Challenges for Life Cycle Assessment of Palm Oil Production System

Heinz Stichnothe[a*] and Cécile Bessou[b]

[a]Thünen Institute of Agricultural Technology, Bundesallee 50, 38116 Braunschweig, Germany
[b] CIRAD, UPR Systèmes de pérennes, pôle ELSA, F-34398 Montpellier, France

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Abstract

Growing demand for palm oil is driven by increasing human population, income growth as well as biodiesel stimulation programs. Covering an area of over ten million ha in Indonesia, palm oil production is also one of the most important sources of crop residues while processing generates large amounts of wastewater. Cultivation and processing of this crop are considered as potentially large sources of emissions. Improving environmental impacts of the palm oil production can help to reduce existing emissions while increasing yield and generating surplus energy and farm income. However, area expansion for oil palm plantation is perceived as closely linked to illegal logging, deforestation and diminishing biodiversity. Apart from ensuring sustainable land use change, the use of residues is the most important criterion in ensuring sustainable palm oil. It is important to note that there are trade-offs (e.g. between maximizing bio energy production, reducing environmental impacts other than greenhouse gases (GHG), and sustaining soil fertility). Nitrogen (N) losses in palm oil production systems are a major environmental and economic issue. Unfortunately, there is little comprehensive knowledge on how to calculate N-budgets in oil palm plantation in order to optimize fertilization, taking into account N-leaching and N-gaseous emissions. Land use, soil-carbon, N-emissions and biodiversity are key aspects of life cycle assessment (LCA) of palm oil production systems and they pose a number of methodological questions.

Keywords: *Management practice; water level; land use; biodiversity*

[*] Corresponding author, Tel.: +49 531 596 4163; Fax: +49 531 596 4199
E-mail address : *heinz.stichnothe@thuenen.de*

1. INTRODUCTION

Growing demand for palm oil is driven by increasing human population, income growth as well as biodiesel stimulation programs, and the demand is likely to increase in coming years up to an added 12 Mha area by 2050[1], i.e. +64% compared to current surface area (18.7 Mha)[2]. Global production of palm oil have more than doubled since 2000[3, 4]. Malaysia and Indonesia produce approximately 87% of the global palm oil[2, 5]. Indonesia is the main palm oil producer and exporter. It exports approximately 70% of its palm oil and 87% of the domestic consumption is used as food[6]. The demand for palm oil and palm kernel oil is fast growing. The world population is currently estimated at 7 billion and will further increase to 8 billion in 2025 and to 9.6 billion by 2050. Total annual vegetable oil demand is predicted to double between 2010 and 2050, from 120 to 240 million metric tons. As for palm oil, total demand is projected to increase from the current level of 51 million tons to 75 million metric tons by 2050[7]. Matching the predicted demand can be achieved by area expansion and/or yield increase. In Malaysia only 0.6 million ha are available for additional oil palm plantations, while the Indonesian government's own land capability survey indicated that up to 24.5 million hectares are suitable for oil palm cultivation.

Demand for electricity is expected to triple between 2011 and 2035 in Indonesia. In the long-term, depleting oil resources may lead to dedicated oil palm plantations in producing countries to ensure national energy security. National regulation No. 25/2013 establishes a mandatory utilization framework in the transportation, industrial, commercial and power generation sectors for biodiesel, bioethanol and bio-oil from 2009 to 2025. Due to this regulation, Indonesian biodiesel consumption increased from 0.13 million liters in 2009 to 0.5 million in 2013 and is projected to reach more than 9 million liters in 2016[8].There is still a huge gap between national supply and demand for biodiesel through 2025.

Palm oil is the dominant estate crop and major contributor to economic development in some regions of Indonesia and Malaysia[9]. The cultivation and harvesting of oil palm is labor intensive, and provides a significant fraction of jobs in many rural areas, employing approximately 4 million Indonesia workers. Given the importance of palm oil to the national economy, the policy on renewable energy is closely linked with its development, particularly as a way to improve living standards and welfare in rural areas.

The oil palm is credited with its high oil yield per unit area, the average oil yield per hectare is 3.7 metric tons of palm oil compared to 0.6 metric tons rapeseed oil and 0.36 metric tons soya oil[10]. The major products from palm oil mills are palm oil, palm kernel oil and palm kernel meal. In addition, a number of residues streams are generated that are frequently considered and treated as waste rather than resources. The use of these residues is a very critical criterion in ensuring sustainable palm oil[11]. Residue management is one of the key factors for GHG emission reduction of the palm oil industry[12]. Reducing GHG emissions all along the production chain can help to reduce global impact, while generating additional energy and farm income at the local level.

Indonesia's plantation sector has come under further scrutiny in the 2010s in the wake of public campaigns led by some NGOs, like that of Greenpeace blaming palm oil for the destruction of forest and orangutan habitats, and later on in reaction to severe forest-burning in Sumatra that caused one of Southeast Asia's worst air-pollution crises, with record levels of smog blanketing neighboring Singapore and Malaysia. Area expansion for oil palm plantation is perceived as closely linked to illegal logging, deforestation, forest fires and biodiversity losses[7]. When replacing tropical forests, new palm plantations provoke the killing of endangered species, uprooting of local communities, and release of huge amounts of GHG[13]. More recently primary forests are protected, hence new palm oil plantation are installed on ï so called ï marginal land such as degraded land, riparian zones and peat land. Furthermore, the potential competition for palm oil between food, feedstock for chemicals and biodiesel applications has given way to a controversial world-wide debate[14-17].

Life Cycle Assessment (LCA) is a suitable approach to assess potential environmental impacts of a commodity chain, including impacts from land use and land use change up to those related to waste management. It allows for identifying improvement options along the whole chain but also trade-offs. Trade-offs may notably exist between maximizing production, reducing environmental impacts, and sustaining soil fertility. It is challenging to identify the best environmental option when conflicting aims should be fulfilled, particularly when it is difficult to get robust results due to persisting methodological challenges. This paper explores some of the most critical methodological challenges in LCA of palm oil production systems following the four steps of LCA, i.e. goal and scope, life cycle inventory, life cycle impact assessment and result interpretation.

2. METHODS

2.1. Goal and scope

Humanity faces a number of challenges at the same time, e.g. food supply for a growing population, reducing GHG to combat climate change, release of reactive nitrogen species, land use changes and loss of biodiversity to name just a few[18, 19]. Some of them are interrelated, e.g. loss of biodiversity is driven by invasive species, land use change, climate change, eutrophication and acidification[20].

The LCA framework allows assessing potential environmental impacts of product systems while taking into account various interventions and impact categories at a glance. This holistic approach is paramount when investigating those global challenges and the contribution of human interventions in the view of selecting best alternatives and reduce human impacts. However, in practice, many LCA studies focus on a reduced number of potential environmental due to various methodological and data constraints. In the case of palm oil, LCA studies frequently focus on the use for energy purposes, and hence on climate change and fossil resource depletion impacts.

Although these two are important, they are insufficient for quantifying other environmental pressures such as eutrophication, acidification, human health effects, etc.

Perennial crops such as oil palms accumulate carbon during their lifetime (25–30 years). Henson showed that mature oil palm on coastal soil in Malaysia caused a net carbon fixation of 11t ha^{-1} $year^{-1}$ based on the eddy covariance technique[21]. This fixation rate will vary depending on the plantation age and management and do not represent an actual net carbon fixation in the biosphere. Indeed, a large proportion of the assimilated carbon is exported to the oil mill[22]. The temporary storage of carbon in trunks might improve the GHG balance of palm plantations[23], but there is no generally accepted method to quantify temporary carbon storage[24]. Main used and reproduced guidelines are those from IPCC[25]. Further guidelines developed on the same basis, such as PAS2050 [26] or the European Renewable Directive[27], all consider potential carbon storage in biomass as long as it represents a stable stock at equilibrium for at least 20 years. However, the ways those stocks are calculated and stock changes modeled still greatly vary across methods and published studies. The accounting of soil organic matter and its potential contribution to several impact categories in LCA is the subject of ongoing discussions and development[28, 29]. Whether or not palm oil plantations are a net sink or source of carbon depends on the soils, climate, cultivation and residue management practices, but also on the history of the site especially land use changes[22, 30].

Frequently, only the productive area of the plantation, and the associated fresh fruit bunches (FFB) yield, is considered. However, practices and performances of a perennial cropping system evolve all over the crop cycle. The modeling choices to account or not for the whole perennial cycle influence LCA results[31]. LCA of perennial crop and products should hence account for the whole cycle through the collection of data representative for the different crop stages[32]. The whole life cycle of oil palms includes the nursery stage (3 month in pre-nursery and 9 month in main nursery) and the early growing stage of immature palms (2 – 3 years), in addition to the productive harvest period[33]. The early growing stages account for 10 – 15% of the entire plantation cycle. Considering the whole growing cycle is particularly relevant for nitrogen losses[34] and hence for the LCI.

2.2. Life Cycle Inventory (LCI)

Specific LCI data, e.g. 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[35]. The lack of representative data is accentuated by the concomitant lack of institutionalized detailed agricultural census in some main producing countries and the great diversity in oil palm practices observed in the field[36, 37]. Nevertheless, the available LCI data for oil palm systems has increased in the past decade with the growing number of LCA studies driven by environmental concerns notably due to oil palm area expansion. Land use change and peat oxidation lead to severe damage to the environment in terms of both biodiversity loss and GHG emissions. Several studies showed the critical impact of various land use change scenarios on the palm oil GHG[38,39]. A proper identification of land use changes, from which types of land and land cover and to which extent, and subsequent land use fluxes and related emissions is therefore very critical. Assessing the impact of oil palm area expansion requires being able to identify the land use changes and land use change impacts, as well as the impact of oil palm land use, e.g. the impact on soil or carbon sequestration. Impacts of land use and land use changes are highly sensitive to soil type and climate conditions so that site or regional-specific assessment is required to cover this aspect sufficiently. However, the development of regional-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 land use change history, carbon stock accounting, fluxes and therefore a lack of adequate and representative site-specific data sets.

In the past 20 years, 95% of the Indonesian oil palm production area was in Sumatra and Kalimantan and increasingly cultivated in peat lands[40]. Tropical peat land stores a huge amount of carbon, roughly 7000 tons Cha^{-1} in below-ground biomass[41] and are highly vulnerable to natural and human disturbances. Under normal weather conditions, peat land in Indonesia is almost entirely waterlogged. However, peat land must be drained through hydrological engineering for oil palm planting. The water level is the main control on greenhouse gas fluxes from tropical peat soils. Crouwenberg et al. calculate emissions of at least 9 t CO_2 $ha^{-1}a^{-1}$ and considered that as conservative estimate because the role of oxidation in subsidence and the increased bulk density of the uppermost drained peat layers are yet insufficiently quantified[42]. Jauhiainen et al. calculated an average minimum heterotrophic respiration emission rate of 80 t CO_2 ha^{-1} a^{-1} at an average water table depth of 0.8 m, in peat land with a thickness greater than 4 m, for a peat surface covered by vegetation and with limited fertilizer applied only in the first year after planting[43]. The decomposition of biomass due to the reduced water table goes along with nitrous oxide emissions. Melling have measured N_2O emissions between 1.1 and 5.2 kg N_2O ha^{-1} a^{-1} in different tropical ecosystem[44] and Jauhiainen 1.6 kg N_2O ha^{-1} a^{-1}on drained tropical peat soil[45]. CO_2 counts for more than 90% of GHG emissions from drained peat soils but there is still a considerable uncertainty concerning the impact of various water level management practices for GHG emissions[39].

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

Land use causes various chemical, physical and biological changes to soil properties and functions such as life support or nutrient cycling. The cause-effect chains from land use are shown in Fig. 1. Despite recent developments in the LCA community, there is not yet any comprehensive impact assessment of the various branches of the cause-effect chains implemented in LCIA[53-56]. Particularly impacts related to co-variations in the connected 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 as well as fauna and hence affect biodiversity within and above the soil. The accounting of land use impacts on soil is very critical for oil palms given the potential peculiarities of perennial crops compared to annual ones and given the various potential scenarios of palm oil mill residues reuse, including competitive ones such as the field application or burning of EFB or POME (i.e. flaring of POME methane). Residues of palm oil mills returned to the plantation may not only reduce GHG emissions but also preserve resources as it reduces the mineral fertilizer demand. In addition, the application of residues or residue products such as EFB or compost on palm oil plantations has further benefits. These include notably the temporary storage of soil carbon, improvement of soil quality and protection from soil erosion. These aspects are not currently part of the life cycle impact assessment[12] due to still limited knowledge in order to model all potential correlated processes and impacts. In order to design the best environmental friendly scenarios of residues and global plantation managements, a proper modeling of impact onto the soil is though crucial.

The management of residues from palm oil mills is paramount to emission reduction and nutrient recycling[48,49]. Particularly the GHG emission depends on the residue/waste management. The way residues are treated in LCA influences allocation choices and the environmental burden they carry along. Those choices further influence the final LCA results[50]. Given the diversity of residues generated from palm oil production (Empty Fruit Bunches (EFB), fibers, shells) and their great amounts (e.g. Palm Oil Mill Effluent (POME)), there exist very diverse ways to reuse these products including various processes and potential impacts. Biogas production from oil palm residues is associated with a very favorable GHG budget[39]. Closed tank digestion prevents spontaneous methane emissions from empty fruit bunch decomposition as well as commonly applied open POME ponds. One cubic meter of POME can cause up to 12 m³ methane emissions, equal to approximately 200 kg $CO_{2\text{-eq}}$. As worst case EFB is dumped which cause GHG-emissions equivalent to 1,000 kg $CO_{2\text{-eq}}t^{-1}$[8, 12]. POME and EFB can also be co-composted, which can lead to emission reductions as well as benefits to soil quality[49]. Indeed, EFB are generally applied back in the plantation in order to maintain soil fertility through increasing organic matter in fragile soil[51, 52]. However, the impacts of compost or EFB on the soil quality, as well as the upstream emissions during the composting process in dependence of different composting practices are still poorly quantified and further data collection is needed in order to better account for these practices within both LCI and LCIA.

2.3. Life Cycle Impact Assessment (LCIA)

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

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The modeling of land use impacts on biodiversity is considered a priority in LCA. Biodiversity can be considered at different levels, 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[57]. Some species are highly sensitive to habitat loss and live in only native habitats, while other species show partial or total tolerance to human-modified habitats; still other species even benefit from the conditions found in human-modified habitats. *For biodiversity, the species-diversity oriented Potentially Disappeared Fraction of species (PDF)-concept is seen as the only really operational concept among those investigated, integrating the potentially lost fraction of natural species over area and time*[58]. Biodiversity loss can be linked to four midpoint indicators (land use, ecotoxicity, acidification and eutrophication) but also to the endpoint indicator ñNatural Environmentò. For Natural Environment, the aim is to quantify the negative effects on the function and structure of natural ecosystems as a consequence of exposure to chemicals or physical interventions. It is proposed to focus endpoint modeling for the Natural Environment on the biodiversity of the exposed ecosystems and, more specifically, on the diversity within the ecosystem based on population diversity (i.e. diversity among species)[58].

Curran et al. evaluated the performance of 31 models for assessing the biodiversity loss from both the LCA and the ecology/conservation literature, they conclude that there is room for improvement and suggest working on a ñconsensus modelò by weighted averaging of existing information in order to complement future development[57]. Currently there is no agreed and harmonized approach how to quantify the spatially distinct environmental impacts of land use change in palm oil producing countries.

Spatially explicit methods are needed in life cycle assessment to accurately quantify impacts of products and processes. Chaudhary et al. use the country-side speciesī area relationship to quantify regional species loss due to land occupation and transformation[59,60]. They combine regional characterization factors with vulnerable scores to calculate global characterization factors. Oil palms grow in tropical areas and tropical biomes have higher characterization factors than those of boreal biomes mainly because of the higher species richness per area.

Finally, dry peat soils are prone to subterranean fire. Subterranean fires smolder, emitting thick white smoke laden with hazardous particles[61]. Such fires in Indonesia became an international health concern in 2013. A similar catastrophe had already happened in 1997 due to long dry period. They cause smog, haze and respiratory problems as far as Malaysia and Singapore. Those were obviously extreme events, that by definition, have the potential of high 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 characterization factors, e.g. for human toxicity. Such information requires dedicated modeling work in perspective with land use change prospective and climate models.

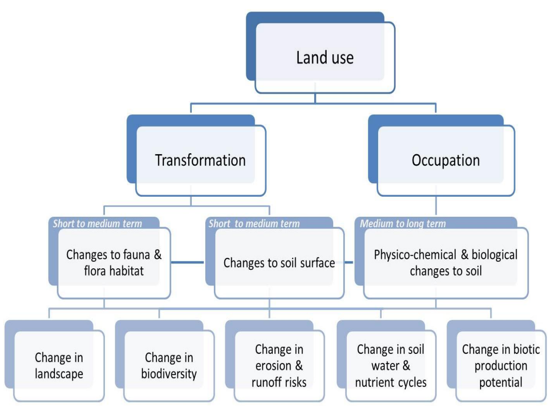

Fig.1. Simplified cause effect chain of land use (change)[1]

2.4. Results interpretation

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

Palm oil mills are multi-output systems and the question is which product gets how much of the emissions. System subdivision is hardly possible 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, e.g. does kernel meal substitute soya meal or wheat? Both is possible but the results would differ. Emissions can be allocated among the various products, e.g. crude palm oil, nuts or following products palm kernel oil and palm kernel meal using physical (mass, energy content, nutrient content, etc.) or economic allocation. Obviously also this choice will alter the results for a particular product. 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 parameterized 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 modeled.

3. CONCLUSIONS

LCA studies of oil palm systems and the derived products are frequently restricted by data gaps. Currently the knowledge on the influence of different management practices on the plantation and/or the palm oil mills reaches from fragmented to not existent. Examples are nutrient management, water level management on peat soils, pest control, residue treatment (EFB, POME and nutshells), energy efficiency in oil mills to name just a few.

Consequently, the foremost challenges are to build a consensus-based modeling framework, to gather regional- and management-specific inventory data and define inventory models in order to estimate emissions and temporary carbon storage effects. Building a national LCA database for oil palm plantation and subsequent conversion processes would be a valuable asset.

The accounting of land use impacts on soil is very critical for oil palms given i) the important challenge related to oil palm expansion and related land use changes and ii) the peculiarities of perennial crops compared to annual ones and due to the various and abundant recycled residues. Particularly impacts related to co-variations in the connected physico-chemical and biological soil properties and soil functions are hardly addressed in LCIA due to still limited knowledge. Several other environmental impact indicators (ecotoxicity, biodiversity, etc.) are still under development and consequently not fully matured.

Peat drainage is required in order to grow oil palm on peat soil. Managing the water level is a serious challenge and determines the release of GHG but also the risk for peat fires. The latter are extreme events and usually not considered in LCA. Given the experience of peat fires from 1997 and 2013 these events have tremendous environmental and health effects that should be analyzed by properly defined scenarios.

Spatially explicit methods and specific characterization factors for palm oil producing countries are needed in life cycle impact assessment to accurately quantify e.g. biodiversity impacts of processes related to and products derived from palm oil production systems. Moreover, current LCIA approaches hardly take rebound effects such as impact of climate change to biodiversity into account.

Results have to be discussed with respect to the particular goal and scope of the study, which also defines the limitation of the analysis. Rebound effects and extreme events might determine the robustness of the obtained results. Such kind of limitations should be estimated by scenario analysis. It is highly recommended to support the final interpretation of results by sensitivity and uncertainty analyses.

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