or halving the IPCC 2006, (chapter 2) values used to account for the carbon stock in the conserved nature, the change in RSPO certified result is below 2% (Table 7, A). The conservative assumption that no nature conservation activity occurs on waterlogged peat soil was adapted. Assuming that nature conservation occurring on peat soil would further lower the GHG contribution of RSPO certified production, as shown in Table 7, B. These two parameters do not affect the non-certified results because no-nature conservation activity is assumed to take place in non-certified production.

We tested the sensitivity of both the certified and non-certified GHG results to the peat soil emission factor (IPCC, 2014b). Assuming a higher emission factor (Table 7, C), the GHG would increase of approximately 23% for certified and 28% for non-certified production, respectively. Yet, the conclusion of the study would not be affected. The peat drainage depth is based on data from 17 out of 63 estates, where peat soil was reported in the RSPO annual assessment reports. Clearly, assuming a deeper peat drainage depth, as in Table 7, D - where the same depth is assumed for the compared production systems - would increase the GHG emission of certified production of approximately 6%. Yet, the certified production would still show a considerable reduction in GHG emission.

4. Conclusion

This paper presents a detailed LCA comparing average RSPO certified and non-certified palm oil. The LCA accounts for a large spectrum of impact categories, relying on a very detailed modelling of both production systems. The comparison aims to shed light on the benefits and trade-offs of RSPO certified palm oil. The objective is to assess the potential effects of consumer and corporate choice of palm oil and to help palm oil producers and suppliers to identify potential areas of improvements in the production systems. The model accounts for oil palm production, milling and refining, and includes several detailed sub models such as: nutrient balances, global dLUC and iLUC modelling, POME treatment and modelling of peat soil contribution to the impacts, among others. The consequential model reflects the consequences of the market's response to changes in production of certified or non-certified palm oil and the effects of the by-products on markets. The attributional model follows the approach of PalmGHG, a GHG accounting tool commissioned by RSPO. The severity of the impact categories were assessed based on the results of three distinct LCA weighting methods, all of which indicate the following as the most relevant impact categories: global warming, nature occupation and respiratory inorganic. Key findings of the consequential LCA are:

- 1 kg of RSPO certified RBD palm oil causes 3.41 (2.61–4.48) kg CO_2 eq. and non-certified 5.34 (3.34–8.16) kg CO_2 eq. Therefore, RSPO certified palm oil is associated with significantly lower GHG emissions (-36%) than non-certified production.
- RSPO certified palm oil nature occupation is 1.63 (1.30–2.05) PDF m^2*year/kg RBD palm oil while non-certified is 2.04 (1.12–3.34) PDF m^2*year/kg RBD palm oil. This means that RSPO certified palm oil causes lower nature occupation (−20%) than non-certified production.
- RSPO certified palm oil respiratory inorganics is 2.58 (1.93–4.17) $gPM_{2.5}$ eq./kg RBD palm oil, while for non-certified is 2.50 (1.55–4.22) $gPM_{2.5}$ eq./kg RBD palm oil. In other words, RSPO

Table 7
Overview of the sensitivity analyses performed for GHG emission's results (kg CO_2 eq.). Consequential model.

Investigated parameter	RSPO certified	Non-certified
A) Carbon stock in nature conservation		
Default: 165 t C/ha	3.41	5.34
Low carbon stock: 83 t C/ha	3.43	5.34
High carbon stock: 330 t C/ha	3.39	5.34
B) Nature conservation on waterlogged peat		
Default: 0% nature conservation on peat	3.41	5.34
10% nature conservation on peat	3.38	5.34
50% nature conservation on peat	3.25	5.34
100% nature conservation on peat	3.09	5.34
C) Peat soil CO_2 emission factor		
Default: peat CO_2 emission factor at 41.4 t CO_2/ha	3.41	5.34
High peat CO_2 emission factor at 84.5 t CO_2/ha	4.22	7.76
D) Peat drainage depth for certified estates		
Default: drainage depth at 57 cm for certified and 73 for non-certified	3.41	5.34
Drainage depth at 73 cm for both certified and non-certified	3.64	5.34

certified palm oil is associated with slightly higher respiratory inorganics (3%) than non-certified production.

Based on a thorough uncertainty analysis, only the comparison between the GHG emissions (global warming results) of the certified and non-certified RBD oil was deemed conclusive. The results for the remaining impact categories shall be interpreted as indicative.

Uncertainties are mainly associated with toxicity impacts, non-renewable energies, mineral extraction and ionizing radiation and ozone layer depletion due to insufficient inventory data. Concerning the carbon footprint, data on the share of oil palm on peat are rare, especially for certified production, and present a great range of variation in literature. The share of oil palm on peat is a key aspect in carbon footprinting of palm oil production. More accurate data on peat soil occupation from oil palm estates would improve the accuracy of the LCA results. Moreover, a streamlined and quality-assured data collection in the RSPO annual assessment reports would facilitate the quantification of the environmental effects of the certification.

CRediT authorship contribution statement

Michele De Rosa: Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:This work is financed through a crowdfunded project by parties, which may be affected by this research.None of them participated in the conceptualisation, design, data collection, analysis or preparation of the manuscript.

Acknowledgments

This study is the outcome of a crowdfunded project. The authors would like to thank the project partners for their financial support and for the valuable inputs provided throughout the development of the project. The partners are: Beiersdorf, DuPont Nutrition and Biosciences, ERASM, Ferrero, Novozymes, Golden Agri-Resources (PT Smart Tbk), and Unilever. The authors would also like to thank the anonymous reviewers for the constructive feedbacks.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.124045.

References

Arvidsson, R., Perssonb, S., Frölingb, M., Svanström, M., 2013. Life cycle assessment of hydrotreated vegetable oil from rape, oil palm and Jatropha. J. Clean. Prod. 19 (2–3), 129–137.

Bessou, C., Chase, L.D.C., Henson, I.E., Abdul-Manan, A.F.N., Milà i Canals, L., Agus, F., Sharma, M., Chin, M., 2014. Pilot application of PalmGHG, the Roundtable on Sustainable Palm Oil greenhouse gas calculator for oil palm products. J. Clean. Prod. 73, 136e145.

Brandi, C., Cabani, T., Hosang, C., Schirmbeck, S., Westermann, L., Wiese, H., 2013. Sustainability Certification in the Indonesian Palm Oil Sector. Benefits and Challenges for Smallholders. DIE Studies. German Development Institute, Bonn, ISBN 978-3-88985-581-7. ISSN 1860-0468.

Carlson, K.M., Heilmayra, R., Gibbsd, H.K., Noojipadyg, P., Burnsg, D.N., Mortonh, D.C., Walkerg, N.F., Paolij, G.D., kremenk, C., 2017. Effect of oil palm sustainability certification on deforestation and fire in Indonesia. Proc. Natl. Acad. Sci. U.S.A. 115 (1), 121–126. January 2, 2018.

Cattau, M.E., Marlier, M.E., DeFries, R., 2016. Effectiveness of Roundtable on Sustainable Palm Oil (RSPO) for reducing fires on oil palm concessions in Indonesia from 2012 to 2015. Environmentl Research Letters 11, 105007. https://doi.org/10.1088/1748-9326/11/10/105007.

Chase, L., Henson, I., Faizal, A., Abdul-Manan, N., Agus, F., Bessou, C., Milà i Canals, L., Sharma, M., 2012. Palm GHG – A Greeenhouse Gas Accounting Tool for Palm Oil Products. The Roundtable for Sustainable Palm Oil – RSPO, Kuala Lumpur, Malaysia. Accessed October 2017. https://www.rspo.org/file/PalmGHG%20Beta%20version%201.pdf.

Choo, Y.M., Muhamad, H., Hashim, Z., Vijaya, S., Puah, C.W., Tan, Y., 2011. Determination of GHG contributions by subsystems in the oil palm supply chain using the LCA approach. Int. J. Life Cycle Assess. 16 (7), 669–681.

De Rosa, M., Knudsen, M.T., Hermansen, J.E., 2016. A comparison of Land Use Change models: challenges and future developments. J. Clean. Prod. 113, 183–193.

Faostat, 2018. FAOSTAT Agriculture Data, Food and Agriculture Organisation of the United Nations (FAO). Rome. http://faostat.fao.org/. Accessed March 2017.

Gassler, B., Spiller, A., 2018. Is it all in the MIX? Consumer preferences for segregated and mass balance certified sustainable palm oil. J. Clean. Prod. 195, 21–31, 2018.

Hauschild, M., Potting, J., 2005. Spatial Differentiation in Life Cycle Impact Assessment - the EDIP2003 Methodology. Environmental News No. 80 2005. Danish Environmental Protection Agency, Copenhagen.

Hutabarat, S., Slingerland, M., Rietberg, P., Dries, L., 2018. Costs and benefits of certification of independent oil palm smallholders in Indonesia. Int. Food Agribus. Manag. Rev. 21 (6), 681–700.

IPCC, 2006. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan. Accessed November 2017. http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html.

IPCC, 2014a. In: Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., Troxler, T.G. (Eds.), 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. IPCC, Switzerland. Accessed August 2014. http://www.ipcc-nggip.iges.or.jp/public/wetlands/pdf/Wetlands_Supplement_Entire_Report.pdf.

IPCC, 2014b. In: Pachauri, R.K., Meyer, L.A. (Eds.), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland. Accessed August 2017. https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_All_Topics.pdf.

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., Rosenbaum, R., 2003. Impact 2002+: a new life cycle impact assessment methodology. Int. J. Life Cycle Assess. 8 (6), 324–330.

Lam, M.K., Lee, K.T., Rahmanmohamed, A., 2009. Life cycle assessment for the

production of biodiesel: a case study in Malaysia for palm oil versus jatropha oil. Biofuels, Bioproducts and Biorefining 3 (6), 601–612.
Ma, A.N., Choo, Y.M., Toh, T.S., Chua, N.S., 2007. Renewable energy from palm oil industry. Not published. Updated version of chapter 17. In: Singh, G., Huan, L.K., Leng, T., Kow, D.L. (Eds.), Oil Palm and the Environment – A Malaysian Perspective. Malaysian Oil Palm Growers Council, Kuala Lumpu, 1999.
Meijide, A., de la Rua, C., Guillaume, T., et al., 2020. Measured greenhouse gas budgets challenge emission savings from palm-oil biodiesel. Nat. Commun. 11.
Merciai, S., Schmidt, J., 2017a. Methodology for the construction of global multi-regional hybrid supply and use tables for the EXIOBASE v3 database. J. Ind. Ecol. 22 (3), 516–531.
Merciai, S., Schmidt, J., 2017b. Land use change and electricity models in a multi-regional hybrid input output framework. In: Paper 25th IIOA Conference in Atlantic City, 19-23 June 2017, USA.
Morgans, C.L., Meijaard, E., Santika, T., Law, E., Budiharta, S., Ancrenaz, M., Wilson, K.A., 2018. Evaluating the effectiveness of palm oil certification in delivering multiple sustainability objectives. Environ. Res. Lett. 13, 064032, 2018.
PAS2050, 2011. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. British Standard (BSI) (ISBN 978 0 580 71382 8).
Puah, C.W., Choo, Y.M., Ong, S.H., 2013. Production of Palm Oil with Methane Avoidance at Palm Oil Mill: A Case Study of Cradle-To-Gate Life Cycle Assessment.
RSPO, 2017. Principles and criteria assessment progress reports. RSPO webpage. Accessed December 2017. https://www.rspo.org/certification/principles-and-criteria-assessment-progress.
RSPO, 2018. Certification in numbers. Roundtable on sustainable palm oil (RSPO). Accessed October 2017. http://www.rspo.org/about/impacts.
Saswattecha, K., Kroeze, C., Jawjit, W., Hein, L., 2015. Assessing the environmental impact of palm oil produced in Thailand. J. Clean. Prod. 100, 150–169.
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 accessed March 2018. http://lca-net.com/p/2742.
Schmidt, J., 2008. Life Cycle Assessment of Palm Oil at United Plantations Berhad. United Plantations Berhad, Teluk Intan, Malaysia.
Schmidt, J., 2010. Comparative life cycle assessment of rapeseed oil and palm oil. Int. J. Life Cycle Assess. 15 (2), 183–197.
Schmidt, J., 2015a. Life cycle assessment of five vegetable oils. J. Clean. Prod. 87, 130–138.
Schmidt, J., 2015b. Nature conservation in life cycle assessment – new method and case study with the palm oil industry. In: Extended Abstract for Presentation at the SETAC2015, Barcelona 3-7 May 2015. Accessed May 2018. http://lca-net.com/p/1818.
Schmidt, J., 2016. Life cycle assessment of palm oil – investigating nature conservation and other GHG mitigation options. In: Paper Presented at the 5th International Conference on Oil Palm and Environment (ICOPE), 2016. May 2018. http://lca-net.com/p/2479.
Schmidt, J., 2017. Life Cycle Assessment of Palm Oil at United Plantations Berhad 2017, Results for 2004-2016. United Plantations Berhad, Teluk Intan, Malaysia. Accessed March 2018. http://lca-net.com/p/2739.
Schmidt, J., Dalgaard, R., 2012. National and Farm Level Carbon Footprint of Milk – Methodology and Results for Danish and Swedish Milk 2005 at Farm Gate. Arla Foods, Aarhus, Denmark. http://lca-net.com/p/220.
Schmidt, J., De Rosa, M., 2018. Enhancing land Use change modelling with IO data. In: Presentation at the SETAC Europe 28th Annual Meeting, Rome 13-17 May 2018. Accessed June 2018. http://lca-net.com/p/3036.
Schmidt, J., de Saxcé, M., 2016. Arla Foods Environmental Profit and Loss Accounting 2014. Environmental Project No. 1860, 2016. Danish Environmental Protection Agency, Copenhagen. http://lca-net.com/p/2343.
Schmidt, J., Weidema, B.P., Brandão, M., 2015. A framework for modelling indirect land use changes in life cycle assessment. J. Clean. Prod. 99, 230–238.
Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J., Theurl, M.C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.H., de Koning, A., Tukker, A., 2018. Exiobase 3: developing a time series of detailed environmentally extended multi-regional input-output tables. J. Ind. Ecol. 22 (3), 502–515.
Tan, Y.A., Muhammad, H., Hashim, Z., Vijaya, S., Puah, C.W., Let, C.C., Ngan, M.A., May, C.Y., 2010. Life cycle assessment of refined palm oil production and fractionation (part 4). Journal of Oil Palm Research 22 (December), 913–926.
UPRD, 2007. Data provided by the United Plantations Research Department, Director of Research Dr. Gurmit Singh. United Plantations Research Department, Teluk Intan, Malaysia.
Vijaya, S., Ma, A.N., Choo, Y.M., Nik Meriam, N.S., 2008. Life cycle inventory of the production of crude palm oil - a gate to gate case study of 12 palm oil mills. Journal of Oil Palm Research (20), 484–494. June.
Weidema, B., 2003. Market Information in Life Cycle Assessment, Environmental Project No. 863. Danish Environmental Protection Agency, Copenhagen.
Weidema, B.P., 2009. Using the budget constraint to monetarise impact assessment results. Ecol. Econ. 68 (6), 1591–1598.
Weidema, B.P., Wesnæs, M., Hermansen, J., Kristensen, T., Halberg, N., 2008. Environmental improvement potentials of meat and dairy products. In: Eder, P., Delgado, L. (Eds.), Sevilla: Institute for Prospective Technological Studies. (EUR 23491 EN).
Wicke, B., Sikkema, R., Dornburg, V., Faaij, A., 2011. Exploring land use changes and the role of palm oil production in Indonesia and Malaysia. Land Use Pol. 28, 193–206. https://doi.org/10.1016/j.landusepol.2010.06.001, 2011.
Woittiez, L.S., van Wijk, M.T., Slingerland, M., van Noordwijk, M., Gillera, K.E., 2017. Yield gaps in oil palm: a quantitative review of contributing factors. Eur. J. Agron. 83, 57–77, 2017.
Yee, K.F., Tan, K.T., Abdullah, A.Z., Lee, K.T., 2009. Life cycle assessment of palm biodiesel: revealing facts and benefits for sustainability. Appl. Energy 86 (Suppl. 1), S189–S196.
Yusoff, S., Hansen, S.B., 2007. Feasibility study of performing an life cycle assessment on crude palm oil production in Malaysia. Int. J. Life Cycle Assess. 12 (1), 50–58.