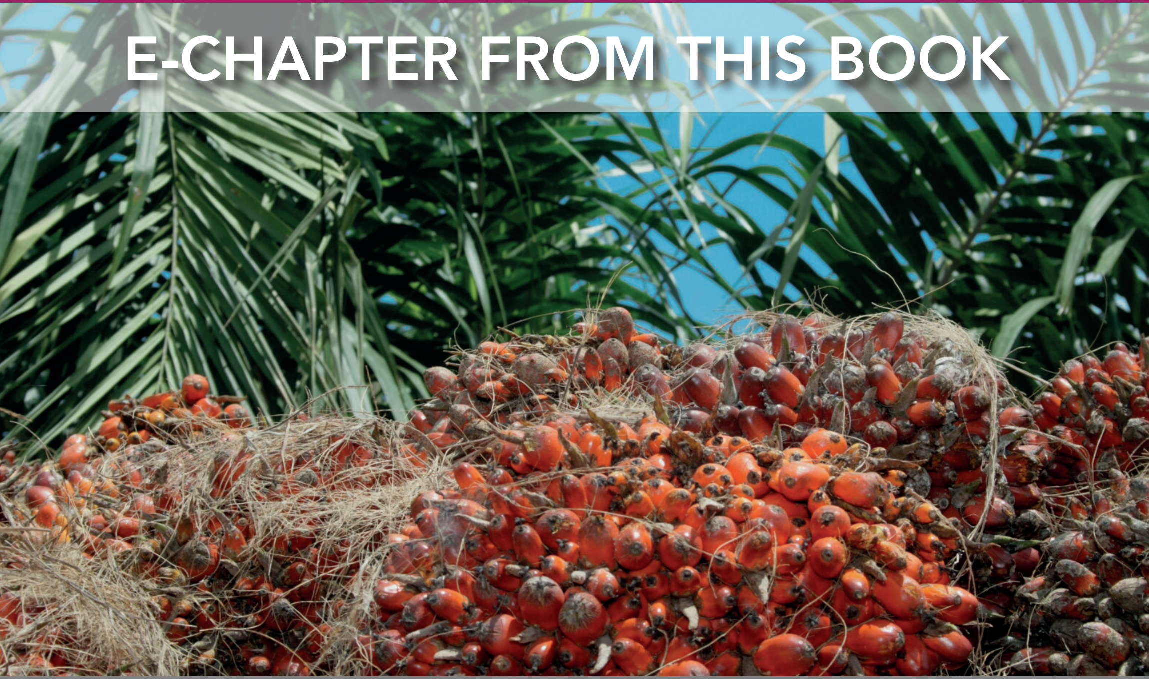
BURLEIGH DODDS SERIES IN AGRICULTURAL SCIENCE

Achieving sustainable cultivation of oil palm

Volume 2: Diseases, pests, quality and sustainability

Edited by Professor Alain Rival
Center for International Cooperation in Agricultural Research for Development (CIRAD), France

E-CHAPTER FROM THIS BOOK



burleigh dodds
SCIENCE PUBLISHING

Life cycle assessments of oil palm products

Cécile Bessou, CIRAD, France; Heinz Stichnothe, Thünen Institute of Agricultural Technology, Germany; Amir F. N. Abdul-Manan, Saudi Aramco, Saudi Arabia; and Shabbir Gheewala, King Mongkut's University of Technology Thonburi, Thailand

1 Introduction

Quantifying environmental impact is becoming a requirement for agricultural commodity chains. Given the various pollution risks (e.g. eutrophication, global warming, ecotoxicity), and the opportunities to mitigate those risks (e.g. increasing nitrogen utilisation efficiency, nutrient recycling, carbon sequestration to reduce global warming), it is crucial to apply models and tools that allow for the identification of best practices in order to reduce the environmental impact of agriculture. It is particularly crucial for increasingly important crops such as oil palm that may impact the environment both during cultivation and due to land use change (LUC) for new plantations.

Over the last 20 years, the area of oil palm plantations has increased drastically. The total productive area reached 18.7 Mha in 2014 compared with 7.5 Mha in 1994, according to FAO[1]. This expansion was particularly remarkable in Indonesia and Malaysia, where the productive areas increased by a factor of two and seven, respectively, over the same time period[1]. Oil palms have the highest oil yield per hectare and palm oil can be used for various purposes. Given the growth of the world's population and the consequent growing demand for food and fuel, the increase in oil palm production is expected to continue, albeit at a slower pace than over the last decade (OECD and FAO, 2013). This increase is also expected to extend to other developing or emerging countries in Africa and Latin

1. http://www.fao.org/faostat consulted on 28 January 2017.

http://dx.doi.org/10.19103/AS.2017.0018.38

Chapter taken from: Rival, A. (ed.), *Achieving sustainable cultivation of oil palm Volume 2: Diseases, pests, quality and sustainability,* Burleigh Dodds Science Publishing, Cambridge, UK, 2018, (ISBN: 978 1 78676 108 8; www.bdspublishing.com)

America, where governments are promoting palm oil development in order to alleviate poverty and increase energy security (Pirker et al., 2016).

Over the last decade, life cycle assessment (LCA) has become the worldwide standard for reporting environmental product declarations (ISO 14025 Type III Environmental Declarations) and the baseline model behind various greenhouse gas (GHG) calculators (BIOGRACE[2], GREET[3], CCaLC[4]) and GHG certification schemes (European Commission, 2009, BSI 2008, ISCC[5]). Initially developed in the 1980s to assess the environmental impact of industrial products and services, such as packaging, life cycle approaches were rapidly applied in increasingly diverse contexts urging for the development of harmonised guidelines. In the 2000s, the framework and methodological aspects of LCA were standardised through international norms (ISO 14040 series 2000–2006), particularly through the structuring and formalisation work led by SETAC[6]. LCA has been applied to agricultural commodities primarily for the purpose of assessing various environmental impacts and trade-offs, for example, bioenergy chains compared with fossil ones. Adaptation of the LCA framework to agricultural products requires scientific and methodological developments that are still ongoing and represent specific challenges for tropical perennial crops such as oil palm (Basset-Mens et al., 2010; Bessou et al., 2013; Bellon-Maurel et al., 2013).

In this chapter, first we briefly present LCA modelling principles and methodological steps, and then review the results from published LCA and GHG assessments of palm oil products. Finally, we discuss the available information on the environmental impact of palm oil and remaining challenges regarding LCA development and applications to palm oil products.

2 LCA principles and methodology

LCA is based on two fundamental principles. Firstly, environmental burdens are gathered throughout the commodity chain or 'life cycle', from raw material extraction ('cradle') to the end-of-life of products or services ('grave'). Secondly, environmental impacts are quantified with respect to a functional unit (FU), either a product quantity (one kilo, one car, etc.) or a usage or service [hours utilised, tonne-kilometre (tkm), etc.]. The entire life cycle of a product has to be taken into account so that local environmental improvements at one production stage or in one location do not result in a problem shifting to another stage or location (Jolliet et al., 2010). Similarly, the comparison of two or more products or services, based on the same FU, is paramount in order to identify all environmental impacts of every compared product, which enables decision-makers to avoid hidden problem shifting. Finally, LCA assesses environmental performance across numerous impact categories, such as climate change, acidification or ozone layer depletion. Such a multi-criteria approach does not focus on any one impact but rather pinpoints the relevant impacts and their origins at given production stages. This holistic approach enables identification of trade-offs and makes decision-making more transparent.

2. http://www.biograce.net/home consulted on 28 January 2017.
3. https://greet.es.anl.gov/consulted on 28 January 2017.
4. http://www.ccalc.org.uk/consulted on 28 January 2017.
5. http://www.iscc-system.org/consulted on 28 January 2017.
6. SETAC: Society of Environmental Toxicology and Chemistry, one of the most important international scientific organisations dealing with structural issues of life cycle assessment (Jolliet et al., 2010).

LCA employs a four-stage methodology (ISO 14040 series 2000–2006):

- definition of the objectives and boundaries of the system to be studied from the beginning to the end of the chain;
- inventory of mass and energy flows used within the system and those released into the environment;
- characterisation or modelling of impacts based on the inventory; and
- interpretation of the results.

Definition of the study objectives (stage 1) implies definition of the FU and the scope of the system processes to be assessed: for example, the LCA of FU = 1 t fresh fruit bunch (FFB) includes accounting for all burdens from all processes, from raw material extraction up to the harvest of FFB at the edge of the palm block, in the relative proportions needed to produce 1 t of FFB. The flows (resources used and substances emitted) are inventoried (stage 2) according to the technical specificities of the studied system. Effects of resource use and emissions generated are quantified and grouped into a limited number of impact categories (stage 3), which are expressed as problem-orientated indicators (global warming potential, eutrophication potential, etc.) or damage-orientated indicators (human health, biotic and abiotic resources, etc.). The respective indicators are calculated based on a linear model (Eq. 1):

$$I_P = \sum_{i}^{n} m_i . CF_{i,P} \qquad (1)$$

where:

I_p is the indicator for the potential impact *P*,

m_i is the mass of the substance *i* contributing to the potential impact *P*,

$CF_{i,P}$ is the characterisation factor for the contribution of substance *i* to the potential impact *P*.

This linear model – a simplification of actual environmental impact mechanisms – does not usually account for local medium sensitivity or threshold effects; hence, LCA impacts are potential and not actual impacts. The interpretation of results (stage 4) is achieved considering uncertainties related to all the previous steps. LCA allows for the identification of environmental impact hot spots, process impact contributions and potential trade-offs between impact categories or process stages.

For example, the impact on climate change is calculated by taking into account an inventory of all GHG emissions per unit product. The emissions are then aggregated into a single impact indicator (global warming potential or climate change) using IPCC's model, which characterises what happens to GHGs in the atmosphere and their relative contributions to the global greenhouse effect. Characterisation factors in the case of climate change are expressed in CO_2 equivalent (CO_{2e}) based on mass.

Despite the intuitive methodological stages and well-documented guidelines, LCA implementation poses some problems because of insufficient data or scientific knowledge, which gives rise to a number of uncertainties, notably when inventorying field emissions and characterising final impacts. Several characterisation methods exist that provide varying environmental profiles, that is, a set of potential impact indicators. In the following section, we review palm oil LCA results, which are available in the literature, without further discussion regarding the underlying issues for LCA implementation. The challenges for LCA implementation to oil palm products are then discussed in detail, that is, stage by stage, in Section 4.

3 Results of LCA applied to oil palm products

3.1 Oil palm LCA studies

Several full or partial LCAs of oil palm products have been published over the last 20 years, with a drastic increase in publication rate over the last ten years (Fig. 1). A review of the Web of Science 1975–2017 database provided 106 publications related to palm LCA, with a large proportion of the published LCA studies focusing on palm oil-based bioenergy. Energy Fuels is the top research field covered, concerning almost 40% of the literature (Fig. 2), and *Biomass & Bioenergy* and *Applied Energy* are among the top five journals (Fig. 3). These publications were notably motivated by the debate on potential net advantages of biofuel compared with their fossil fuel equivalents and the subsequent release of the European Directive on Renewables (2009/28/EC), which details sustainability criteria including minimum GHG savings compared with the use of

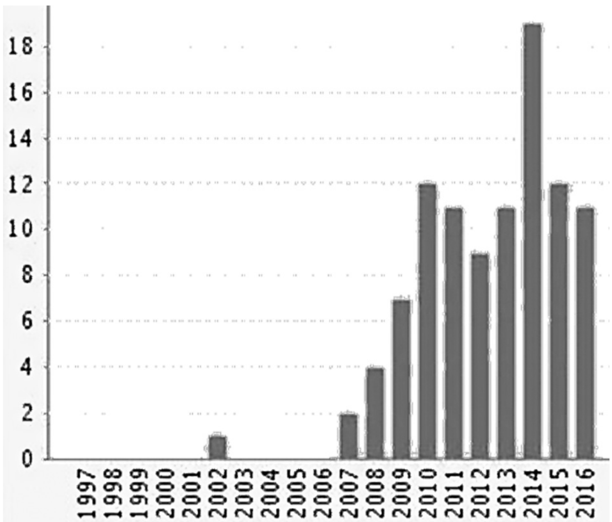


Figure 1 Published items during each year over the last 20 years from the Web of Science (February 2017). Searching terms were TOPIC: (palm NEAR/1 oil) *AND* TOPIC: (lca OR 'life cycle assessment' OR 'life cycle' OR 'lifecycle'); the total output included 248 items, some were then withdrawn due to a mistake in the Web of Science KeyWords Plus. The final item count was 106 publications.

fossil fuels. Hence, most of the published palm oil-based LCA studies focused on GHG (or climate change impact) and energy balance (or fossil resource depletion) (Manik and

Field: Web of Science Categories	Record Count	% of 106	Bar Chart
ENERGY FUELS	41	38.679 %	
ENVIRONMENTAL SCIENCES	38	35.849 %	
ENGINEERING ENVIRONMENTAL	29	27.358 %	
GREEN SUSTAINABLE SCIENCE TECHNOLOGY	21	19.811 %	
BIOTECHNOLOGY APPLIED MICROBIOLOGY	16	15.094 %	
ENGINEERING CHEMICAL	16	15.094 %	
FOOD SCIENCE TECHNOLOGY	12	11.321 %	
AGRICULTURAL ENGINEERING	11	10.377 %	
CHEMISTRY APPLIED	9	8.491 %	
CHEMISTRY PHYSICAL	6	5.660 %	

Figure 2 Published items classified according to their research topics, that is, Web of Science Categories.

Field: Source Titles	Record Count	% of 106	Bar Chart
INTERNATIONAL JOURNAL OF LIFE CYCLE ASSESSMENT	12	11.321 %	
JOURNAL OF CLEANER PRODUCTION	10	9.434 %	
JOURNAL OF OIL PALM RESEARCH	10	9.434 %	
BIOMASS BIOENERGY	8	7.547 %	
APPLIED ENERGY	6	5.660 %	
TENSIDE SURFACTANTS DETERGENTS	5	4.717 %	
RENEWABLE ENERGY	4	3.774 %	

Figure 3 Published items classified according to journal titles.

Halog, 2013; Bessou et al., 2013). A small number of published LCA have actually looked over the available panel of environmental impacts provided by LCA methodology. In the following sections, we first review environmental information on palm biofuel and then focus on palm oil LCA.

3.2 Environmental impact of palm oil-based bioenergy

Most LCA studies on palm oil-based bioenergy have been conducted in Malaysia and Thailand (with 29% and 12% of the total 106 recorded items, respectively); the few remaining predominantly cover Indonesia (more recent publications), Brazil, Colombia and Cameroon. The large majority of these studies assessed the cradle-to-grave (well-to-wheel) system boundary of palm methyl ester (PME), that is, including all processes from background input production (e.g. fertiliser manufacture) up to the vehicle tank, assuming total combustion or including engine efficiency to calculate final energy and GHG indicators.

The two main energy indicators commonly used are the Net Energy Ratio (NER = output/input) and the Net Energy Gain or Balance (output-input). Although the common LCA indicator for energy use is usually expressed in total used fossil resource equivalents, these indicators give an approximation of the environmental impact in terms of fossil resource depletion. Energy indicators may include or exclude co-products depending on the allocation ratios or whether system expansion was applied. Results vary greatly among studies (with a mean NER value of approximately 2.9) notably regarding yields, the handling of co-products, the inclusion or exclusion of capital goods (infrastructure) and discrepancies in terms of transport scenarios. Despite some differences, all studies highlight the great importance, in terms of energy costs, of both the agricultural production of palm oil feedstock and transesterification. The oil extraction stage at the mill shows low energy requirement in comparison due to the internal recycling of co-products for energy purposes. During the agricultural stage, the upstream production of fertilisers and fruit transport are the most energy-intensive steps. The upstream production of methanol is the main contributor to the energy costs of both industrial phases; however, if bioethanol replaced methanol, the NER could be improved up to ~3.6 (Papong et al., 2010).

GHG balances also vary greatly among studies and the main influencing factor is whether LUC is accounted for or not, as the type of previous land use determines the final GHG balance. The mean GHG balance (Fig. 4), accounting for various LUC scenarios, reaches 40 g CO_{2e}/MJ (9 g CO_{2e}/MJ without LUC), but is multiplied tenfold when peatland forest is converted to palm plantations (in the upper range of the min-max values). Net savings of GHG are possible when palms are planted on degraded lands or grasslands, and depend

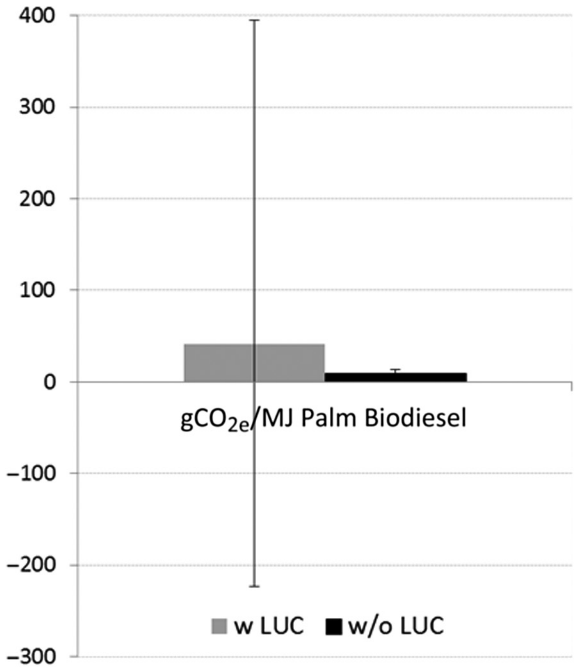


Figure 4 Comparison of LCA results on palm biodiesel (PME) based on data collected in Manik and Halog 2013: Mean GHG balance and minimum and maximum values with or without including land use change (LUC).

upon the existing carbon stock of previous land uses. Compared with fossil fuels, palm biodiesel is disadvantageous in terms of GHG if peatlands are converted or if tropical forests are cleared and the palm plantation lasts less than a century (Reinhardt et al., 2007). Otherwise, GHG savings ranging between 55% and 89%, compared with fossil diesel, can be achieved (Wicke et al., 2008; Pleanjai et al., 2009; Thamsiriroj and Murphy, 2009; Achten et al., 2010). Besides LUC, the main GHG sources are fertilisers (70–90% in field emissions, 10–30% emissions at the manufacturing site), methane emissions from the treatment of palm oil mill effluent (POME) when methane is not captured and the transesterification process (methanol and electricity) (Pleanjai et al., 2009; Thamsiriroj and Murphy, 2009; Achten et al., 2010; Choo et al., 2011).

Moreover, not all studies that include LUC use the same methodology to calculate GHG impact, which hinders any comparison. The major calculation parameters that vary are the carbon stocks accounted for (considered biomass compartments and amount of carbon released/stored) and the time frame for amortisation (Wicke et al., 2008; Hansen et al., 2014). Some of the studies that do not include LUC-related GHG emissions directly in the balance give information on the carbon debt or payback time[7] together with other results. This carbon debt varies between 8 and 169 years for palm biodiesel with mean and median values of 54 and 43 years, respectively (Fargione et al., 2008; Wicke et al., 2008; Pleanjai et al., 2009; Achten et al., 2010; de Souza et al., 2010; Harsono et al., 2012).

It is important to note that GHG accounting methodologies adopted by regulators within existing biofuel directives can also differ quite substantially. These regulations impose thresholds of minimum GHG emission reductions that biofuels must achieve, relative to fossil fuels, to show compliance. The adoption of a well-to-wheels LCA-based accounting perspective within regulations helps to ensure that such policies lead to actual reductions in global emissions as opposed to shifting the burden to a different economic sector or geographical region. Despite this, there are still many regulations today that continue to mandate the use of biofuels in transport without imposing a minimum GHG emissions reduction criterion, and therefore risk worsening global GHG emissions by forcing the substitution of fossil fuels with a biofuel that can potentially have higher emission intensity (Abdul-Manan et al., 2015).

Two of the most advanced biofuel regulations currently available are the EU's Renewable Energy Directive (RED) and the US Renewable Fuels Standard 2 (RFS2). The EU's RED requires biofuels to initially achieve a minimum reduction of 35% GHG emission, which is then increased to 50% for new plant installations operating from October 2015, and 60% for all biofuels effective from 2018 (European Commission, 2015). The US RFS2 stipulates that for a biofuel to be granted 'renewable fuel' status, it has to demonstrate a minimum GHG emission reduction of 20% (EPA, 2010). Although these regulations both adopt an LCA approach, the detailed GHG accounting methodologies they relied on are in reality very different, which prohibits any direct comparison.

An important distinction between the US RFS2 and the EU's RED is the way they take LUC into account. Presently, both regulations require the incorporation of direct LUC (dLUC) effects when accounting for biofuel GHG emissions. dLUC is the direct alteration of lands by the farmers themselves to produce biofuel crops. Indirect LUC (iLUC) is the unintended change of land use worldwide, typically from carbon-rich non-agricultural land to carbon-poor agricultural land, in response to economic pressures arising from the increasing

7. Years needed to recover the carbon loss due to LUC based on the annual GHG savings allowed by biofuel when displacing fossil fuel (Fargione et al., 2008; Gibbs et al., 2008).

demand for biofuels. iLUC requires a sophisticated economic modelling of global supply and demand of lands worldwide and how they respond to economic pressures. Today, both regulators acknowledge the importance of iLUC in terms of GHG emissions and its potential influence on reducing GHG from biofuels. The US RFS2 and the California Low Carbon Fuels Standard have included iLUC GHG penalties in their regulatory LCA, while policymakers in the EU opted for a virtual control of iLUC through limiting the maximum amount of conventional first-generation biofuels, like palm biodiesel, to be claimed under the EU's RED (Abdul-Manan, 2017), thus assuming that first-generation biofuel feedstocks are more likely to drive iLUC.

Using their respective methodologies, both the US RFS2 and the EU's RED have provided estimated reduction potentials of GHG emissions for palm biodiesel. Under the EU's RED framework, the GHG savings potential for typical palm biodiesel processes without and with methane capture are 36% (54 g CO_{2e}/MJ) and 62% (32 g CO_{2e}/MJ), respectively. These values exclude dLUC, which operators need to estimate to show compliance. However, according to the EU's RED sustainability criteria, no dLUC should occur after 1 January 2018 at the expense of lands with high carbon stock or high biodiversity value. In comparison, the GHG emissions reduction potential for palm biodiesel under RFS2 has been estimated to average approximately 17% (76 g CO_{2e}/MJ); this value includes both dLUC and iLUC. The large difference between the regulatory values in the EU and the United States are attributable to the methodological distinctions, including the treatment of LUC but also allocation, fossil references and so on.

Although the control of GHG emissions is a major issue in biofuel regulations, they also include further pass-or-fail sustainability criteria such as elements relating to the protection of land with high conservation value, prevention of habitat loss, fair and equitable treatment of workers and communities and so on. Only GHGs are quantified using an environmental LCA approach in spite of the much wider potential for the use of LCA techniques in biofuel sustainability impact assessments. The scientific literature details many studies which evaluate other environmental impacts of biofuel production (Achten et al., 2010; Puah et al., 2010; Arvidsson et al., 2011; Silalertruska and Gheewala, 2012). These studies concomitantly highlight the important contribution of the agricultural phase to other impact categories, for example, eutrophication and acidification potentials, carcinogens and respiratory inorganics. Fertilisers which leak into the environment contribute significantly to eutrophication and acidification. The use of biodiesel in engines also adds to the potential impact of eutrophication and acidification (Arvidsson et al., 2011), and contributes significantly to the impact category of respiratory inorganics (Puah et al., 2010).

3.3 Environmental impact of oil palm fruits and palm oil

LCA studies on palm fruits and oil are less numerous than those focusing on palm biodiesel, but they globally cover more impact categories and provide more details on the agricultural phase (Yusoff and Hansen, 2005; Reijnders and Huijbregts, 2008; Zulkifli et al., 2009; Vijaya et al., 2010; Schmidt, 2010; Stichnothe and Schuchardt, 2011). A few studies also focus on GHG assessment (Chuchuoy et al., 2009; Choo et al., 2011; Kaewmai et al., 2012; Bessou et al., 2014).

As expected, the main contributors to the GHG balance of crude palm oil (CPO) are the same as for palm biodiesel, except transesterification, with LUC and peat oxidation being critical and potentially overwhelming drivers (Schmidt, 2007; Reijnders and Huijbregts, 2008; Zulkifli et al., 2009), followed by methane emissions from the treatment of POME and fertiliser-related emissions, notably N_2O field emissions (Schmidt, 2007; Choo et al., 2011; Chase et al., 2012; Bessou et al., 2014). Nevertheless, the impact of POME can be significantly reduced if biogas is captured at the mill level (Chavalparit et al., 2006; Choo et al. 2011; Bessou et al., 2014; Harsono et al., 2014) or, to a lesser extent, if raw or partially treated POME are injected into a composting process for organic residues (Singh et al., 2010; Stichnothe and Schuchardt, 2010).

In a pilot application of palm GHG (RSPO GHG calculator, Chase et al., 2012) on mills in Southeast Asia and Latin America, the average GHG balance was 1.67 t CO_{2e}/t CPO and ranged from −0.02 to +8.32 t CO_{2e}/t CPO (Bessou et al., 2014). Of the mills not supplied by a peat area, land clearing, POME methane emissions and fertiliser-related emissions accounted for 41–80%, 15–35% and 3–19% of total GHG emissions, respectively. The impact of fossil fuel use was not significant (0–5% and 0–2% of total emissions at the field and mill levels, respectively). Such a low impact was due to the low mechanisation level in the plantations and the recycling of numerous residues providing heat and power to operate the mill (with the potential production of excess electricity). Most field fuel use is dedicated to FFB transport; hence, the impact of fuel use may vary greatly according to FFB harvesting logistics.

Published GHG balances (or the climate change impact indicator) range between −0.55 and 24 t CO_{2e}/t CPO with median values around 1–2 t CO_{2e}/t CPO when LUC is applied to mixed previous land uses and less than 10% peatland, and methane is not captured (Reijnders and Huijbregts, 2008; Schmidt, 2010; Choo et al., 2011; Bessou et al., 2012).

Looking at the other impact categories, the agricultural phase remains the main contributor, except for human toxicity or respiratory inorganics impact categories, which are mainly caused by boiler emissions (Stichnothe and Schuchardt, 2011; Bessou et al., 2012). Mill emissions can also contribute to eutrophication which is driven by the emission of nitrogen and phosphorus compounds. The main eutrophication factors at the agricultural stage are nitrate leaching, and phosphorus and nitrate run-off. Other N-compound emissions also contribute to acidification and photochemical ozone impact categories. While palm oil generally performs worse than other oil crops on climate change impact, when LUC occurs and leads to carbon loss from previous land use (e.g. in the case of deforestation or peat oxidation), palm oil can perform better than rapeseed oil with regard to eutrophication, acidification, ozone depletion and photochemical ozone impacts when effective management is in place (Schmidt, 2010).

4 Challenges in building LCA of oil palm products

4.1 Issues at the Goal and Scope level

The Goal and Scope steps of the first stage of LCA are critical as they define the validity domain of the final outputs. The boundary of the studied system must be delineated in order to ensure that all potential environmental impacts linked to the investigated product or service are taken into account. At the same time, there might be trade-offs needed between an exhaustive system assessment and gathering representative and consistent data. Iterative adjustments from stage-to-stage are often needed to carry out a robust LCA.

Being a perennial crop, oil palms last for at least 25 years in the field, during which time the crop stand goes through different development phases. The whole life cycle of oil palms includes the nursery stage (three months in pre-nursery and nine months in the main nursery), the early growing stage of immature non-productive palms (2–3 years) in addition to the productive harvest period (Stichnothe et al., 2014). Palm trees older than 25–28 years old (depending on planting material and site conditions) are often too high for harvesting to be kept longer in the field. The early growing stages account for 10–15% of the entire plantation cycle. These long and partitioned cycles require specific management, which usually combines long-term management strategies and short- or medium-term adjustments. Moreover, it also implies complex and evolving interactions with the ecosystem, which can affect the potential performance of the crop and management efficacy. Nevertheless, in most published studies, only the productive area of the plantation and the associated FFB yield are considered. Given the potential significant contribution of the early stages and the variability in practices and performances throughout the long productive period, the modelling choices to account or not for the whole perennial cycle can influence LCA results (Bessou et al., 2016). Hence, when defining the goal and scope of an oil palm product LCA, attention should be paid to the whole perennial cycle in order to produce representative results. Considering the whole growing cycle is particularly relevant for nitrogen losses (Pardon et al., 2016a) and hence for the life cycle inventory (LCI).

Another peculiar aspect of perennial compared with annual crops is the potential importance of changes in carbon stocks (Mithraratne et al., 2008). Henson showed that mature oil palms on coastal soil in Malaysia generated a net carbon fixation of 11 t ha^{-1} y^{-1} based on the eddy covariance technique (Henson, 1999). This fixation rate varies depending on the plantation age and management, and it does not represent an actual net carbon fixation in the biosphere. Indeed, a large proportion of the assimilated carbon is exported to the oil mill (Melling et al., 2010).The temporary storage of carbon in oil palm stipes might improve the GHG balance of palm plantations (Lam et al., 2009), but there is no generally accepted method for quantifying temporary carbon storage (Levasseur et al., 2012). The most generally used and reproduced guidelines are those from IPCC (IPCC, 2006). Further guidelines developed on the same basis, such as PAS2050 (BSI, 2011) or the European Renewable Directive (European Commission, 2009), all consider potential carbon storage in biomass as long as it represents a stable stock at equilibrium for at least 20 or 25 years. The way stocks are calculated and changes are modelled varies considerably across methods and published studies. Whether or not oil palm plantations are a net sink or source of carbon depends on the soils, climate, cultivation and residue management practices; however, the history of the site, especially LUCs (Melling et al., 2005, Melling et al., 2010), may significantly affect the GHG balance of end products such as palm biodiesel (see Section 3.1). Defining if and how LUC should be included in the LCA is a crucial parameter in the goal and scope definition of the LCA of palm products.

4.2 Issues related to LCI data collection

Specific quantified LCI data, for example, history of LUCs, influence of plantation management practices, nitrogen budget of oil palms, residue treatment, etc., are frequently missing, which is a current issue in tropical crop LCA (Basset-Mens et al., 2010). In the oil palm sector, the lack of representative data is accentuated by the concomitant lack of detailed institutionalised agricultural census for certain key producing countries and the great diversity in oil palm practices observed in the field (Lee et al., 2014; Moulin et al., 2016). Current knowledge regarding the influence of different management practices on the plantation and/or the palm oil mills varies from fragmented to non-existent. Examples include nutrient management, water level management on peat soils, pest control, residue treatment (empty fruit bunches (EFB), POME and nutshells), energy efficiency in oil mills, to name just a few. This critical lack of data persists despite the recent growing number of LCA studies driven by environmental concerns notably due to the expansion of oil palm areas.

LUC and peat oxidation lead to severe damage to the environment in terms of both biodiversity loss and GHG emissions. The proper identification of LUCs, from the type and extent of land cover, and subsequent land use fluxes and related emissions is therefore critical. Assessing the impact of oil palm area expansion requires the identification of LUCs and LUC impacts, as well as the impact of oil palm land use, for example, the impact on soil or carbon sequestration. Impacts of land use and LUCs are highly sensitive to soil type and climate conditions so that site or region-specific assessment is required to adequately cover this aspect. The development of region-specific LCI methods is hampered by the lack of regional and site-specific data. Moreover, there is still a lack of consensus on the methodology to address LUC history, carbon stock accounting, fluxes and therefore a lack of adequate and representative site-specific data sets.

Over the past 20 years, 95% of the Indonesian palm oil production area has been located in Sumatra and Kalimantan, and palms have been increasingly cultivated on peatlands (Afriyanti et al., 2016). Tropical peatlands store a huge amount of carbon, roughly 7000 t C ha^{-1} in below-ground biomass (Moore et al., 2013) and are highly vulnerable to natural and human disturbance. Under normal weather conditions, peatland in Indonesia is almost entirely waterlogged, which must be drained via hydrological engineering prior to oil palm planting. The water level is the main control for GHG fluxes from tropical peat soils. Crouwenberg et al. (2010) calculated emissions of at least 9 t CO_2 ha^{-1} y^{-1} and considered that to be a conservative estimate, because the role of oxidation in subsidence and the increased bulk density of the uppermost drained peat layers are insufficiently quantified (Couwenberg et al., 2010). The decomposition of biomass due to the lowering of the water table levels also goes along with nitrous oxide emissions. Despite dedicated research (Melling et al., 2007; Jauhiainen et al., 2012a,b) and recent guidelines (IPCC, 2013), there is still considerable uncertainty on the impact of various water level management practices on peat emissions and on the various direct and indirect fluxes and impacts of peat cultivation; hence, LCI for oil palm plantations on peat soil are not comprehensive.

Nitrogen losses in agroecosystems are a major environmental and economic issue. Indeed, agroecosystems receive approximately 75% of the reactive nitrogen created by human activity (Galloway et al., 2008; Galloway et al., 2013). In oil palm plantations, nitrogen fertilisation is a common practice that is associated with water pollution risks and GHG emissions (Corley and Tinker, 2008; Choo et al., 2011; Comte et al., 2012), notably nitrous oxide, a very potent GHG[8]. Furthermore, fertilisers constitute 46–85% of plantation field costs (Caliman et al., 2001; Goh and Härdter, 2003; Silalertruksa et al., 2012). Oil palm plantations have three main peculiarities affecting nitrogen dynamics in a way that differs from other cropping systems: the long duration of the growing cycle, the marked spatial heterogeneity and the large internal fluxes and pools of nitrogen. Substantial losses of reactive nitrogen can occur during the immature phase, when palms are still young and legume cover is vigorous; as well as during the mature phase in areas with sparse or no soil cover; or where high amounts of organic and mineral fertilisers are applied (Pardon et al.,

8. Nitrous oxide has a global warming potential 298 times greater than carbon dioxide on the same mass basis (IPCC, 2007).

2016a). Pardon et al. investigated several models to estimate nitrogen losses of oil palm plantations; most of the models indicated substantial losses at the early growing stage of oil palms. On average, 31% of nitrogen losses occur during the immature growing phase (Pardon et al., 2016b), which is frequently not taken into account in an LCA of oil palm plantations (see Section 4.1). The greatest uncertainty involves the loss of nitrogen via the emission of gaseous nitrogen compounds (N_2O, NO_x, N_2, NH_3) (Pardon et al., 2016a). Reactive nitrogen emissions contribute to several environmental problems, such as climate change, eutrophication or acidification. The lack of precise estimation of the nitrogen compounds released into the environment thus causes a great deal of uncertainty in the associated impact categories, emphasising the need for representative and robust LCI data on nitrogen fluxes as far as possible.

The management of organic residues from palm oil mills is paramount to emission reduction and nutrient recycling (Stichnothe and Schuchardt, 2010, Kaewmai et al., 2013). Given the diversity of residues generated by the production of palm oil (EFB, fibres, shells, etc.) and their respective large amounts (e.g. POME), there are very diverse ways to reuse these products via various processes and potential impacts. One cubic metre of POME treated in conventional open ponds can generate up to 12 m^3 of methane emission, equivalent to approximately 200 kg CO_{2e}. Biogas production from improved POME treatment is associated with a highly favourable GHG budget (Bessou et al., 2014). A worst-case scenario is dumping EFB, causing GHG emissions equivalent to 1000 kg CO_{2e} t^{-1} (Stichnothe and Schuchardt, 2011; Langeveld et al., 2016). POME and EFB can also be co-composted, which can lead to emission reductions as well as benefits to soil quality (Stichnothe and Schuchardt, 2010). Indeed, EFB are generally applied back to the plantation to maintain soil fertility through increasing the organic matter content (Saletes, 2004, Carron et al., 2015). The application of palm oil mill residues back to the field may not only reduce GHG emissions but also preserve resources as it reduces the demand for mineral fertilisers. The impact of compost or EFB on soil quality, as well as upstream emissions during the various composting processes, are still poorly quantified. Further data collection is needed to better account for these practices within both LCI and life cycle impact assessment (LCIA).

4.3 Challenges in impact pathway characterisation

The development of several LCIA methodologies has created confusion partly due to differing results even for some midpoint or endpoint indicators. Several areas/indicators (soil property change, ecotoxicity, biodiversity, etc.) are still under development and consequently not fully ready for general use.

Land use causes various chemical, physical and biological changes to soil properties and functions such as life support or nutrient cycling. Despite recent developments by the LCA community (Milà i Canals et al., 2007; Oberholzer et al., 2012; Garrigues et al., 2013; Saad et al., 2013; Bos et al., 2016), there is currently no comprehensive impact assessment of the various branches of the cause–effect chains implemented in LCIA. In particular, impacts related to co-variations in the associated physico-chemical and biological soil properties and soil functions are hardly addressed in LCIA. Moreover, physical and chemical changes of surface and soil have further effects on flora and fauna and hence affect biodiversity within and above the soil. The accounting of land use and LUC impacts is critical for oil palms given the issue of area expansion and the peculiarities of oil palm as a perennial crop, that is, the long-term cultivation cycle with constant land cover and biomass accumulation, and the deep rooting system of the plant (see Section 4.1). In addition, practices related to the recycling of residues back to the field may also influence soil quality (see Section 4.2). Comprehensive impact pathways to relate the long-term trends and the influence of practices on the temporary storage of soil carbon, improvement of soil quality and protection from soil erosion are not currently part of the LCIA (Stichnothe and Schuchardt, 2011) as the existing level of knowledge impedes the modelling of all potential correlated processes and impacts. To design the best environmentally friendly scenarios of residues and global plantation management, the proper modelling of impact on soil is crucial.

The modelling of land use impacts on biodiversity is also considered a priority in LCA. Biodiversity can be considered at different levels, namely ecological diversity (ecosystems), population diversity (species) and genetic diversity (genes). The quantification is complex and many diverging approaches have been proposed in an expanding literature on the topic (Curran et al., 2016). Biodiversity loss can be linked to four midpoint indicators (land use, ecotoxicity, acidification and eutrophication) but also to the endpoint indicator 'Natural Environment'. Curran et al. (2016) evaluated the performance of 31 models to assess the biodiversity loss from both the LCA and the ecology/conservation literature. The authors concluded that there is room for improvement and suggested working on a 'consensus model' by the weighted averaging of existing information to complement future development (Curran et al., 2016). Currently, there is no agreed and harmonised approach which addresses how to quantify the spatially distinct environmental impacts of LUC in palm oil-producing countries.

Spatially explicit methods are needed in LCA in order to accurately quantify impacts of products and processes. Chaudhary et al. (2015) used the countryside species–area relationship to quantify regional species loss due to land occupation and transformation (Chaudhary et al., 2015; de Baan et al., 2015). These authors combined regional characterisation factors with vulnerable scores to calculate global characterisation factors. Oil palms grow in tropical areas and tropical biomes have higher characterisation factors than those of boreal biomes mainly because of their higher species richness per area.

Finally, dry peat soils are prone to subterranean fires, which smoulder and emit thick white smoke laden with hazardous particles (Goldstein, 2016). Such fires in Indonesia became an international health concern in 2015, enhanced by long and intense drought periods related to a severe El Niño episode occurring in the region; a similar catastrophe occurred in 1997. Such fires cause smog, haze and respiratory problems as far away as Malaysia, Singapore and the Philippines. Those were obviously extreme events that, by definition, have the potential to cause considerable health and other environmental impacts but whose occurrence is rare. The frequency, intensity and persistence of such extreme events are still important characteristics for deriving characterisation factors, for example, for human toxicity. Such information requires dedicated modelling work in combination with LUC and climate models.

4.4 The challenge of interpreting results

Results have to be discussed with respect to the particular goal and scope of the study, which in turn also define data requirements but also the limitation of the analysis. Describing the consequences of modelling choices, such as total or productive plantation area, LCI models (IPCC, crop model, etc.), time period (year, plantation cycle or several plantation cycles) considered and so on, is crucial, as all such factors can influence the results. The spatial dimension is given by the scope of the study, for example, a specific plantation, a particular region or national production. The obtained results are only valid for the system under investigation. Although this may seem obvious, results are frequently generalised without proper evidence.

Palm oil mills are multi-output systems and the difficulty is quantifying and identifying which product contributes to the emissions. System subdivision is not feasible as palm kernels cannot be obtained separately. System expansion is possible but difficult to interpret and the substitution method is prone to arbitrary choices for co-product substitutes, for example, can kernel meal be a substitute for soya meal or wheat? In attributional LCA, emissions can be allocated among the various products, for example, CPO, nuts or other downstream products such as palm kernel oil and palm kernel meal, while using physical (mass, energy content, nutrient content, etc.) or economic relationships. Obviously, all these choices will alter the results for a particular product (Wiloso et al., 2015). It is highly recommended to conduct a sensitivity analysis for the different options as well as an uncertainty analysis before discussing results. The epistemic uncertainty analysis is particularly crucial for LCI field emission models that are not well parameterised for tropical perennial crops such as oil palm, and for cause–effect processes, notably those related to soil functions, which are still not fully understood and modelled.

5 Oil palm LCA improvement tracks

5.1 The search for representative data sets

LCA studies of oil palm systems and their derived products are frequently restricted by data gaps. Consequently, the principal challenge is to build a consensus-based modelling framework, to gather regional- and management-specific inventory data and to define inventory models in order to estimate emissions and temporary carbon storage effects. Building a national LCI database for oil palm plantations and subsequent conversion processes would be a valuable asset.

Independent to the system boundaries studied, the agricultural phase, in particular fertiliser input, plays a key role in determining the final environmental profile. It is hence paramount to adjust fertiliser input to enhance productivity while limiting loss to the environment. To do so, there is an urgent requirement for adapted models (mechanistic or operational models) that allow for more precise estimation of field emissions linked to fertilisers. Indeed, the great majority of LCAs use IPCC emission factors to estimate nitrate leaching and run-off as well as ammoniac or nitrous oxide emissions. These emission factors are poorly calibrated for tropical regions (Bouwman et al. 2002a,b; Stehfest and Bouwman, 2006) and they do not take into account the specificities of perennial cropping cycles such as palm plantations. A recent review emphasised that the combined initial structure and long-term evolution of oil palm plantations induce specific spatio-temporal patterns in nitrogen fluxes that are poorly quantified and thus need further research. This review also highlighted that nitrogen losses through leaching and volatilisation may be important and all nitrogen gaseous losses remain unknown (Pardon et al., 2016). More field measurements are needed to establish more relevant emission factors.

Research projects are ongoing that will shed some light on ways to reduce uncertainty in the LCA results. Development work on other approaches, such as agro-ecological indicators, are complementary as they enable a better account of local conditions and practices to build up the LCA inventories. New knowledge and model developments are also expected to accurately account for the comprehensive role of organic fertilisers in soil quality and potential field emissions.

5.2 The need for comprehensive impact assessments

There are 13–18 impact category indicators in the current standard LCA methods (ILCD, ReCiPe; respectively). Nevertheless, a great proportion of published LCA studies on oil palm products solely focus on GHG and energy balances. Many LCA impact indicators need to be more widely explored across palm oil production systems such as the impacts of pesticides (e.g. paraquat or glyphosate) on terrestrial or freshwater ecotoxicity, or the impact of irrigation systems on water depletion (Nilsalab et al., 2016; Silalertruska et al., 2016). Given the important contribution of fertilisers to environmental impact during the agricultural phase, the eutrophication and acidification impacts related to nitrogen and phosphate inputs would also need to be further investigated. Several other environmental impact indicators (ecotoxicity, biodiversity, etc.) are still under development and consequently not ready for use.

The accounting of land use impacts on soil is critical for oil palm given i) the important challenge related to oil palm expansion and related LUCs and ii) the peculiarities of oil palm as a perennial compared with annual crops and due to the various and abundant recycled residues. Particular impacts related to co-variations in the associated physico-chemical and biological soil properties and soil functions are hardly addressed in LCIA due to limited knowledge. The impact of peat drainage on soil quality and causal relationship with increased risk of peat fires also need to be further investigated, and modelled within the LCA framework.

Finally, the limits of the linear globalised model may be overcome by developing regional characterisation factors that can be used to adapt the linear model to the sensitivity of the local environment. Such factors are particularly critical in the case of very local impacts that are more sensitive to changes in the immediate environment – such as eutrophication – or resources unequally distributed on the global scale, such as water in dryland areas. Such regional factors have not yet been highly developed in regions where palm plantations are established and in the context of LUC may affect the medium sensitivity during the transition phase in particular.

6 Conclusion

LCA is a very useful tool for assessing the environmental impacts of oil palm products as it helps to identify the hot spots across the whole commodity chain while avoiding hidden trade-offs between different environmental impacts. Studies show that the oil palm cultivation stage contributes to a major share of several impacts including climate change, acidification and eutrophication, though the palm milling stage can also release significant GHGs if wastewater is not properly managed. Palm mills also contribute significantly to toxicity effects due to the particulate emissions from boilers.

The assessment of GHGs that contribute to climate change has been widely carried out and a large contribution is from LUC and nitrogen fertiliser production and application. For palm LCAs, delineation of the system boundaries is critical to provide consistency to studies, which can be particularly confounded by the challenge of accurately defining and calculating the impacts from LUC and carbon stocks. This is in part linked to a lack of consensus on the methodologies for the calculation and also to the limited availability of robust and reliable inventory data on the history of LUCs, influence of plantation management practices, nitrogen budget of oil palms and residue treatment.

In the oil palm sector, the lack of representative data is accentuated by the great diversity in cultivation practices observed in the field. Currently, specific data and consequently knowledge on the influence of different management practices on the plantation and the palm oil mills are limited. The nitrogen dynamics of oil palm are complicated due to the long growing cycle, spatial heterogeneity and large internal fluxes and pools of nitrogen, which lead to great uncertainty in the assessment of climate change, acidification and eutrophication impacts. There is also a considerable lack of data on the various options of residue management which can affect the assessment results.

Significant challenges also remain when selecting impact assessment methods for characterising land use, biodiversity and including the effects of temporary carbon storage. Land use causes various chemical, physical and biological changes to soil properties and functions such as life support or nutrient cycling. There is currently no comprehensive impact assessment of the various branches of the cause–effect chains implemented in LCIA. In particular, impacts related to co-variations in the associated physico-chemical and biological soil properties and functions are insufficiently addressed. Moreover, physical and chemical changes of surface and soil have further effects on flora and fauna and hence affect biodiversity. Comprehensive impact pathways to relate long-term trends and the influence of practices on the temporary storage of soil carbon, improvement of soil quality and protection from soil erosion are not currently part of the LCIA. To design the best environmentally friendly scenarios of residues and global plantation management, correct modelling of impact on the soil is crucial.

To address the challenges of conducting palm LCAs, a consensus-based modelling framework is needed which can consistently define the inventory data needs for estimating emissions from fertiliser application and temporary carbon storage. Regionalised land use models need to be developed along with complementary agro-ecological indicators for better characterisation of the effects of oil palm cultivation. Finally, the obtained results have to be discussed with respect to the particular goal and scope of the study, including model, allocation and other methodological choices as well as data quality assessment, which when combined, define the validity domain of the results and hence the application limitation of the analysis. Such limitations should be estimated by scenario analysis. It is highly recommended to support the final interpretation of results by sensitivity and uncertainty analyses.

7 Where to look for further information

Key organisations for LCA development:

SETAC: http://www.setac.org/
UNEP SETAC Life Cycle Initiative: http://www.lifecycleinitiative.org/

LCA networks in Southeast Asia:

Indonesian LCA Network (ILCAN): http://www.ilcan.or.id/
Thai LCA Agri Food Asia Network: http://www.lcaagrifoodasia.org

LCA networks in Europe:

European Platform: http://eplca.jrc.ec.europa.eu/
French Environmental Lifecycle and Sustainable Assessment: http://www.elsa-lca.org/?lang=en
German LCA network: http://www.lcanet.de/en/

Dedicated journals and conferences:

International Journal of LCA: http://link.springer.com/journal/11367
Journal of Cleaner Production: https://www.journals.elsevier.com/journal-of-cleaner-production
Indonesian Journal of LCA and Sustainability: http://ijolcas.ilcan.or.id/index.php/IJoLCAS

Environmental Toxicology and Chemistry:

http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1552-8618

Integrated Environmental Assessment and Management:

http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1551-3793
LCA-Food conferences: http://lcafood2016.org/
SETAC Europe LCA Case Study Symposium: http://events.setac.eu/?contentid=179

8 References

Abdul-Manan, A. F. N., Baharuddin, A. and Chang, L. (2015). Application of theory-based evaluation for the critical analysis of national biofuel policy: A case study in Malaysia. *Evaluation and Program Planning*, 52: 39–49.

Abdul-Manan, A. F. N. (2017). Lifecycle GHG emissions of palm biodiesel: Unintended market effects negate direct benefits of the Malaysian Economic Transformation Plan (ETP). *Energy Policy*, 104: 56–65.

Achten, W. M. J., Vandenbempt, P., Almeida, J., et al. (2010) Life cycle assessment of a palm oil system with simultaneous production of biodiesel and cooking oil in Cameroon. *Environmental Science and Technology* 44: 4809–15. doi:10.1021/es100067p.

Afriyanti, D., Kroeze, C. and Saad, A. (2016). 'Indonesia palm oil production without deforestation and peat conversion by 2050'. *Science of the Total Environment* 557–558: 562–70.

Arvidsson, R., Persson, S., Fröling, M. and Svanström, M. (2011). Life cycle assessment of hydrotreated vegetable oil from rape, oil palm and Jatropha. *Journal of Cleaner Production* 19: 129–37. doi:10.1016/j.jclepro.2010.02.008.

Basset-Mens, C., Benoist, A., Bessou, C., Tran, T., Perret, S., Vayssières, J. and Wassenaar, T. (2010). Is LCA-based eco-labelling reasonable? The issue of tropical food products. In: *7th International Conference on Life Cycle Assessment in the Agri-Food Sector*.

Bellon-Maurel, V., Aissani, L., Bessou, C., Lardon, L., Loiseau, E., Risch, E., Roux, P. and Junqua, G. (2013). What scientific issues in Life Cycle Assessment applied to waste and biomass valorization? Editorial. *Waste Biomass Valorization* 4(2): 377–83.

Bessou, C., Vélu, A. and Caliman, J. P. (2012). LCA of palm oil in sumatra, comparison of cropping systems. In: *International Conference on Oil Palm and Environment (ICOPE 2012)*. Bali, Indonésie, 22–4 février 2012.

Bessou, C., Basset-Mens, C., Tran, T. and Benoist, A. (2013). LCA applied to perennial cropping systems: A review focused on the farm stage. *The International Journal of Life Cycle Assessment* 18(2): 340–61.

Bessou, C., Chase, L. D. C., Henson, I. E., et al. (2014). Pilot application of PalmGHG, the Roundtable on Sustainable Palm Oil greenhouse gas calculator for oil palm products. *Journal of Cleaner Production* 73: 136–45. doi:10.1016/j.jclepro.2013.12.008.

Bessou, C., Basset-Mens, C., Latunussa, C., Vélu, A., Heitz, H., Vannière, H. and Caliman, J.-P. (2016) Partial modeling of the perennial crop cycle misleads LCA results in two contrasted case studies. *The International Journal of Life Cycle Assessment* 21(3): 297–310.

Bos, U., Horn, R., Beck, T., Lindner, J.P. and Fischer, M. (2016). *LANCA® - Characterisation Factors for Life Cycle Impact Assessment, Version 2.0*. Fraunhofer-Verlag, Stuttgart, Fraunhofer.

Bouwman, A. F., Boumans, L. J. M. and Batjes, N. H. (2002a). Emissions of N_2O and NO from fertilized fields: Summary of available measurement data. *Global Biogeochemical Cycles* 16: 1058.

Bouwman, A. F., Boumans, L. J. M. and Batjes, N. H. (2002b). Modeling global annual N_2O and NO emissions from fertilized fields. *Global Biogeochemical Cycles* 16: 11. doi:10.1029/2001GB001812.

BSI (2011) *PAS2050: Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services*, British Standards Institution, London.

Caliman, J. P., Hardianto, J., Ng, M., et al. (2001). Strategy for fertilizer management during low commodity price. In: *Cutting-edge Technologies for Sustained Competitiveness: Proceedings of the 2001 PIPOC International Palm Oil Congress, Agriculture Conference, Kuala Lumpur, Malaysia, 20–22 August 2001*. Malaysian Palm Oil Board (MPOB), Kuala Lumpur, Malaysia, pp. 295–312.

Carron, M. P., Auriac, Q., Snoeck, D., Villenave, C., Blanchart, E., Ribeyre, F., Marichal, R., Darminto, M. and Caliman, J. P. (2015). Spatial heterogeneity of soil quality around mature oil palms receiving mineral fertilization. *European Journal of Soil Biology* 66: 24–31.

Chase, L. D. C., Henson, I. E., Abdul-Manan, A. F. N., Agus, F., Bessou, C., Mila i Canals, L. and Sharma, M. (2012). *The PalmGHG Calculator: The RSPO Greenhouse Gas Calculator for Oil Palm Products, Betaversion*. RSPO, Kuala Lumpur.

Chaudhary, A., Verones, F., de Baan, L. and Hellweg, S. (2015). Quantifying land use impacts on biodiversity: Combining species–area models and vulnerability indicators. *Environmental Science & Technology* 49(16): 9987–95.

Chavalparitm, O., Rulkensm, W. H., Molm, A. P. J. and Khaodhairm, S. (2006). Options for environmental sustainability of the crude palm oil industry in Thailand through enhancement of industrial ecosystems. *Environment, Development and Sustainability* 8: 271–87. doi:10.1007/s10668-005-9018-z.

Choo, Y. M., Muhamad, H., Hashim, Z., et al. (2011). Determination of GHG contributions by subsystems in the oil palm supply chain using the LCA approach. *The International Journal of Life Cycle Assessessment* 16:669–81. doi:10.1007/s11367-011-0303-9.

Chuchuoy, K., Paengjuntuek, W., Usubharatana, P. and Phungrassami, H. (2009). Preliminary study of Thailand carbon reduction label: A case study of crude palm oil production. *Europial Journal of Science Research* 34: 252–9.

Comte, I., Colin, F., Whalen, J. K., et al. (2012). Agricultural practices in oil palm plantations and their impact on hydrological changes, nutrient fluxes and water quality in Indonesia. In: D. L. Sparks, *Advances in Agronomy*. Elsevier, Newark, USA, pp. 71–124.

Corley, R. H. V. and Tinker, P. B. H. (2008). *The Oil Palm*. Fifth Edition. Blackwell Science Ltd, UK.

Couwenberg, J., Dommain, R. and Joosten, H. (2010) Greenhouse gas fluxes from tropical peatlands in south-east Asia. *Global Change Biology* 16(6): 1715–32.

Curran, M., Maia de Souza, D., Antón, A., Teixeira, R. F. M., Michelsen, O., Vidal-Legaz, B., Sala, S. and Milà i Canals, L. (2016) How well does LCA Model land use impacts on biodiversity?—a comparison with approaches from ecology and conservation. *Environmental Science & Technology* 50(6): 2782–95.

de Baan, L., Curran, M., Rondinini, C., Visconti, P., Hellweg, S. and Koellner, T. (2015). High resolution assessment of land use impacts on biodiversity in Life Cycle Assessment using species habitat suitability models. *Environmental Science & Technology*., 49(4) : 2237–44.

de Souza, S. P., Pacca, S., de Ávila, M. T. and Borges, J. L. B. (2010). Greenhouse gas emissions and energy balance of palm oil biofuel. *Renew Energy* 35:2552–61. doi:10.1016/j.renene.2010.03.028.

European Commission (2015). Directive (EU) 2015/1513 of the European Parliament and of the Council of 9 September 2015 amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable. *Official Journal of the European Union*.

EPA (2010). Part II Environmental Protection Agency. 40 CFR Part 80. Regulation of Fuels and Fuel Additives: Changes to Renewable Fuels Standard Program; Final Rule. National Archives and Records Administration, Washington.

European Commission (2009). Directive 2009/28/EC of the European parliament and of the council of 23 April 2009 on the promotion of the use of energy from renewable sources. *Official Journal of the European Union*, June 5th.

Fargione, J., Hill, J., Tilman, D., et al. (2008). Land clearing and the biofuel carbon debt. *Science* 319: 1235–8. doi:10.1126/science.1152747.

Galloway, J. N., Townsend, A. R., Erisman, J. W., et al. (2008). Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. *Science* 320: 889–92. doi:10.1126/science.1136674.

Galloway, J. N., Leach, A. M., Bleeker, A. and Erisman, J. W. (2013). A chronology of human understanding of the nitrogen cycle. *Philosophical Transactions of the Royal Society B: Biological Science* 368:20130120. doi:10.1098/rstb.2013.0120.

Garrigues, E., Corson, M., Angers, D., Werf, H. G. and Walter, C. (2013). Development of a soil compaction indicator in life cycle assessment. *The International Journal of Life Cycle Assessment* 18(7): 1316–24.

Gibbs, H. K., Johnston, M., Foley, J. A., Holloway, T., Monfreda, C., Ramankutty, N. and Zaks, D. (2008) Carbon payback times for crop-based biofuel expansion in the tropics: The effects of changing yield and technology. *Environemental Research Letters* 3(3): 034001. doi:10.1088/1748-9326/3/3/034001.

Goh K.-J. and Härdter R. (2003). General oil palm nutrition. In: F. Härdter (Ed.) *Oil Palm Manag Large Sustain Yields*. PPIPPIC-IPI, Singapore, pp. 191–230.

Goldstein, J. E. (2016). Knowing the subterranean: Land grabbing, oil palm, and divergent expertise in Indonesia's peat soil. *Environment and Planning A* 48(4): 754–70.

Hansen, S. B., Olsen, S. I. and Ujang, Z. (2014). Carbon balance impacts of land use changes related to the life cycle of Malaysian palm oil-derived biodiesel. *International Journal of Life Cycle Assessment* 19: 558–66. doi:10.1007/s11367-013-0672-3.

Harsono, S. S., Prochnow, A., Grundmann, P., et al. (2012). Energy balances and greenhouse gas emissions of palm oil biodiesel in Indonesia. *GCB Bioenergy* 4:213–28. doi:10.1111/j.1757-1707.2011.01118.x.

Harsono, S. S., Grundmann, P. and Soebronto, S. (2014). Anaerobic treatment of palm oil mill effluents: Potential contribution to net energy yield and reduction of greenhouse gas emissions from biodiesel production. *Journal of Cleaner Production* 64: 619–27. doi:10.1016/j.jclepro.2013.07.056.

Henson, I. E. (1999). Comparative ecophysiology of oil palm and tropical rain forest. In: *Oil Palm and the Environment*. Malaysian Oil Palm Growers' Council, Kuala Lumpur, Malaysia.

IPCC (2006). *Guidelines for National Greenhouse Gas Inventories*. Vol 4. Agriculture, Forestry and Other Land Use, WMO/UNEP. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.

IPCC (2007). Summary for Policymakers. In: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller (Eds) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. p. 18.

IPCC (2013). In: T. Hiraishi, T. Krug, K. Tanabe, N. Srivastava, J. Baasansuren, M. Fukuda and T. G. Troxler (Eds), *Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Intergovernmental Panel on Climate Change, Switzerland.

Jauhiainen, J., Hooijer, A. and Page, S. E. (2012a). Carbon dioxide emissions from an Acacia plantation on peatland in Sumatra, Indonesia. *Biogeosciences* 9(2): 617–30.

Jauhiainen, J., Silvennoinen, H., Hämäläinen, R., Kusin, K., Limin, S., Raison, R. J. and Vasander, H. (2012b). Nitrous oxide fluxes from tropical peat with different disturbance history and management. *Biogeosciences* 9(4): 1337–50.

Jolliet, O., Saadé, M., Crettaz, P. and Shaked, S. (2010). *Analyse du cycle de vie. Comprendre et réaliser un écobilan*. 2e édition. Presses Polytechniques et Universitaires Romandes, Lausanne, Suisse. ISBN 978-2-88074-886-9. 302p.

Kaewmai, R., H-Kittikun, A. and Musikavong, C. (2012). Greenhouse gas emissions of palm oil mills in Thailand. *International Journal of Greenhouse Gas Control* 11:141–51. doi:10.1016/j.ijggc.2012.08.006.

Kaewmai, R., H-Kittikun, A., Suksaroj, C. and Musikavong, C. (2013). Alternative technologies for the reduction of greenhouse gas emissions from palm oil mills in Thailand. *Environmental Science & Technology* 47 (21) : 12417–25.

Lam, M. K., Lee, K. T. and Mohamed, A. R. (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): 601–12.

Langeveld, J. W. A., Guisson, R. and Stichnothe, H. (2016). Mobilising Sustainable Supply Chains – Biogas Cases, IEA Bioenergy Task 43.

Lee, J. S. H., Abood, S., Ghazoul, J., Barus, B., Obidzinski, K. and Koh, L. P. (2014). Environmental impacts of large-scale oil palm enterprises exceed that of smallholdings in Indonesia. *Conservation Letters* 7(1): 25–33.

Levasseur, A., Lesage, P., Margni, M. and Samson, R. (2012). Biogenic carbon and temporary storage addressed with dynamic Life Cycle Assessment. *Journal of Industrial Ecology* 17(1): 117–28.

Manik, Y. and Halog, A. (2013). A meta-analytic review of life cycle assessment and flow analyses studies of palm oil biodiesel. *Integrated Environmental Assesessment Management* 9(1): 134–41.

Melling, L., Hatano, R. and Goh, K. J. (2005). Soil CO_2 flux from three ecosystems in tropical peatland of Sarawak, Malaysia. *Tellus Series B-Chemical and Physical Meteorology* 57(1): 1–11.

Melling, L., Hatano, R. and Goh, K. J. (2007). Nitrous oxide emissions from three ecosystems in tropical peatland of Sarawak, Malaysia. *Soil Science and Plant Nutrition* 53(6): 792–805.

Melling, L., Goh, K. J., Bouvais, C. and Hatano, R. (2010). Carbon flow and budget in a young mature oil palm agroecosystem on deep tropical peat. From: http://www.geog.le.ac.uk/carbopeat/media/pdf/yogyapapers/p43.pdf.

Milà i Canals, L., Romanyà, J. and Cowell, S. J. (2007). Method for assessing impacts on life support functions (LSF) related to the use of 'fertile land' in Life Cycle Assessment (LCA). *Journal of Cleaner Production* 15(15): 1426–40.

Mithraratne, N., McLaren, S. and Barber, A. (2008). Carbon footprinting for the Kiwifruit supply chain—report on methodology and scoping study. Landcare research Contract Report LC0708/156, prepared for New Zealand Ministry of Agriculture and Forestry, p 61.

Moore, S., Evans, C. D., Page, S. E., Garnett, M. H., Jones, T. G., Freeman, C., Hooijer, A., Wiltshire, A. J., Limin, S. H. and Gauci, V. (2013). Deep instability of deforested tropical peatlands revealed by fluvial organic carbon fluxes. *Nature* 493(7434): 660–3.

Moulin, M., Wohlfahrt, J., Caliman, J.-P. and Bessou, C. (2016). Deciphering agricultural practices and environmental impacts in palm oil plantations in Riau and Jambi provinces, Indonesia. *International Journal of Sustainable Development & World Ecology*: 1–12.

Nilsalab, P., Gheewala, S. H., Mungkung, R., Perret, S. R., Silalertruksa, T. and Bonnet, S. (2016). Water demand and stress from oil palm-based biodiesel production in Thailand. *The International Journal of Life Cycle Assessment* 1–12. Available at http://link.springer.com/10.1007/s11367-016-1213-7 (verified 6 March 2017).

Oberholzer, H.-R., Freiermuth Knuchel, R., Weisskopf, P. and Gaillard, G. (2012). A novel method for soil quality in life cycle assessment using several soil indicators. *Agronomy for Sustainable Development* 32(3): 639–49.

OECD, FAO (2013). *Oilseeds and Oilseed Products*. OECD-FAO Agricultural Outlook 2013. OECD Publishing, Paris.

Papong, S., Chom-In, T., Noksa-nga, S. and Malakul, P. (2010). Life cycle energy efficiency and potentials of biodiesel production from palm oil in Thailand. *Energy Policy* 38: 226–33. doi:10.1016/j.enpol.2009.09.009.

Pardon, L., Bessou, C., Nelson, P. N., Dubos, B., Ollivier, J., Marichal, R., Caliman, J.-P. and Gabrielle, B. (2016a). Key unknowns in nitrogen budget for oil palm plantations: A review. *Agronomy for Sustainable Development* 36(1): 1–21.

Pardon, L., Bessou, C., Saint-Geours, N., Gabrielle, B., Khasanah, N., Caliman, J.-P. and Nelson, P. N. (2016b) Quantifying nitrogen losses in oil palm plantations: Models and challenges. *Biogeosciences* 13(19): 5433–52.

Pirker, J., Mosnier, A., Kraxner, F., Havlík, P. and Obersteiner, M.. 2016. What are the limits to oil palm expansion? *Global Environment Change* 40: 73–81.

Pleanjai, S., Gheewala, S. H. and Garivait, S. (2009). Greenhouse gas emissions from the production and use of palm methyl ester in Thailand. *International Journal of Global Warming* 1:418–31.

Puah, C. W., Choo, Y. M. and Ma, A. N. (2010). Life cycle assessment for the production and use of palm biodiesel (part 5). *Journal of Oil Palm Research* 22.

Reijnders, L. and Huijbregts, M. A. J. (2008). Palm oil and the emission of carbon-based greenhouse gases. *Journal of Cleaner Production* 16: 477–82. doi:10.1016/j.jclepro.2006.07.054.

Reinhardt, G., et al. (2007). *Conclusive Evaluation of Studies Assessing the Environmental Impact of the Use of Palm Oil as a Bioenergy Carrier*. IFEU, Germany.

Saad, R., Koellner, T. and Margni, M. (2013). Land use impacts on freshwater regulation, erosion regulation, and water purification: A spatial approach for a global scale level'. *The International Journal of Life Cycle Assessment* 18(6): 1253–64.

Saletes, S., Caliman, J. P. and Raham, D. (2004). Study of mineral nutrient losses from oil palm empty fruit bunches during temporary storage. *Journal of Palm Oil Research* 16(1): 11–21.

Schmidt, J. H. (2007). Life assessment of rapeseed oil and palm oil. Ph.D. thesis, Part 3: Life cycle inventory of rapeseed oil. Aalborg University.

Schmidt, J. H. (2010). Comparative life cycle assessment of rapeseed oil and palm oil. *The International Journal of Life Cycle Assessessment* 15: 183–97. doi:10.1007/s11367-009-0142-0.

Silalertruksa, T. and Gheewala, S. H. (2012). Environmental sustainability assessment of palm biodiesel production in Thailand. *Energy* 43(1): 306–14.

Silalertruksa, T., Gheewala, S. H., Pongpat, P., Kaenchan, P., Permpool, N., Lecksiwilai, N. and Mungkung, R. (2016). Environmental sustainability of oil palm cultivation in different regions of Thailand: Greenhouse gases and water use impact. *Journal of Cleaner Production*. Available at http://linkinghub.elsevier.com/retrieve/pii/S0959652616319084 (verified 6 March 2017).

Silalertruksa, T., Bonnet, S. and Gheewala, S. H. (2012). Life cycle costing and externalities of palm oil biodiesel in Thailand. *Journal of Cleaner Production* 28: 225–32. doi:10.1016/j.jclepro.2011.07.022.

Singh, R., Ibrahim, M., Esa, N. and Iliyana, M. (2010). Composting of waste from palm oil mill: A sustainable waste management practice. *Reviews in Environmental Science and Biotechnology* 9(4): 331–44. doi:10.1007/s11157-010-9199-2.

Stehfest, E. and Bouwman, L. (2006). N_2O and NO emission from agricultural fields and soils under natural vegetation: Summarizing available measurement data and modeling of global annual emissions. *Nutrient Cycling Agroecosystems* 74: 207–28. doi: 10.1007/s10705-006-9000-7.

Stichnothe, H. and Schuchardt, F. (2010). Comparison of different treatment options for palm oil production waste on a life cycle basis. *The International Journal of Life Cycle Assessment* 15(9): 907–15.

Stichnothe, H. and Schuchardt, F. (2011). Life cycle assessment of two palm oil production systems. *Biomass Bioenergy* 35: 3976–84. doi:10.1016/j.biombioe.2011.06.001.

Stichnothe, H., Schuchardt, F. and Rahutomo, S. (2014). European renewable energy directive: Critical analysis of important default values and methods for calculating greenhouse gas (GHG) emissions of palm oil biodiesel. *The International Journal of Life Cycle Assessment* 19: 1294–304.

Thamsiriroj, T. and Murphy, J. D. (2009). Is it better to import palm oil from Thailand to produce biodiesel in Ireland than to produce biodiesel from indigenous Irish rape seed? *Applied Energy* 86: 595–604. doi:10.1016/j.apenergy.2008.07.010.

Vijaya, S., Choo, Y. M., Halimah, M., Zulkifli, H., Yew, A. T. and Puah, C. W. (2010). Life cycle assessment of the production of crude palm oil (part 3). *Journal of Oil Palm Research* 22, 895–903.

Wicke, B., Dornburg, V., Junginger, M. and Faaij, A. (2008). Different palm oil production systems for energy purposes and their greenhouse gas implications. *Biomass Bioenergy* 32: 1322–37. doi:10.1016/j.biombioe.2008.04.001.

Wiloso, E. I., Bessou, C. and Heijungs, R. (2015). Methodological issues in comparative life cycle assessment: Treatment options for empty fruit bunches in a palm oil system. *The International Journal of Life Cycle Assessment* 20(2): 204–16.

Yusoff, S. and Hansen, S. (2005). Feasibility study of performing an life cycle assessment on crude palm oil production in Malaysia (9 pp). *International Journal of Life Cycle Assessessment* 12: 5058. doi:10.1065/lca2005.08.226.

Zulkifli, H., Halimah, M., Mohd Basri, W. and Choo, Y. M. (2009). Life cycle assessment for FFB production. In: *PIPOC 2009 Palm oil - Balancing Ecologies with Economics*. Kuala Lumpur, Convention Center, Malaysia.