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Hansen, Sune Balle; Olsen, Stig Irving; Hauschild, Michael Zwicky; Wangel, Arne

Publication date:
2012

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

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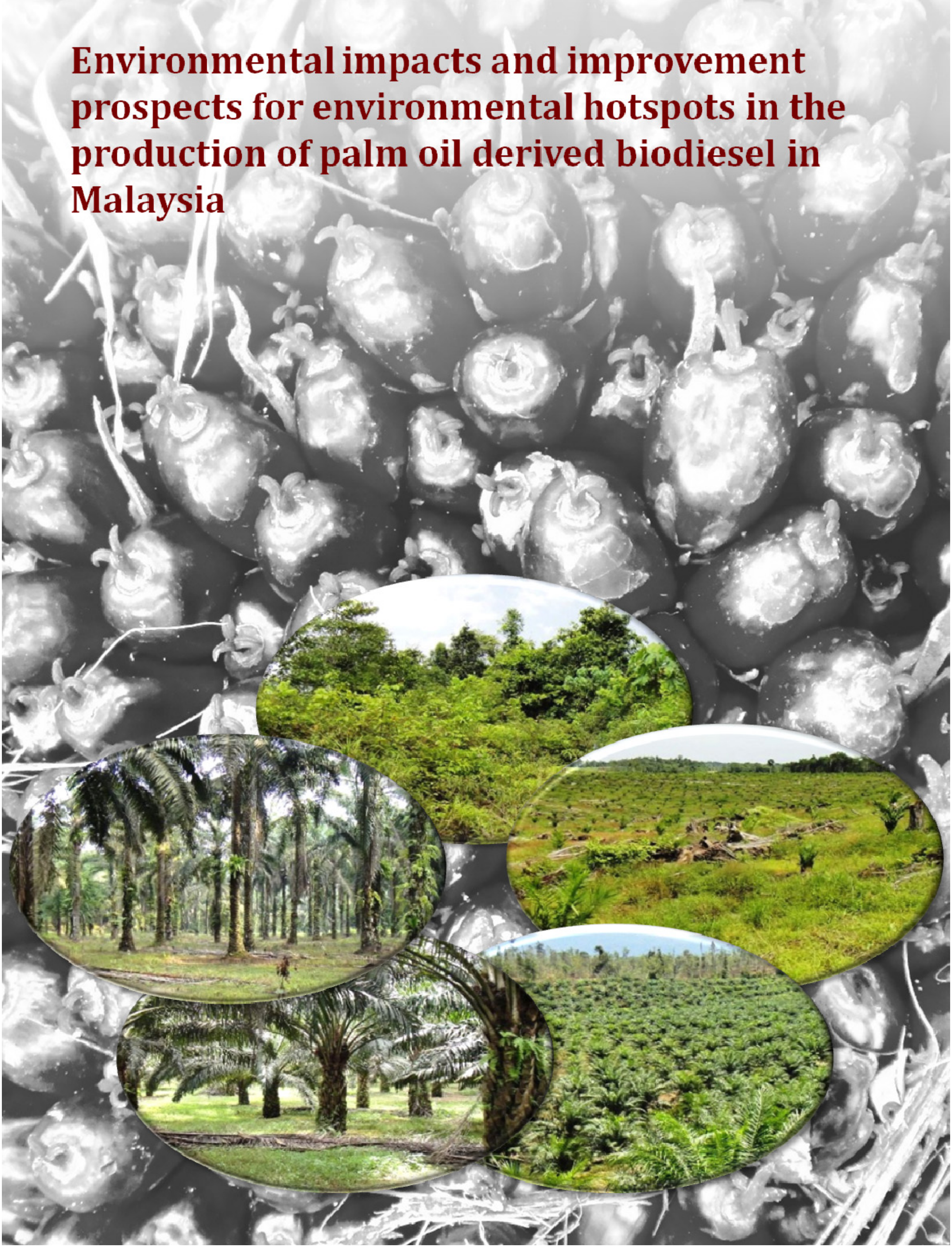

Sune Balle Hansen

PhD Thesis
November 2012

Technical University of Denmark

DTU Management Engineering
Department of Management Engineering

'Nature's gift to Malaysia, Malaysia's gift to the world'

Malaysian Palm Oil Board

– for Ayden and Lara

Preface

The idea for this project was born when I was working as an engineer for a wastewater treatment- and biogas plant company in Malaysia. Building biogas plants for the palm oil industry provided close insight into the practices at the palm oil mills and the realization that palm oil can be both an environmental liability and a potential super-crop with high yields and low emission potentials sparked the interest for further investigations.

Through direct involvement as research assistant in the first life cycle assessment conducted on palm oil, which was done at University of Malaya in 2004[1], I was aware that data was scarce and that the primary goal would be to produce life cycle inventory data.

I had good response when I pitched the idea of LCI data generation in palm oil production to QSA at DTU Management Engineering and University of Technology Malaysia (UTM) was lined up as local partner. A subsequent request to Shell for project funding was equally successful after it was decided to turn the project focus onto biodiesel production from palm oil and thus, thanks to Shell Global Solutions, the project was a reality.

The framework of the project was established with Stig Olsen, Arne Wangel and Michael Hauschild from QSA and main supervisor and co-supervisors respectively. Professor at Faculty of Chemical Engineering and Vice-chancellor at UTM, Zaini Ujang, took the place of local supervisor during the stay in Malaysia and Veronika Dornburg from Shell Global Solutions was assigned at representative for the sponsor. I have been attached to QSA at DTU and Razak School for Engineering and Advanced Technology at UTM. I would like to send my sincerest gratitude to all the above for their guidance and support throughout the project.

Special thanks also to Christine Molin at QSA for securing the sponsor agreement with Shell when the things were almost falling apart. Also to academic and technical staff at Department of Geotechnics and Transportation at UTM for assisting in soil sampling and Christian Davis from Shell Global Solutions for toiling (unfortunately in vain) to get the soil carbon analysis equipment working.

Malaysian palm oil FELDA stepped in as a partner in the project and secured access to plantations, mills and palm oil data. Without their involvement the project would never have succeeded. I am truly grateful to the directors and staff for welcoming me into the world of palm oil.

This dissertation summarizes, elaborates, discusses and concludes the research, which resulted in three papers for publication in international journals.

Kgs. Lyngby, 16 November 2012

Sune Balle Hansen

[1] Yusoff and Hansen (2007). The study was published in International Journal of Life Cycle Assessment. Online in 2005 and in hardcopy in 2007.

Abstract

Palm oil is the largest and fastest growing vegetable oil on the world market and the prospects of biodiesel production will further spur the expansion. In order to contribute to the knowledge base on current environmental impacts and potential improvements in the palm oil industry this study sets out to generate LCI data for central, yet underexplored elements in the production of biodiesel with a focus on greenhouse gasses (GHG).

The research follows an attributional modelling framework, but does include system expansion to account for the use of residues from the palm oil production. The reference flow of the study is 1 MJ palm oil derived biodiesel, which has been chosen to facilitate comparisons of the results to fossil diesel and other biodiesels. The impact focus is on global warming potential with extensive quantification of GHG emissions and potential reduction. Other impact categories are included mainly with the purpose of documenting whether the proposed GHG reduction initiatives result in problem shifting.

Land use changes (LUC) are the most controversial aspect of palm oil production with large potential GHG emissions and impacts on biodiversity. With global warming and extinction of animals and plants in tropical areas being easily communicated to the public, palm oil has been the target of numerous scare campaigns. Conversely, the palm oil industry is adamant that palm oil and oil palm plantations are sequestering carbon and supporting a wide range of flora and fauna. Through critical selection of literature data, field studies and application of state-of-the-art LCA methodology, this study is quantifying the GHG emissions from palm oil related LUC for the two most common previous land uses in Malaysia, namely logged-over forest and rubber plantations. In order to be able to assess the impacts from average palm oil production in Malaysia, a Malaysian average LUC scenario was set up and assessed.

Solid residues from the production of palm oil constitute two tons dry weight organic matter per ton palm oil produced. Current use of this potential resource is limited to mulching of plantation residues and empty fruit bunches (EFB) from the mills and use of press fibre and kernel shells in the mill boilers. The mill wastewater called palm oil mill effluent (POME) is treated anaerobically in open lagoons emitting large amounts of methane. In recent years it is becoming more popular to sell kernel shells for use in industrial boilers, and biogas plants with methane capture for the POME treatment are slowly making their entry, but the potential uses and environmental benefits of such uses have only been sporadically explored. Residue energy recovery for substitution of fossil fuels is explored here through application of biomass power plants, pyrolysis and biogas production.

Modelling the results of the LUC study and the residue use study into a GaBi model, various scenarios were set up to test the environmental potentials of management decisions in respect to LUC choices, yield optimization and residue use. The study also includes an assessment of the management practices of corporations and smallholders and an economic feasibility study to assess financial aspect of environmental improvements.

The results show that biodiesel production from conventionally produced palm oil with national average LUC emissions emits only marginally less GHG than the life cycle emissions of fossil diesel. This study, however, shows that significant environmental improvements are available with currently available

technologies to bring the impacts well below the fossil diesel emissions, and do so with economic profitability.

Residue use shows a big potential for improvement. The conventional residue management causes net GHG emissions where the prospective fossil fuel substitutions through residue energy recovery alone is so significant that net GHG emissions from the PME production process can become close to CO_2 neutral when not including LUC. An added bonus for the palm oil industry is that such improvements are likely to result in a net income through sales of residues and/or residue use products.

LUC emissions can potentially result in so large GHG emissions when high-carbon stock land is converted to oil palm that no environmental improvements or management strategies will be able to make the produced palm oil sustainable. On the other hand, conversion of low-carbon stock land or land with a temporary carbon stock can result in low or even negative LUC emissions thus giving PME carbon neutral potentials when combined with environmental initiatives in the production. A methodological choice made in this study of focusing on the Malaysian average LUC emissions results in LUC contributions of app. 40% of the total conventional biodiesel production emissions of 70 g CO_2/MJ.

The impacts from LUC as well as the biodiesel production process can, however, be improved through management strategies. Increasing yields have a direct correlation with lower LUC emissions per MJ biodiesel and with potentials of up to 75% yield increases from the plantations, Malaysian average LUC emissions could thus be reduced by about 50%, which in combination with residue use would lower the overall PME emissions by 80%.

Such a scenario would require an optimization of the production system, which may be possible from a few dedicated producers, but is very unlikely as a Malaysian average scenario in a foreseeable future. However, the two future scenarios set up in this study show that the GHG emissions from biodiesel are likely to drop by almost 15% in 2015 and close to 65% by 2020 thus putting biodiesel on track to meet the sustainability criteria.

Assessing other impact categories than global warming potential (GWP) shows that all impact categories experience reduced impacts due to the proposed environmental improvements in the management scenarios set up in this study. Thus, even though most other impact categories experience lower reductions that GWP, it can be concluded that the proposed improvements do not result in problem shifting.

Through the data collection process in this study it has become evident that many holes in life cycle inventory data for palm oil production still exist. Thus, this study recommends extensive further studies within areas like biodiversity, nitrogen emissions, water footprint and many more as well as further studies on LUC and residue use.

Resumé

Palmeolie er den største og hurtigst voksende vegetabilske olie på verdensmarkedet, og udsigterne til produktion af biodiesel vil yderligere anspore væksten. For at bidrage til vidensgrundlaget for aktuelle miljøpåvirkninger og potentielle forbedringer i palmeolieindustrien har denne undersøgelse til formål at generere LCI data til centrale, men underudforskede elementer i produktionen af biodiesel fra palmeolie med fokus på drivhusgasser (GHG).

Forskningen følger attributional modelleringsrammer, men omfatter også systemudvidelse for at redegøre for anvendelsen af restprodukter fra palmeolieproduktionen. Referenceudvekslingen i studiet er 1 MJ biodiesel udvundet af palmeolie. Dette er valgt for at muliggøre sammenligninger af resultaterne med emissioner fra fossil diesel og andre typer biodiesel. Miljøpåvirkningerne har fokus på global opvarmning med omfattende kvantificering af GHG og potentielle reduktioner af disse. Andre påvirkningskategorier er inkluderet primært med det formål at dokumentere, om de foreslåede GHG reduktionstiltag resulterer i forskydning af miljøproblemer til andre områder end global opvarmning.

Ændringer i arealanvendelse (LUC) er det mest kontroversielle aspekt af palmeolieproduktionen med store potentielle GHG-emissioner og konsekvenser for biodiversiteten. Med den globale opvarmning og udryddelse af dyr og planter i tropiske områder, som let kan formidles til offentligheden, har palmeolie været mål for talrige skræmmekampagner. Omvendt står palmeolieindustrien stejlt på, at palmeolie og palmeolieplantager binder kulstof og støtter en bred vifte af flora og fauna. Gennem kritisk udvælgelse af data fra litteraturen, feltstudier og anvendelse af state-of-the-art LCA metode kvantificerer dette studie GHG-emissionerne fra palmeolierelateret LUC for de to mest almindelige tidligere arealanvendelser i Malaysia, som er selektivt fældet skov og gummiplantager. For at kunne vurdere påvirkningerne fra den gennemsnitlige produktion af palmeolie i Malaysia, blev et scenarie for gennemsnitlig malaysisk LUC ligeledes opstillet og vurderet.

Faste restprodukter fra produktionen af palmeolie udgør to tons tørvægt organisk stof per ton palmeolie produceret. Den nuværende anvendelse af denne potentielle ressource er begrænset til jorddækning med restprodukterne fra plantagen og de tomme frugtklaser (EFB) fra møllerne og anvendelse af fiber og kerneskaller i møllens kedel. Palmeoliemøllespildevandet (POME) behandles anaerobt i åbne laguner, hvilket udsender store mængder metan. I de senere år er det blevet mere almindeligt for møller at sælge kerneskaller til brug i industrielle kedler, og biogasanlæg med metanopsamling til POME-behandlingen er langsomt at gøre deres indtog, men de potentielle anvendelser og miljømæssige fordele ved sådanne anvendelser er kun sporadisk undersøgt. Energiudnyttelse af restprodukterne som substitution for fossile brændsler er udforsket i dette studie gennem anvendelse af biomasseanlæg, pyrolyse og biogasproduktion.

Resultaterne af LUC studiet, og brugen af restprodukterne blev modelleret i GaBi og forskellige scenarier blev etableret for at afprøve de miljømæssige potentialer af ledelsesmæssige beslutninger i forhold til LUC valg, optimering af palmeolieafkastet og brugen af affaldsprodukterne. Undersøgelsen omfatter også en vurdering af miljøforskellene mellem storbrug og mindre jordejere og en økonomisk forundersøgelse til vurdering af de finansielle aspekter af miljøforbedringerne.

Resultaterne viser, at biodieselproduktion fra konventionelt produceret palmeolie med nationale gennemsnitlige LUC emissioner kun udsender marginalt mindre drivhusgasser end livscyklus udledninger

fra fossilt diesel. Dette studie viser imidlertid, at det med miljømæssige forbedringer og brug af nuværende tilgængelige teknologier er muligt at bringe miljøpåvirkningerne langt under de tilsvarende fossile dieselemissioner. Og det kan gøres det med økonomisk rentabilitet.

Brug af restprodukter viser et stort potentiale for forbedringer. Den konventionelle brug af restprodukter forårsager netto GHG-emissioner, hvorimod de potentielle fossile brændstofbesparelser ved energiudnyttelse af restprodukterne alene er så betydelige, at netto GHG-emissionerne fra biodieselproduktionsprocessen kan blive tæt på CO_2-neutrale, når der ikke inkluderes LUC. En ekstra bonus for palmeolieindustrien er, at sådanne forbedringer kan forventes at resultere i en nettoindkomst gennem salg af restprodukter og/eller produkter af genanvendelsen.

LUC emissioner kan potentielt resultere i så store drivhusgasemissioner, når arealer med højt kulstofindhold i biomass og jord omdannes til oliepalme, at ingen miljømæssige forbedringer eller forvaltningsstrategier vil være i stand til at gøre den producerede palmeolie bæredygtig. På den anden side kan omlægning af arealer med lavt kulstofindhold eller arealer med et midlertidigt kulstoflager resultere i lave eller endog negative LUC emissioner og dermed give biodiesel kulstof neutrale potentialer, når det kombineres med miljøtiltag i produktionsprocessen. Et metodisk valg i denne undersøgelse om at fokusere på de malaysiske gennemsnitlige LUC emissioner resulterer i LUC bidrag på ca. 40% af de samlede konventionelle biodieselproduktionsemissioner, som er på 70 g CO_2/MJ.

Påvirkningerne fra LUC samt biodieselproduktionsprocessen kan dog forbedres gennem ledelsesstrategier. Stigende palmeolieafkast har en direkte sammenhæng med lavere LUC emissioner pr MJ biodiesel og med potentialer på op til 75% stigning i afkastet fra fra plantagerne, kunne malaysiske gennemsnitlige LUC emissioner reduceres med omkring 50%, hvilket i kombination med brug af restprodukter vil sænke de totale biodiesel GHG-emissioner med 80%.

Et sådant scenario ville kræve en optimering af produktionssystemet, som kan være muligt for nogle dedikerede producenter, men er meget usandsynligt som malaysisk gennemsnitsscenarie i en overskuelig fremtid. De to fremtidsscenarier oprettet i denne undersøgelse viser dog, at GHG-emissionerne fra biodiesel forventes at falde med næsten 15% i 2015 og tæt på 65% frem mod 2020, hvilket bringer biodiesel fra palmeolie på vej rette vej til at opfylde bæredygtighedskriterierne.

Vurdering af andre påvirkningskategorier end global opvarmning viser, at alle påvirkningskategorier oplever reducerede påvirkninger som følge af de foreslåede miljøforbedringer i de opstillede scenarier i dette studie. Selvom de fleste andre påvirkningskategorier oplever lavere reduktioner i påvirkningerne end global opvarmning, kan det konkluderes, at de foreslåede forbedringer ikke resulterer i forskydning af miljøproblemer.

Gennem indsamlingen af data i denne undersøgelse er det blevet klart, at der fortsat er mange huller i livscyklusdatagrundlaget for palmeolieproduktion. Således anbefaler dette studie omfattende undersøgelser inden for områder som biodiversitet, kvælstofudledning, vandpåvirkninger og mange flere, samt yderligere undersøgelser af LUC og brug af restprodukter.

Abbreviations

CH_4	Methane
CO_2	Carbon dioxide
CPKO	Crude palm kernel oil
CPO	Crude palm oil
EFB	Empty fruit bunch
EM	Environmental management
EU-RED	European Union Renewable Energy Directive
FFA	Free fatty acid
FFB	Fresh fruit bunch
GHG	Greenhouse gas
GWP	Global warming potential
HHV	Higher hearing value
ILCD	International Reference Life Cycle Data System
ILUC	Indirect land use change
IPCC	Intergovernmental panel for climate change
LCA	Life cycle assessment
LCI	Life cycle inventory
LHV	Lower heating value
LUC	Land use change
N_2O	Nitrous oxide, laughing gas
NGO	Non-governmental organization
PME	Biodiesel (Palm methyl ester)
POME	Palm oil mill effluent
RPO	Refined palm oil
USD	US Dollar ($)

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1 Introduction

The Southeast Asian country Malaysia situated a few degrees north of the Equator consists of the Malaysian peninsula and Malaysian Borneo. The land area is just short of 330,000 km^2 with a population of app. 30 million. During the British rule in late 18^{th} century to 1957, the oil palm was imported from West Africa as a decorative plant in the late 19^{th} century and in 1917 the first commercial oil palm plantations and palm oil mills were established. The rapid expansion of palm oil started with the emerging global market in the 1960s. In 1975 a total of 2% of the Malaysian land area was covered with palm oil. In 2011 that had increased to 15% at a total planted area of 5 million hectare (50,000 km^2) and a total crude palm oil (CPO) production of 18.9 million tons bringing Malaysia more than 25 billion USD in export earnings (MPOB 2012). Palm oil is the biggest vegetable oil in the world holding approximately 1/3 of the world market with a wide range of uses as cooking oil, ingredient in packaged foods, cosmetics and as biodiesel. Malaysia was the biggest palm oil producer in the world until 2006 when Indonesia overtook that position.

In recent years, the production of biodiesel from vegetable oils to replace fossil diesel has been received much attention. Biodiesel is a methyl ester produced from refined vegetable oil and an alcohol in a transesterification process. In the case of palm oil, the biodiesel product is called palm methyl ester (PME). The prospects of PME have put increased environmental focus on the production emissions. The production of biodiesel from vegetable oils is known as first generation biodiesel. Second and third generation biodiesel is produced from waste products and algae, which will to a large extend lessen environmental impacts. However, the production technologies of these newer generations have not yet made them commercially available. This project focuses on first generation PME.

As for all agricultural crops, land use change (LUC) plays a role in establishing an oil palm plantation when it comes to greenhouse gas (GHG) emissions and biodiversity impacts. NGOs have targeted palm oil as one of the primary forces of rainforest clearing in Southeast Asia; a claim which is debatable. In Malaysia, the land uses most often converted to oil palm are state forest, rubber plantations and other agriculture. State forest is forest, which has been earmarked by the Malaysian Government for logging and future development, so as timber is extracted from the land in any case, the full rainforest clearing impacts cannot be allocated to palm oil. At COP15, Malaysia pledged to maintain virgin forest cover on a minimum of 50% of its total land area. The Government, however, reserves the rights to develop the remaining land.

A brief state-of-the-art on life cycle assessments (LCA) is given in the following to clarify the background for the chosen focus areas of this study. A more comprehensive literature review can be found in chapter 2.

Using LCA as a tool to quantify environmental impacts from palm oil and PME has become increasingly widespread in recent years although significantly more studies have been carried out on biodiesel from rapeseed and soy. LCA has proven effective in establishing overviews of the life cycle of palm oil and identifying the areas contributing most significantly to the environmental impacts. However, the limitations of LCA have been clearly demonstrated as well. Due to the immense data load and subjective frameworks and system boundaries, there are as many different results as there are studies, depicting palm oil production as anything from close to zero impact to environmental culprit. A factor influencing most if not all existing LCAs on palm oil is the scarcity of reliable life cycle inventory (LCI) data. Quantities of direct inputs and outputs like fertilizer and pesticide use, transport, yields, residue generation etc have been fairly thoroughly documented. However, LCI data, which is more dependent on experimental data generation, like the fate of pesticides and nitrogen in the plantations, emissions from residues and the potential benefits of residue use as well as actual LUC emissions and impacts on biodiversity are indicative at best. Also, studies have focused solely on steady state assessments on conventional palm oil production, without quantitative assessments of the potential benefits of environmental improvements in the production. Based on the large quantities of residues in the palm oil production (app. 2 ton dry weight per ton palm oil) and the potentially very high emissions from LUC, these two have been chosen as focus areas in this study. Finally, to assess the conventional production and potential benefits achievable by plantation and milling management strategies, a number of production scenarios are set up for environmental evaluation. These include conventional production for corporations and smallholders, and various scenarios featuring environmental improvements. A preliminary economic feasibility assessment of residue use is included as well. In line with most studies and sustainability requirements for biofuels, this study focuses mostly GHG although more impact categories have been included to assess whether proposed environmental improvements would lead to problem shifting. The three focus areas in this study have resulted in three papers:

1. Greenhouse gas reductions through enhanced use of residues in the life cycle of Malaysian palm oil derived biodiesel (hereafter referred to as the residue use paper, Hansen et al. 2012)
2. Carbon Balance Impacts of Land Use Changes related to the Life Cycle of Malaysian Palm Oil derived Biodiesel (hereafter referred to as the LUC paper)
3. Environmental Management Options in Malaysian Palm Oil derived Biodiesel Production (hereafter referred to as the management paper)

The papers can be found in full in Appendix 1-3.

On top of these three focus areas, a feature article and a conference paper have been produced focusing on softer aspects of environmental impacts in the palm oil industry (see Appendix 5).

In 2009, the European Union Renewable Energy Directive (EU-RED) was released, dictating that a biofuel must achieve minimum 35% reduction in GHG compared to its fossil counterpart to be labelled renewable (European Parliament 2009). In order to have a tangible limit to refer the GHG emissions from PME production to, the EU-RED is used for comparative purposes although the simplified GHG accounting methodology in EU-RED does not match the methodology of this study in all aspects. This is described in more details in the respective papers. For simplicity purposes, the limit of 55 g CO_2-eq/MJ for biodiesel to labelled renewable in EU-RED is used in this study to describe environmental sustainability.

2 State-of-the-Art

2.1 General LCA on palm oil

The first LCA on palm oil found was the study by Yusoff and Hansen (2007), which was available online from 2005. As the title 'Feasibility assessment of performing a life cycle assessment of crude palm oil production in Malaysia' suggests, this study was not focusing on a detailed and precise LCI, but rather on the methodology of performing an LCA in this new field. LUC was not included quantitatively in the study. At the commencement of this study in late 2009 a handful of LCAs on palm oil production in Malaysia, all including LUC to some extent, had been published with as many different results as there were studies due to the immense data load and subjective frameworks and system boundaries. Whereas Tan et al.(2009) and Yee et al. (2009) depicts palm oil as having close to zero impact, the study in Indoniesia by Danielsen et al. (2009) puts palm oil in a much less favourable light. The GHG emission reductions of PME range from well above the 35% CO_2 savings compared to conventional diesel (Birath and Defranceschi 2009) as required by EU-RED (European Parliament, 2009), to contributing even higher CO_2 emissions than diesel in life cycle perspectives (Reijnders and Huijbregts 2008). Wicke et al. (2008) paints a more nuanced picture with the inclusion of several scenarios of previous land uses and conclude that palm oil production does in fact range from sustainable to unsustainable depending on production and LUC. Germer and Sauerborn (2008) address only LUC impacts in their review and conclude that the LUC impacts can range from carbon sink when degraded land is converted to immense carbon losses when rainforest or peatlands are converted. Except for Yusoff and Hansen (2007), which includes a full range of EcoIndicator99 impact categories, all other studies at hand focused solely on GHG with the addition of biodiversity in Danielsen et al. (2009). It should be noted that Tan et al. (2009) and Yee et al. (2009) display very poor understanding of LCA methodology and have an obvious bias towards the sustainability of palm oil and PME. Outside Malaysia/Indonesia, only three LCA related studies were identified, namely Pleanjai et al. (2009) and Pleanjai and Gheewala (2009) from Thailand and Yanez Angarita et al. (2009) from Brazil/Columbia. Whereas Pleanjai et al. (2009) quantify GHG emissions, the two latter studies focus solely on energy and do not account actual emissions.

Since 2010 more studies have been published, but with the same picture of very diverse conclusions. Two studies should be highlighted here: 1. Schmidt (2010) conducted the first study applying consequential framework incl. a simple biodiversity indicator (vascular plants only). 2. Choo et al. (2011) is an LCA conducted by the Malaysian Palm Oil Board, which is the biggest research body for the Malaysian palm oil industry. The study has presented the most detailed LCI on CPO and PME, but does lack details on residue use and LUC. Choo et al., (2011) has thus been used as a platform LCI for this study on top of which has been added residue use and LUC data.

Amongst a number of limitations in the LCIs of the various studies, common for all LCA publications on palm oil and PME is that LUC is a potentially major contributor of GHG in the production of palm oil/PME, but that the quantitative impacts vary a great deal between studies. Also, the potential use of the vast amounts of waste products generated are not included as all studies are steady state without considering potential improvements to the system.

In the past decade global warming has become the number one environmental concern worldwide as suggested in the reviewed LCAs. The substitutions of fossil fuels in power generation has been around for decades, however, the substitution of transportation fuel with e.g. bioethanol and biodiesel for commercial use is a relatively recent science (Basiron 2007). As the main driver for the use of biodiesel is the reduction of GHG emissions, this study focuses mainly on inputs and emissions related to global warming. Focusing only on global warming creates some obvious risks of inaccurate environmental conclusions and problem shifting. For the residue use and LUC focus areas, the lack of data on emissions related to other impact categories have, however made this limitation necessary. As the residue uses focus on land application and energy recovery of the organic wastes, it is argued that GHG emissions can be expected to be the main environmental impact although eutrophication could also play a significant role. In the land use context, biodiversity impacts are expected to be the most significant alongside GHG emissions, but eutrophication and water footprint, could potentially be significant as well. This study has been limited to discuss biodiversity impacts qualitatively in chapter 6. For the environmental management options, other impacts categories have been included using EcoInvent2.0 processes and ReCiPe midpoint impact characterization method in GaBi4.

2.1.1 Residue use

Studies carried out on environmental impacts from the production of palm oil and PME have solely been focusing on the current practices in the production process without investigating the potential benefits of environmental improvements in the system (e.g. Schmidt 2007 and Choo et al. 2011).

Several studies focus on the waste quantities produced (e.g. Yusoff 2006) and the various recycling technologies. Apart from the technologies described in Sections 3.1 – 3.6 in the main article, reuse of palm oil residues have been researched e.g. within bioethanol from EFB (Tan et al. 2010), citric acid from EFB (Bari et al. 2009) and POME (Alam et al. 2008), plywood/fibreboards from EFB and trunks (Khalil et al. 2010), and cellulose enzyme from EFB (Alam et al. 2009). However, only few of these mention the quantitative environmental impacts and benefits from the technology and none have investigated the actual benefits in a life cycle perspective. Among the various waste treatments available, this study focuses on technologies, which are available for full scale implementation and that provide energy recovery (electricity, steam etc.) or carbon sequestration. The chosen technologies are thus 1. Incineration with energy recovery, 2. Pyrolysis, 3. Biogas.

Biochar is a product of pyrolysis along with bio-oil and syn-gas. The two latter have uses for energy recovery as well as in oleo-chemical application whereas the biochar can be used as charcoal, activated carbon or as a soil fertility enhancer (Lehmann and Joseph 2009). It is in the capacity of the latter that biochar has potentials in the palm oil industry. Biochar, which contains app. 50% non-biodegradable carbon, can be produced from all the solid residues from the plantations and mill. The full potentials of the biochar have not yet been established, but research indicates that it will 1. Sequester carbon in the soil for centuries or even millennia (e.g. Lehmann et al. 2006), 2. Improve the fertility of the soil through enhancing nutrient availability, soil cation exchange capability and water holding capacity as well as other interaction with microorganisms (Warnock et al. 2007). This double benefit makes biochar very interesting. Especially in relation to regeneration of degraded land and the potentials of using these lands for oil palm expansion.

2.1.2 Land use change, LUC

LUC is the main topic in the ongoing heated debate between the palm oil industry and NGOs. Although numerous studies have been conducted on the effects of LUC in reference to establishing oil palm plantations none have been able to unite the opposing parties. The studies generally focus on biodiversity and/or GHG emissions and carbon sequestration from above and below ground biomass. Whereas general impact trends have been established on the biodiversity effects and net GHG emissions from LUC there is still no general consensus on the reliability of these results.

There are numerous variables to consider in the studies on LUC and as many of these are chosen subjectively due to a lack of industry specific guidelines, the results of two similar studies can point in opposite directions. Guidelines of the Intergovernmental Panel for Climate Change (IPCC) for GHG inventory for LUC (IPCC 2006) are being criticized by the palm oil industry for being based solely on European scenarios. Below, some of the main technical discussion points are presented qualitatively.

Previous land use – Oil palm plantations have been and are replacing a variety of landscapes: Primary forest, Secondary forest, other plantations, other crops and fallow land. LUC related GHG emissions vary significantly depending on the previous land use and the existing soil carbon. Thus the chosen site for a new palm oil plantation can have significant impact on the overall environmental impacts of palm oil production (e.g. Reijnders and Huijbregts 2008). The general point of view of the palm oil opposition is that oil palm plantations are in most cases directly or indirectly planted on former rainforest areas. Conversely the palm oil industry claims that only a tiny percentage of rainforest clearing is due to palm oil, which is largely planted on land, which has been or will be logged for timber and that the land will be cultivated in any case whether through oil palm, other agricultural crops or urbanization (e.g. IPLC 2009). How much rainforest clearing can be allocated to palm oil is thus still an open debate.

Biodiversity in plantations – Most biologists stress the point that the rich biodiversity in the rainforests involve many species domestic only to this part of the world thus facing extinction with the clearing of the rainforest (e.g. Danielsen et al. 2009). The palm oil industry on the other hand claims that the biodiversity in the palm oil plantations is almost as high as in rainforests and that bordering areas between rainforests and oil palm plantations have even higher biodiversity than conventional rainforests as animals will seek towards the plantations to feed on the oil palm fruits (e.g. IPLC 2009). Biodiversity covers a vast range of flora and fauna and varies greatly from area to area even over short distances. Various methodologies exist in quantitative assessments of biodiversity thus limiting comparability and resulting in the ability to shape the results of a study to fit a certain agenda.

Carbon sequestration – The opposition focuses on the immense carbon emissions by clearing rainforest while the palm oil industry claims that replanting the area with oil palm will lock considerable amount of carbon and turn the plantation into a carbon sink. During the IPLC (2009) the palm oil industry repeatedly argued that carbon sequestration at the palm oil plantations is generally underestimated in studies.

Peat soil – Carbon release from peat soil after land clearing and soil drainage with subsequent bacterial breakdown of the peat and carbon release is considered to be the biggest contributor to carbon emissions from LUC (e.g. Page et al. 2011). The palm oil industry, however, finds the emissions exaggerated and based on invalid European models. Recent independent studies have also found emissions from oil palm plantations on peat in Malaysia to be similar to or even lower than emissions from virgin peat (Melling et al.

2012), although these studies are not yet completed and many factors still have to be investigated (Melling et al., 2012).

On the quantitative side, a number of studies have reported on the GHG emissions/balances related to LUC. Amongst others, Germer and Sauerborn (2008) have conducted a thorough review of GHG emissions from LUC and Lasco (2002) studied the forest growth after logging whereas Khalid et al. (1999a) and Khalid et al. (1999b) quantified the carbon stored in oil palms at the end of the plantation cycle. Less literature is available on the soil carbon equilibrium in Malaysian oil palm plantations, which is only measured in one reference, namely Mathews et al. (2010) and estimated in Germer and Sauerborn (2008).

In order to increase the knowledgebase on soil carbon in oil palm plantations, this study included soil carbon sampling from oil palm plantations as well as logged forest. Soil carbon sampling was carried out at 8 plantations of various ages and one logged forest in close proximity to the plantations. The sampling and sample preparations were carried out successfully, but technical difficulties at project sponsor Shell Global Solutions' laboratories, where the samples were to be analysed, has meant that no results have been obtained from the samples at the time of submission of this thesis. As no soil carbon results are included, the theoretical background and methodology of the sampling and analysis have been omitted as well.

Common for all studies on palm oil related LUC is that they do not include the concept of temporary carbon storage. Most studies include carbon sequestration in the plantations on equal terms with carbon emitted from forests and as such the net carbon emission is $C_{emitted}$-$C_{sequestered}$. As the oil palm plantations are felled (and replanted) every 25-30 years, such methodology is not in accordance with LCA methodology as per the ILCD Handbook (European Commission 2010). The temporary sequestration should either not be included at all, or be given temporary storage credit, i.e. $X/100 \cdot C_{stored}$ where X is the number of years of carbon storage as per European Commission (2010). As the oil palms have a near linear growth pattern over the 25 years, the average carbon molecule in the palms is stored for 12.5 years, so the temporary storage given to an oil palm plantation should be $0.125 \cdot C_{stored}$.

2.1.3 Environmental management

The environmental impacts of some processes and the benefits of others at the oil palm plantations and palm oil mills make environmental management (EM) choices important. Two main factors guide the EM choices of farmers and millers: Will and financial ability. In the case of the latter it is especially the independent smallholders who, due to their low income and small scale, are unable to improve their management practices. Ayat et al. (2008) and Donough et al. (2010) have discussed the issues faced by oil palm plantation smallholders in Malaysia and Indonesia. However, no studies have identified the environmental consequences of smallholder vs. corporation operation of an oil palm plantation.

Assuming that capital is available to initiate environmental improvements at mills and plantations, the environmental benefits as well as the feasibility of these improvements should be quantified. No studies have been identified covering this either, although Basri and Arif (2009) does present financial discussions of some management choices like fertilizers, replanting and yield improvements.

3 Goal & Scope

3.1 Goal Definition

The results of the study are intended to be applied to the identification of inputs and outputs contributing to potential environmental impacts and identification of potentials for impact reductions along the PME production chain for the purpose of contributing to environmental management decision making and for use as a platform for further LCA studies, both descriptive and comparative.

The study is carried out to create awareness of some of the less studied areas of the palm oil industry and to provide preliminary data on these areas. The results given will not be finite, but must be updated as more data is generated.

The target audiences of the results are palm oil/biodiesel stakeholders and the academic LCA community. The parameterized GaBi model generated in the study can be used to enable quick and site specific results based on nursery, plantation, mill and biodiesel plant inputs. It should be noted that the data in the model are to a large extent based on assumptions and Malaysian average palm oil data, so the results should not be assumed representative for individual plantations and mills in decision contexts without data verification.

3.2 Scope Definition

Based on the goal definition the scope of the study is derived. The scope dictates the requirements of the study to reach the goal in respect to methodology, framework and quality.

Functional Unit

The reference flow of the study is 1 MJ PME with a lower heating value (LHV) of 37 MJ/kg ready for shipment from a Malaysian biodiesel plant. Under each stage in the palm oil production system, stage-specific local reference flows are, however, used as follows:

1. Nursery stage reference flow: 1 palm seedling
2. Plantation stage reference flow: 1 ton fresh fruit bunches, FFB
3. Land Use Change reference flow: 1 ha
4. Milling stage reference flow: 1 ton CPO
5. Biodiesel plant reference flow: 1 MJ PME

Modelling Framework

Attributional modelling is applied in the study with a few consequential touches. In the case of residues use from the plantations and mills, substitution is applied and in the case of LUC, some simplified induced emissions are applied. These consequential applications are described in more details in the residue use paper (Appendix 1) and the LUC paper (Appendix 2) respectively.

System Boundaries

The modelled system is a cradle-to-gate starting at the nursery and ending at the biodiesel plant storage. The focus is on the plantation and milling stages. All the produced papers are dealing with aspects within these two stages. Figure 1 depicts the system boundaries.

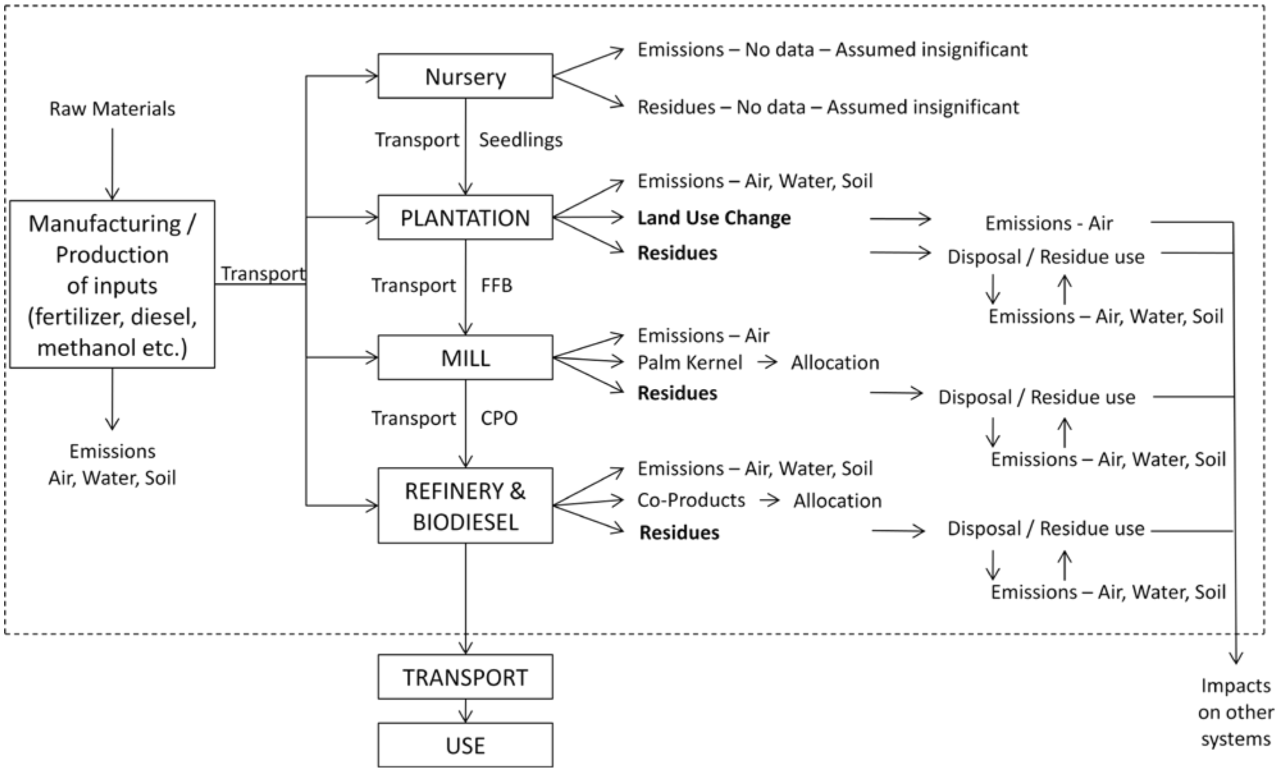

Figure 1 – System Boundaries
The focus areas of the study are marked in bold.

The assessment includes inventory and characterization. No normalization and weighting are performed.

The main focus of the study is on GHG and global warming potential (GWP). Other impact categories than global warming potential are included mainly to test that the results of the recommendations do not lead to problem shifting.

Data collection and data generation was carried out through fieldwork in Malaysia as well as literature studies. The data generation included experimental data for biogas potentials from EFB. See Appendix 4 for details. The LCI data was modelled in Gabi 4 using EcoInvent 2.0 database and ReCiPe midpoint impact categorization method.

Time Horizon

System input and output data incl. emissions are average data for the FU over the 25-year period of an oil palm cycle whereas the impact time horizon is 100 years. Temporary carbon storage in the oil palm plantations is included as described in the LUC paper (Appendix 2).

The validity period of the results depends on the development of the palm oil industry and whether the said development moves in the predicted direction. It is not recommended to use the results of this study without data verification beyond 2015.

Sensitivity Analysis

The results of the respective papers are subjected to sensitivity analyses.

4 System Description

4.1.1 Nursery

In the nursery, seedlings are grown in polybags during the first 10–12 months of their development. There are two types of nursery practice — single stage and double stage. Most oil palm nurseries practice the latter. The double-stage nursery consists of a prenursery and a main nursery stage. In prenursery, seeds sown in small polybags are kept under the shade to protect them from direct sunlight until they are approximately 3–4 months old. In the subsequent main nursery stage, the seedlings are planted in larger polybags and grown without a protective shade until they are 10–12 months old and ready for planting in the plantation (Choo et al., 2011).

Sprinkler systems water the seedlings twice daily. The seedlings are supplied with nutrients and protected from pests through fertilizer and pesticide applications, respectively. Dithiocarbamate is the most commonly used pesticide in the oil palm nursery.

As per Choo et al. (2011) app. 20% of seedlings are lost during nursery stage and planting in the plantation.

4.1.2 Plantation

Oil palms are planted at a density of 128–148 palms/ha on mineral soils depending on the slope of the land. A legume cover crop is sown to prevent erosion and fix nitrogen from the atmosphere. The cover crop dies off when the palms become big enough to shade the ground. A circle, i.e., the palm circle, with no vegetation is established around each palm. The palm circle prevents encroachment of weeds. Later, when the palm matures, the circle allows easy access for harvesting and picking of loose fruits. Small amounts of herbicides are applied to keep the palm circle free from weeds. An oil palm bears its first fresh fruit bunches (FFB) within 2–3 years and continues to do so for the next 20–25 years. Each palm produces 1 FFB every 10–21 days. Each FFB weigh up to 50 kg and contains 1,000-2,000 fruitlets. Harvesting of ripe FFB is manually carried out every using a blade when palms are short and a sickle mounted on lightweight pole for taller palms. Normally, two fronds beneath the fruit bunch are pruned before harvesting. The pruned fronds are placed in long rows in the field between the palm rows for mulching. The FFB are driven to the palm oil mill in 5- to 10-t lorries on the day they are harvested. As mills are normally placed centrally in the plantations, the average distance is about 5 km.

Nursery

Plantation

The most common fertilizers applied in the oil palm plantation are muriate of potash, ammonium sulfate, kieserite and rock phosphate. Fertilizers are transported to plantations using lorries, while field tractors are used to transport them from the store to the estate where the fertilizers are broadcast manually or by using motorized spraying equipment.

Herbicides are usually only required in the first few years when the canopy is insufficient to prevent sunlight from reaching the weeds. Most herbicides are manually applied using knapsack spraying equipment. Pesticides are also used sparingly in the plantations as integrated pest management using bioagents like barn owl and BT virus are most often used to combat rodents and insects. Organophosphorous pesticides are normally only used on ad hoc bases during more serious breakouts.

Replanting of oil palms is carried out when palms are 25–30 years old because of the difficulty in harvesting tall palms and lower FFB yields. The palms are felled, chipped and left in the plantation to decompose over app. 2 years releasing nutrients for the young palms. More details on the use of trunks as well as fronds are given in the residue use paper (Appendix 1)

When establishing an oil palm plantation on state forest, the forest is logged for timber prior to land conversion. In some cases the logging takes place immediately prior to land development in which case logging is done by clear cutting. If land development is not imminent, selective logging is applied. Some allocation issues for the LUC emissions arise, which are discussed in the LUC paper (Appendix 2). Malaysia used to be one of the major rubber producers in the world. However, the growing market share of synthetic rubber is resulting in lower rubber prices, thus making palm oil more profitable for local farmers. Conversion of peatlands is not uncommon. An estimated 15% of Malaysian oil palm plantations are planted on peat soil. During the conversion the peat is drained resulting in potential large emissions of GHGs from the disposed and decaying peat. However, recent research indicates that the emission increases from converted peatlands are not significant. This is discussed in the LUC paper as well.

4.1.3 Milling

The palm fruitlets consist of an oily mesocarp flesh, from which the palm oil is derived, as well as an oily kernel, from which palm kernel oil is derived. The kernel is enclosed in a hard shell. Both oils have multiple uses, but only the palm oil is suitable for human consumption and biodiesel.

Frond pile

Young oil palm with trunk mulch

Fresh fruit bunches (FFB)

Oil palm with fruits

At the mill, the FFB are first sterilized by steam for about 90 min. This sterilization step loosens the individual fruits from the bunch and deactivates the enzyme which causes the breakdown of the oil into free fatty acids (FFA).

The sterilized FFB are sent to a stripper where the fruits are separated from the bunch. The empty fruit bunches (EFB) are most often sent back to the plantations for mulching as fertilizer substitute, but some are subjected to other uses as described in the residue use paper (Appendix 1). The mulching of the EFB, although substituting inorganic fertilizer, is also likely to emit CH_4 and N_2O although no such data has been published. Some assumptions are made in the residue paper. After the stripper, the fruits are sent to a digester where mechanical stirring creates a homogeneous oily mash. The digested mash is then pressed using a screw press to remove the major portion of the CPO. At this point, the CPO comprises a mixture of oil, water and fruit solids, which is screened in a vibrating screen and then clarified in a continuous settling tank. The supernatant oil flows through an oil purifier to a vacuum dryer to remove moisture, while the underflow oil/sludge/water mix passes through a desander and centrifugal purifier to remove remaining solids, sludge and water before the oil is sent to the vacuum dryer.

The press cake from the screw press contains mesocarp fibre and nuts, which are separated in a fiber cyclone. The nuts are then cracked to produce kernels and shells. The kernels are shipped to a kernel crushing plants to be processed into crude palm kernel oil (CPKO), while the mesocarp fiber and some of the shells are used as boiler fuel. The remaining shells are sold to traders who resell them as fuel for industrial boilers. More details in the residue use paper. The CPKO plant is not included in this study. The steam boiler for the sterilization also drives a turbine producing electricity for the mill. Only during start-up of the process and when there is no production, diesel is needed to drive a generator.

The wastewater from the palm oil mill is called palm oil mill effluent (POME) and consists of condensate from the sterilizer and slurry from the centrifugal purifier. It has a high organic content of about 55-60,000 mg/l and is conventionally treated in open anaerobic lagoons before discharge to the water ways. The resulting methane emissions are the single largest contribution to GHG emissions in the palm oil production system only exceeded in some cases by LUC impacts. More POME discussions can be found in the residue use paper (Appendix 1).

Palm oil fruit

Empty fruit bunches (EFB) as mulch

4.1.4 Refining

Whether CPO is used for PME or other applications, a refining step is necessary. Most biodiesel plants have a built-in refinery, so they can receive CPO. Irrespectively of whether the refinery is external or at the biodiesel plant, the process is the same. Phosphoric acid is used for degumming of the oil and bleaching earth is used for adsorptive cleansing. Heat for the process is supplied from a steam boiler, which also supplies steam for the subsequent deacidification and deodorizing steps. Palm fatty acid distillate is a co-product of the refined palm oil (RPO) while spent bleaching earth and wastewater are considered waste products.

4.1.5 Transesterification

Continuous transesterification of RPO with methanol in the presence of sodium hydroxide is the process most often applied by commercial biodiesel plants in Malaysia. In simple terms, a glycerol molecule in the oil is replaced by the methanol molecule to produce PME.

The transesterification process is a three-stage reaction process followed by washing, drying and polishing of the reaction products. RPO is mixed with methanol and sodium hydroxide (catalyst), heated to the reaction temperature and fed into a series of continuously stirred tank reactors. After each tank, glycerol is separated from the methyl ester to achieve maximum yield.

Upon completion of the reaction, the PME phase is heated in a plate heat exchanger and sent to a series of flash tanks, where excess methanol is removed by evaporation. In a parallel stream, the glycerol phase is also heated in a plate heat exchanger and sent to a series of flash tanks likewise to evaporate the residual methanol before storage. The combined methanol vapour is sent to a rectification column for purification. The recovered methanol is recycled to the methanol-feed tank for reuse.

The PME is washed with hot water to remove residual glycerol, methanol and soap. A centrifugal separator ensures efficient separation of wash water and thorough removal of the impurities following which the methyl ester is dried under vacuum. The final product is cooled in a heat recovery system before it is sent to storage through a polishing filter.

5 Results & Discussions

This chapter presents the overall results of the study. Results presented in the papers are summarized and additional results are brought in to answer the problem statement of the study.

The results in the residue use study and the resulting paper have been calculated using Excel with inclusion of the life cycle results from Choo et al (2011). The following studies on LUC and management options use results produced from the GaBi model, but based on the same LCI from Choo et al. (2011) as well as the residue use and LUC data collected during the study. Whereas the Excel model only uses immediate emissions of CO_2, CH_4 and N_2O for the residue uses, the GaBi model uses life cycle data including other GHGs as well as capital goods. Other differences in the Excel model and the GaBi model are that the Excel model uses a heating value for PME of 40 MJ/kg and uses mass allocation to co-products as given in Choo et al. (2011) whereas the heating value in the GaBi model is set to 37 and allocation is done by energy content as in EU-RED (European Parliament 2009). The 40 MJ/kg used in Choo et al (2011) is termed 'energy value'. It can be assumed that this refers to higher heating value (HHV) whereas the 37 MJ/kg used in EU-RED and a number of other studies, is lower heating value (LHV). It is argued that energy allocation gives a more representative value of the co-products. The allocation calculations can be found in the LUC paper. Finally the reference flow, which was kg CO_2-eq/ton PME in the Excel model was changed to g CO_2-eq/MJ PME in the GaBi model to ease the comparison with fossil diesel and other biodiesels.

In section 5.1 the GaBi model has been used to recalculate the main results presented in the residue use paper. An assessment of discrepancies between the Excel model and the GaBi model has been made and is presented in section 5.1.

5.1 Residue Use

This section presents the main results of the residue use study subjected to the GaBi model. The original results can be found in the residue use paper in Appendix 1. In the residue use paper, the scenario using the residues for energy recovery is termed the Prospective scenario. With the inclusion of several other scenarios in the GaBi model, the scenario was re-labelled the Residue Energy Recovery scenario. That term is used consistently here to avoid confusion.

The results of the conventional PME production scenario and the Residue Energy Recovery scenario from the Excel model and the GaBi model have been compared after eliminating known variations by adjusting the PME heating value and the allocation in the Excel model to those used in the GaBi model. The comparison sees the GHG emissions from the conventional scenario decreasing by from 46 (Excel) to 42 (GaBi) g CO_2-eq/MJ PME. 2 g CO_2-eq/MJ can be explained by landfilling of 5% of the EFB being assumed in the Excel model. This impact is relatively significant in a life cycle perspective and subject to large uncertainty in terms of both actual amounts of landfilled EFB and the emissions from such landfilling. It was thus chosen not to include it in the GaBi model but rather to assume that any landfilled EFB has the same degradation pattern as EFB used as mulch.

The Residue Energy Recovery scenario emissions increase from 2 (Excel) to 6 (GaBi) g CO_2-eq/MJ PME. A review of the GaBi model showed that the GHG reductions in the Residue Energy Recovery scenario are approximately 20% lower for the use of solid residues than in the Excel model due to the additional details and different process assumptions included in the GaBi processes. Also, in the case of POME, a 5% methane leakage from the biogas plant is assumed in the GaBi model, which was not included in the Excel model. The high GWP of methane means that this leakage causes 40% less GHG reductions from POME use in the Residue Energy Recovery scenario compared to the Excel model. The variations between the two models can thus be accounted for.

The overall results show that with complete use of the palm trunks at the plantations and the EFB, shells and POME at the mills for energy recovery purposes, the production of PME can become close to CO_2 neutral when not considering the GHG emissions from LUC. It was also concluded that capturing the methane from the anaerobic digestion of POME is the most important residue use improvement and that ensuring the use of EFB will provide the biggest benefits among the solid residues. Table 1 depicts the GHG emissions and savings for the conventional system and the residue energy recovery system from the GaBi model. The results see the potential life cycle GHG reductions from residue use drop from 95% in the Excel model to 86% due to the above mentioned variations in the models. The conclusions of the residue study are, however, not affected.

Table 1 – GHG emissions and savings from residue use in PME production incl. energy allocation[1]

	Trunks	Fronds	EFB	Shells	POME	Total
Conventional residue scenario						
g CO_2/MJ PME	0	1.2	-0.3	-4.0	20.4	17
Residue Energy Recovery scenario						
g CO_2/MJ PME	-4.3	0	-8.1	-5.1	-2.3	-19
Residue GHG reductions [g CO_2/MJ PME**]**						36
PME production life cycle						
Conventional life cycle GHG balance[2] subjected to 26% energy allocation						42
Prospective life cycle GHG balance[2] with improved residue utilization [g/MJ PME]						6
Potential life cycle GHG emission reductions						86%

[1] Energy allocation to non-PME co-products up to and including milling: 17%. See allocation calculations in the LUC paper in Appendix 2
[2] Results from Choo et al. (2011) with inclusion of the residue use emissions and savings

The original residue study and the residue use paper included a sensitivity analysis, in which some best and worst cases were set up for the assumptions and the sensitivity in input data. Although the GaBi model allows certain flexibility, it does not cater for detailed changes in input data without risking permanent changes to the model. Thus, the sensitivity analysis has not been recreated using GaBi data. However, as the input data and results in the Excel model and the GaBi model are similar, the main findings of the sensitivity analysis are still assumed to be valid for the GaBi model results. The sensitivity analysis showed that through the difference between the best case emissions of conventional use and the worst case benefits of implementing the energy recovery uses, the minimum GHG reductions of the residue use are more than 25 g CO_2-eq/MJ PME produced. This is equivalent to more than a 40% reduction in the net GHG emissions compared to conventional PME production thus giving PME a saving of more than 70% compared to fossil diesel assuming CO_2-neutral LUC.

The residue use study also included experimental data generation as presented in the residue use paper. The main results for the experimental work on biogas potentials from EFB showed a promising biogas yield. On top of that, the fibre fraction of the degassed EFB was not degraded and can easily be separated from the digestate for other residue use applications. By 2020 all palm oil mills in Malaysia will have a biogas plant to treat POME in accordance with PEMANDU (2012), and only small additional investments will make co-digestion with EFB possible to significantly boost the methane production. From a GHG emissions point of view, there are, however, no significant advantages of subjecting EFB to biogasification rather than incinerating them for electricity production in a biomass power plant. It should also be noted that the experiments were small scale under steady state conditions. Larger scale testing under continuous or semi-continuous flow is needed to draw firm conclusions. Detailed results can be found in the residue use paper.

The review of management options in the PME production, which led to the creation of the scenarios presented in the management paper, showed that the main potentials for environmental improvements are yield increase and residue uses. The management paper shows that yield increases, which could be as high as 75% for some plantations within the next decade compared to 2007-2011 levels, will be able to reduce the GHG emissions from PME production by app. 20%. As shown in Table 1, the residues can reduce production emissions by more than 85%. Combining the yield improvement and residue use in an optimal scenario creates a completely GHG neutral production of PME when LUC is not included according to the results in the management paper. It should be mentioned that whereas residue use provides the most GHG reductions in the PME production itself, it does not improve LUC emissions. The yield improvement has big potentials in that aspect as will be discussed in section 5.2. Three other scenarios including residue use, namely the biochar scenario and two realistic near-future scenarios, 2015 and 2020 are discussed in section 5.1.1 and 5.2.

With the creation of the GaBi model, other impacts than GWP have been quantified. These show that PME production with improved residue use generally lowers the emissions significantly in all categories except in the case of freshwater eutrophication. The freshwater eutrophication is mainly caused by fertilizer use in the plantations and sees only a very moderate improvement as the fertilizer use is not significantly impacted by the use of the residues. No indications of problems shifting to other impact categories were observed although the benefits of the residue use generally did not improve the other categories to the same extent as it did for GWP, which supports that holistic environmental management plans should not be based on GWP alone.

An economic feasibility study (see management paper in Appendix 3) showed that there are not only environmental benefits for palm oil producers from the use of residues, but economic benefits as well. In fact the palm oil industry will earn 10-20 USD per ton of CO_2 saved through residue use. Mills can either sell EFB and shells to traders at a 2012 market price of app. 8 USD/ton and 60 USD per ton respectively or use the residues in private residue energy recovery facilities and sell the products (e.g. electricity). The market price of shells is much higher than for EFB as the low moisture content makes them readily available for energy recovery purposes. Through construction of biomass power plants and biogas plants, electricity can be produced and sold to the national grid at a 2012 price of 0.11 USD/kWh. Although the potential income from plantation and mill residues of app. 75 USD per ton CPO produced are much below the 2012 CPO market price of app. 1,000 USD/ton, an average mill can still make app. 2.5 mill. USD/year from the sale of residues and/or electricity. In comparison, the same mill produces CPO at a gross value of app. 60 mill.

USD/year. Increased residue market prices can, however, be expected with the increasing focus on biomass use. The payback time for a biomass power plant has been calculated to app. 10 years at the current electricity prices and not including potential carbon credit income. Methane captured in biogas plants from the POME digestion at the mill can either be burned in the mill boiler to substitute solid wastes, which can subsequently be sold by the mill or used in a biomass power plant, or electricity can be produced directly from the methane and sold to the national grid. A biogas plant including gas engines has a calculated payback time of just over 4 years. The sale of plantation residues can also provide a small, but not insignificant side income for plantation smallholders who are often barely making enough income to maintain their plantations and sustain their families. A smallholder with a 5 ha plantation could get an equivalent income of up to 600 USD/year from trunks and fronds, which is equivalent to the monthly salary of a low-ranking office staff in Malaysia.

5.1.1 Biochar

According to the biochar scenario in the management paper, producing biochar from all trunks, EFB and shells and 50% of the frond while leaving the last 50% as mulch will turn PME production into a carbon sink when not including LUC. In the scenario a modest 5% increase in yields are assumed. This is in reality likely to be higher with the improved soil fertility that the biochar will provide. Although the scenario is no doubt a utopia, to depict the scale of the potential GHG reductions, this section quantifies impacts if the biochar scenario was implemented throughout Malaysia. The sequestration of carbon in the soil from the biochar alone amounts to 14 mill. ton CO_2 per year to which can be added another 14 mill. ton CO_2 for substituted fossil fuels through fertilizer reductions and energy potential in the bio-oil and syngas. A total of 28 mill. ton CO_2 will be sequestered or avoided equal to 15% of the total Malaysian GHG emissions in 2009. If a higher yield due the increased soil fertility is included in the calculations, the number will of course increase.

Research is currently undertaken in Malaysia to construct a mobile pyrolysis unit, which can be taken to plantation sites, which are replanting, to use the oil palm trunks and fronds as feedstock. This way the feedstock requires only a minimum of transportation and the biochar can be applied directly into the holes for the new palms.

5.2 Land Use Change

The LUC study focuses on land conversion to oil palm plantations from rubber plantations and state forest and sets up a national average for LUC emissions per ha of oil palm plantation. Note that in accordance with LCA methodology (European Commission, 2010) LUC emissions are allocated to the first generation of the oil palm plantations. Thus, any subsequent generations are thus exempted for LUC emissions. A plantation can thus be highly unsustainable in its first generation, but completely sustainable in subsequent generations. This potentially opens sustainability loopholes for biodiesel producers, which is discussed in the following paragraph.

PME is a direct derivative of palm oil in line with numerous other palm oil uses and the expansion of oil palm plantations in Malaysia can be assumed to result in LUC from the prevailing marginal land independently of the use of the palm oil. The net overall emissions from Malaysian palm oil related LUC are therefore independent from which land is used for PME and which land is use for other palm oil products. Thus, in line with LCA methodology (e.g. Finnveden et al. 2009), it is argued in this study that whether PME is produced from a plantation on former state forest, rubber or other land use, the average Malaysian LUC values should be used to assess the sustainability of the PME. This way, the LUC emissions of a single plantation have very diminished effects on the overall LUC emissions, which can be discouraging for a farmer, who aims to make a sustainable plantation. On the other hand, by not averaging the emissions, palm oil companies can simply produce PME from plantations not planted on state forest and palm oil for other applications on former state forest. This way the PME is credited as sustainable without achieving actual environmental benefits. The methodology of averaging emissions moves the incentives from the individual farmer to the national strategies thus encouraging LUC improvements on a large scale. It could be further argued that the average emissions from the whole SEA region or even worldwide palm oil production should be used, but as such data is not available, this study is limited to the Malaysian scenario. Only in the rare case when a company who wishes to produce PME establishes an oil palm plantation on a piece of land, which would not have been converted if the end product was another palm oil product than PME, can the LUC emissions from that specific plantation be allocated directly to the PME produced there.

The Malaysian average LUC emissions are calculated as the average emissions of all plantations in Malaysia where plantations more than 25 years old have been given zero emissions. Detailed explanations can be found in the LUC paper.

Another way of assessing impact of LUC emissions beyond the first generation is though LUC payback time, which is the number of years it takes for biodiesel produced from a certain area of land to pay back the GHG emissions from LUC.

As presented in the LUC paper, temporary carbon storage credit is given to the plantations, which are felled and replanted every 25 years. The temporary nature of the carbon captured in the oil palm plantations, makes carbon sequestration of relatively low significance in a life cycle perspective.

As the carbon stored in rubber plantations likewise is considered temporarily stored, the net emissions from conversion of rubber to oil palm are relatively low although the carbon storage in rubber plantations is higher than in oil palm plantations. The study assumes that the displaced rubber is replaced by synthetic rubber as the global synthetic rubber production is increasing faster than natural rubber production. As synthetic rubber production emits slightly higher GHG emissions than natural rubber production, this additional induced emission is added to the LUC emissions. The total LUC emissions from rubber to oil palm are, however, still small in a life cycle perspective amounting to about 15% of the total GHG emissions for conventional PME production.

The picture changes significantly when state forest is converted to oil palm. As a virgin forest has often existed for thousands or millions of years, the carbon stock in the forest is considered equal to fossil carbon in LCA methodology (e.g. European Commission 2010). Although approximately 50% of the carbon loss is allocated to logging for state forest conversion, the fossil nature of the carbon means that LUC emissions are more than twice as high as the GHG emissions from the PME production processes per MJ PME.

Malaysian average emissions are highly dominated by state forest conversions as more than 40% of oil palm conversions in the past 25 years have taken place on state forest. This amounts to 30% of all Malaysian oil palm plantations of all ages. LUC emissions thus currently contribute almost 40% of the average Malaysian PME production emissions thus bringing the emissions to almost 70 g CO_2/MJ palm oil, which is above the EU-RED limit of 55 g CO_2/MJ for renewable energy. It should be noted that from a regulatory viewpoint, LUC emissions for plantations established up to 25 years ago cannot be included. EU-RED only takes emissions since 2008 into consideration (European Parliament 2009). Applying this methodology, the average Malaysian PME production only emits 45 g CO_2/MJ and is thus clearly below the EU-RED limit. The emission cut-off due to plantation age is further discussed later in this chapter.

Figure 2 shows the LUC payback time under the various scenarios in the GaBi model. Please see the management paper for detailed descriptions of the scenarios. Residue use was the most promising environmental improvement in the PME production without the inclusion of LUC. Figure 2 shows that the Vision 35/25 scenario, which is based on Malaysian Government targets of 35 ton FFB/ha/year (75% improvement) and 25% oil extraction rate the mill (25% improvement) by 2020 but no other improvements, has LUC payback times lower than the Residue Energy Recovery scenario.

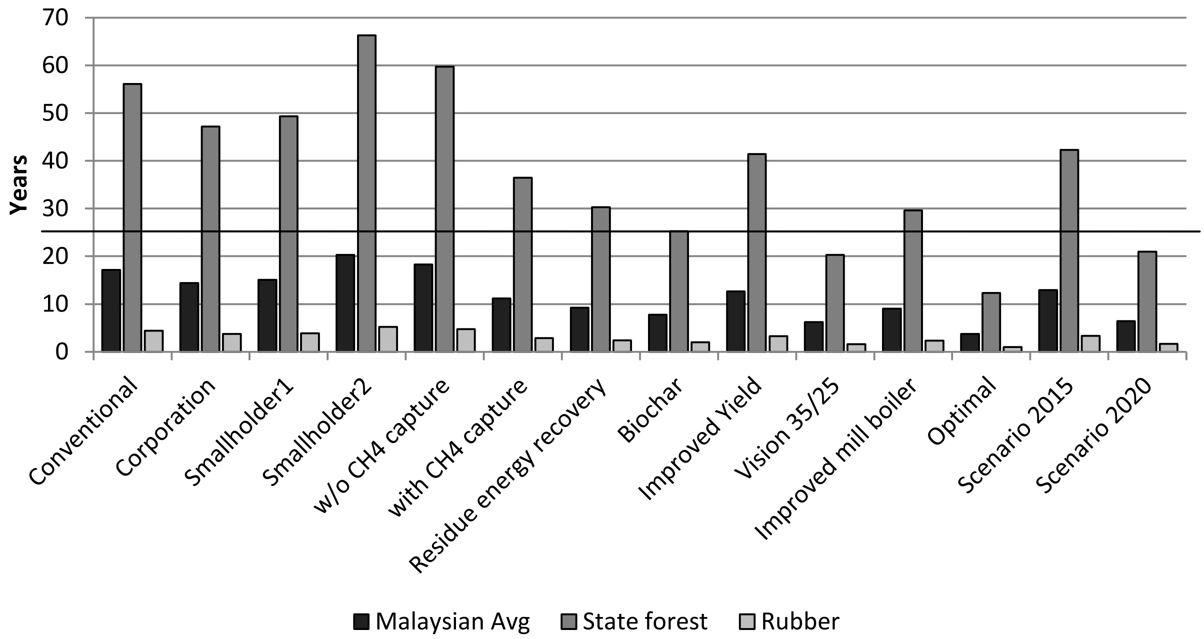

Figure 2 – LUC emissions payback time for PME
The horizontal line at 25 years represents the duration of one oil palm cycle.

Scenario 2015 and Scenario 2020 are predictions made in the study of the actual development in the Malaysian palm oil industry based on Malaysian Government targets and current development trends. The scenarios show the payback time is falling significantly. The actual payback time for Malaysian average LUC will thus be less than the 17 years predicted in the steady state Conventional scenario. For a plantation established today, a payback time of 11 years can be expected, taking the gradual environmental improvements in the PME production up until 2020 into consideration.

The Malaysian average LUC emissions include LUC emissions for plantations planted in the past 25 years, as LUC emissions should be allocated to the first plantation cycle (European Commission, 2010). It is debatable whether to take into account emissions, which were generated before the severity of the emissions was fully understood. Figure 3 shows the accountable emissions and payback times from average Malaysian LUC based on emission cut-off by age of the emission; i.e. how old a plantation should be before its LUC emissions can be omitted from an assessment. Conventional PME production is sustainable as per the definition in section 1 if the cut-off age for LUC emissions is lower than 10 years. With the expected environmental improvements in the coming years as per Scenario 2015 and Scenario 2020, PME will be able to meet the sustainability criteria with inclusion of the full 25 years LUC emissions by 2017 if the ratio of previous land uses converted to oil palm remains the same.

Future LUC emissions for palm oil will be highly subjective to the marginal land considerations. The oil palm area in Malaysia expands by app. 0.14 mill. ha per year (MPOB, 2012). In order to test the sensitivity of the average Malaysian LUC to LUC changes in the coming years, the error bars in Figure 3 depicts the emissions and payback time next year with only conversion of state forest in that year (positive error bar) and an alternative approach of converting only degraded/GHG neutral land in the next year (negative error bar). Thus, the error bars represent the range of positive of negative changes to the Malaysian average LUC emissions and payback times achievable in one year.

Not surprisingly, the relative sensitivity to the changes in the coming year is higher, the shorter the accountability period of past LUC emissions is with a variation of app. +/- 5% for the 25-years cut-off to app. +/- 20% for the 5-year cut-off. The variations in the payback time are app. one additional year with the increase in state forest conversion and app. half a year shorter payback time with conversion from GHG neutral land. With firm environmental strategies in hand, significant reductions in the LUC emissions from palm oil in Malaysia are thus possible even over a short time period. In the past 10 years, the average palm oil related LUC in Malaysia has consisted of 56% state forest, 25% rubber plantations and 18% other agricultural land with a trend of an increasing fraction of the LUC being from state forest. National strategies must turn this marginal land trend from state forest towards degraded land and grasslands and ensure that strategies are implemented to regenerate these lands to make them attractive for the palm oil industry. As per section 5.1.1, biochar provides a potential closed-loop solution to this.

Indirect land use changes (ILUC) have not been included in this study, but a brief discussion is made in section 6.2.

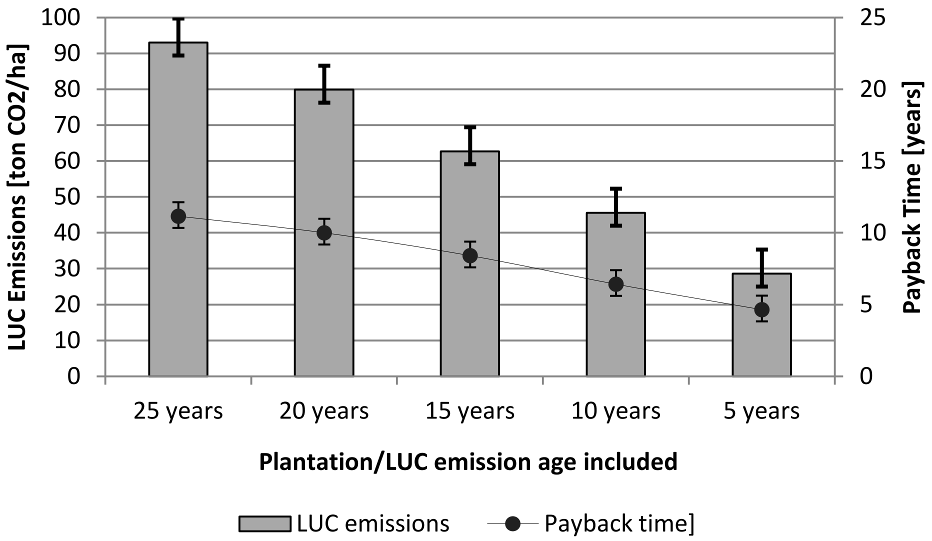

Figure 3 – Malaysian average LUC emissions and payback time with emission age cut-off

5.3 Environmental Management

The environmental management study has three focus areas namely 1) environmental impacts from corporations and smallholders, 2) environmental impacts in prospective scenarios, 3) economic feasibility of the prospective scenarios. Focus areas 2 and 3 are largely related to residue use and LUC, which is covered in sections 5.1 and 5.2 with additional data and discussions available in the management paper in Appendix 3, so this section concentrates on focus area 1.

It must be noted that the data collected on yields and fertilizer and pesticides application from plantation smallholders is subject to higher variations than expected and the dataset cannot be characterized as statistically significant, so the results of the study are indicative.

The results show that differences in the GHG emissions from corporations and smallholders are within 5% of each other, which, with the level of uncertainty is inconclusive. The main differences identified between smallholders and corporations are the uses of fertilizers/pesticides and the corresponding yields. Smallholders have a smaller fertilizer and pesticide consumption, but generally lower yields as well, so the trade-off between the two determines the environmental performance. Whereas smallholders tending carefully to their plantation are able to reach the same level of yield as the corporations with lower fertilizer input and thereby clearly perform better environmentally speaking, some smallholders are not attentive of their plantation and/or cannot afford enough fertilizer to generate a good yield. The low yield is especially a problem as it leads to higher land requirements and thereby more LUC as was depicted in Figure 2. Governmental development programs could turn the vicious circle of low yield-low income-low fertilizer application-low yield around with added environmental benefits by providing small loans to the smallholders for a few seasons until the yield has improved and more income can be generated per ha.

Looking at other impact categories than GHG, the smallholders do have an environmental advantage due to the lower fertilizer and pesticide use; especially within freshwater eutrophication.

6 Other challenges not yet fully included in LCA methodology

6.1 Biodiversity

The international literature unanimously agrees on the significant impacts on biodiversity from the conversion from forest to oil palm plantations. A total number for the biodiversity impact is difficult to quantify as the impacts are different for plants, mammals, birds and insects. Sodhi et al. (2009) created an ecological health classifier based on the various biodiversity parameters and concluded that the ecological health is 36% higher in primary forest than in plantations and 22% higher than in disturbed forest. Based on this it can be argued that the biodiversity impacts are much less severe when the plantation replaces secondary forest. However, Sodhi et al. (2009) treats all plantations under one and Fitzherbert et al. (2008) argue that oil palm supports less biodiversity than forest species plantations (e.g. rubber, coffee and cocoa). The general trend in the literature is that oil palm supports only about half of the biodiversity compared to primary forest and that secondary forest is thus a much preferred alternative in biodiversity terms (e.g. Berry et al. 2010). The palm oil industry in Malaysia has been striving to minimize the biodiversity impacts from oil palm plantations through wildlife corridors and buffer zones. However, as long as forest is converted to palm oil there will always be a significant biodiversity impact, which severely harms overall sustainability efforts of the industry.

6.2 Indirect land use change, ILUC

ILUC is relevant in relation to palm oil in two main aspects:

1. When conversion of another crop like rubber is converted to oil palm takes place, the lost rubber production will be replaced by synthetic rubber production (induced production) or by establishing a rubber plantation somewhere else (ILUC). Depending on what land the new rubber plantation is placed on and the market forces in place, this can create another round of ILUC etc. ILUC often takes place across country and even regional boundaries and the dependence of market forces largely moves the focus from an environmental assessment to a market assessment. From an environmental point of view, ILUC and induced production are as relevant to the sustainability of a product as direct LUC, but the complexity of establishing valid data is beyond the resources available for most studies, including this one.
2. Palm oil is the fastest growing vegetable oil on the world market and thus the marginal oil (Schmidt and Weidema 2008), i.e. the oil which is most likely to be produced in order to cover increasing world demands for vegetable oil. This means that by producing biodiesel from e.g. rapeseed oil, the demand for rapeseed oil for other applications will likely be met by palm oil, i.e. induced production. When assessing the impacts of producing biodiesel from rapeseed oil, the impact from the production of palm oil must be included in the assessment. LUC impacts from palm oil production thus become ILUC impacts for rapeseed biodiesel. This puts additional pressure on academia and the palm oil industry to work together to reduce emissions in general and especially the large emission related to forest conversion.

6.3 Socio-economic and regulatory aspects

The sustainability of a product is influenced by environmental, economic and social aspects. This section will highlight some of the socio-economic discussions and dilemmas and regulatory initiatives related to PME production without attempting to provide solutions and conclusions.

Socio-economic

The expansion of oil palm plantations into forests has obvious socio-economic impacts on local communities and the impacts go in both directions. Whereas some studies have focused on the negative aspects of forest communities being displaced (e.g. Colchester et al. 2007), there are examples (e.g. Rist et al. 2010)) of local communities being able to afford infrastructure and schools with the arrival of oil palm plantations. These aspects as well as labour wages, discrimination and working conditions amongst others are parameters often included in social LCA (Jørgensen et al. 2008). Such studies would have very high relevance in a country like Malaysia where labour rights are limited. The socio-economic aspects can also lead back to environmental impacts. The development of a community will inevitably lead to higher consumption and thus increased environmental footprint; on a regional/global level through production of the consumed goods and on a local level through unsanitary waste disposal. The latter is often seen in Malaysia and has in some circles been termed 'the banana leaf mentality': Banana leaves are traditionally used as plates and packaging material in Malaysia. After use, the banana leaves are simply discarded in the nearest convenient location where it degrades. In a developed community, the banana leaves are often replaced by plastic based products, but in the case of communities going through rapid development, the banana leaf mentality of simply throwing the rubbish on the ground still exists thus leading to plastic bags and wrappers and even batteries being seen everywhere at the side of the roads.

Regulatory

The future of biodiesel is largely dependent on regulations of large bodies like the EU. With EU-RED (European parliament 2009), the focus on renewable biofuels was kick-started in the EU with the aim of 10% of vehicle fuel from renewable sources by 2020. Numerous environmental assessments have, however, shown that most first generation biodiesel is not renewable following the EU-RED criteria; especially with the inclusion of ILUC. It now appears that the EU is planning to change the strategy away from first generation biofuels although it is currently only a proposal to do so (Andersen 2012). Such an initiative from the EU along with ongoing academic research is likely to create a worldwide trend and potentially halt the production of PME before it has really taken off.

However, new regulatory turns may happen in the future. Impacts of biodiesel production is held against the life cycle impacts of fossil diesel. As the global oil reservoirs are slowly depleting, higher and higher life cycle emissions will be associated with fossil diesel. It could be argued that the marginal fossil will soon be oil sands, which has life cycle GHG emissions 15-20% higher than conventional oil and potentially higher impacts in other impact parameters as well (Charpentier er al. 2009). Such changes in reference systems may give first generation fuels based on energy crops a revival unless other technologies are developed to provide the necessary energy.

7 Conclusions

This study sets out to generate LCI data for central, yet underexplored elements in the production of PME with a focus on GHG. The choice of LUC was taken with the aim of establishing an inventory of the GHG emissions from current practices using LCA methodology not previously used on oil palms. From a more dynamic angle the elements of residue use and environmental management choices were included to be able to incorporate potential environmental improvements into the assessment.

PME production from conventionally produced palm oil with national average LUC emissions emits 70 g CO_2/MJ, which is only 17% lower than the life cycle emissions of fossil diesel. This study, however, shows that significant environmental improvements are available with currently available technologies to bring the impacts well below the defined sustainability limit of 55 g CO_2/MJ with economic profitability.

Residue use shows a big potential for improvement. The conventional residue management at plantations and mills of mulching fronds, trunks and EFB and treating POME in open lagoons causes net GHG emissions. On the contrary, the prospective residue use of energy recovery through biomass power plants, pyrolysis and biogas will substitute fossil fuels either directly in industrial boilers or through avoided electricity production and create GHG reductions in the production of PME. The fossil fuel substitution from residue use alone is so significant that net GHG emissions from the PME production process can become close to CO_2 neutral at 6 g CO_2/MJ when not including LUC. An added bonus for the palm oil industry is that such improvements are likely to result in a net income of 10-20 USD/ton CO_2 saved through sales of residues and/or residue use products.

LUC emissions can potentially result in so large GHG emissions when high-carbon stock land is converted to oil palm that no environmental improvements or management strategies will be able to make the produced palm oil sustainable. The GHG emissions from LUC contributions to PME planted on former state forest are thus 92 g CO_2/MJ in the first 25 years of production. On the other hand, conversion of low-carbon stock land or land with a temporary carbon stock can result in low or even negative LUC emissions thus giving PME carbon neutral potentials when combined with environmental initiatives in the production. This potential can, however, be influenced by ILUC, which is not included in this study. The methodological choice of focusing on the Malaysian average LUC emissions results in LUC contributions of 28 g CO_2/MJ with moderate improvement potentials of just over 1 g/CO_2/MJ per year if all future LUC is done through CO_2 neutral LUC. With the current trend in palm oil related LUC in Malaysia, the improvement is likely to be much slower.

The impacts from LUC as well as the PME production process can, however, be improved through management strategies. Increasing yields have a direct correlation with lower LUC emissions per MJ PME and with potentials of up to 75% yield increases from the plantations, Malaysian average LUC emissions could thus go as low as 15 g CO_2/MJ, which would also be the net GHG emissions from PME production with the combined residue use and yield improvement potentially making the production process CO_2 neutral.

Such a scenario would require an optimization of the production system, which may be possible from a few dedicated producers, but is very unlikely as a Malaysian average scenario in a foreseeable future. However, the two future scenarios set up in this study show that the GHG emissions from PME are likely to drop from the current 70 g CO_2/MJ to 62 g CO_2/MJ in 2015 and 29 g CO_2/MJ in 2020 and are thus on track to meet the sustainability criteria.

Assessing other impact categories than GWP shows that all impact categories experience reduced impacts due to the proposed environmental improvements in the management scenarios set up in this study. Thus, even though most other impact categories experience lower benefits that GWP, it can be concluded that the proposed improvements do not result in problem shifting. Holistic environmental management plans in the palm oil industry should, however, assess other impact categories than GWP in order to ensure the best overall environmental improvements.

8 Perspectives & Research Recommendations

It is the hope that the results of this study may contribute to the continuous research on and application of environmental improvements in the production of palm oil, whether it is used for PME or other applications. Palm oil is the biggest, cheapest and fastest growing vegetable oil on the world market and despite the scare campaigns of many NGOs it is not going away. The high yields per ha and the potential low impact production makes it attractive environmentally speaking as long as the conversion of forests are avoided. Research should thus be conducted by academia, the palm oil industry and NGO's not to limit the production of palm oil but rather to ensure the sustainable production of it.

This study has identified the following topics as the most critical research areas in the quest for a complete palm oil LCI and thus for holistic environmental management plans:

- Carbon stock measurements of all areas earmarked or suitable for oil palms and the development of carbon stock maps to help the Government and the palm oil industry to coordinate future expansions in a sustainable manner.
- Research on restoration of degraded lands e.g by the use of biochar could help divert the future oil palm expansions away from forests.
- Peatlands are potential emitters of immense amounts of GHG and the unique biodiversity of wetlands are under threat as well. The actual impacts of peatland conversion to oil palm must be thoroughly researched.
- Avoiding forest conversion when expanding oil palm plantations could lead to ILUC or other indirect impacts. These chain reactions must be studied in the Malaysian scenario.
- This study has shown that residue use can have a very significant positive impact on the carbon balance of palm oil production. In depth LCAs are needed for other potential uses like biochemical applications to generate data basis for future decision making on residue use.
- Nitrogen emissions to air (N_2O) and water in the plantations due to fertilizers and mulching could result in significant climate change potentials and eutrophication. Studies of the nitrogen balances and microbiological processes should be undertaken.
- The fate of pesticides should be studied, both in terms of the application, which is done manually with often poor safety measures and in the soil.
- The water footprint of palm oil is potentially significant and should be studied.
- Ensuring yield increases will help limiting the plantation expansions. The palm oil industry itself is already conducting intense research in this field.

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10 Appendices

- Appendix 1 – Residue Use Paper
    - Appendix 1a – Supplementary Data
- Appendix 2 – Land Use Change Paper
    - Appendix 2a – Supplementary Data
- Appendix 3 – Management Paper
- Appendix 4 – Fieldwork in Malaysia
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Appendix 1 – Residue Use Paper

Greenhouse gas reductions through enhanced use of residues in the life cycle of Malaysian palm oil derived biodiesel

Sune Balle Hansen, Stig Irving Olsen, Zaini Ujang

Bioresource Technology, 2012

References to appendices 1-7 made in the paper are for the supplementary data submitted to the journal for online access. The supplementary data can be found in Appendix 1a

Bioresource Technology 104 (2012) 358–366

Contents lists available at SciVerse ScienceDirect

Bioresource Technology

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

Greenhouse gas reductions through enhanced use of residues in the life cycle of Malaysian palm oil derived biodiesel

Sune Balle Hansen [a,b,*,1], Stig Irving Olsen [a], Zaini Ujang [c]

[a] DTU Management Engineering, Technical University of Denmark, Produktionstorvet Building 424, 2800 Kgs. Lyngby, Denmark
[b] UTM Razak School of Engineering and Advanced Technologies, University of Technology Malaysia, KL International Campus, Jalan Semarak, 50300 Kuala Lumpur, Selangor, Malaysia
[c] Office of the Vice-Chancellor, University of Technology Malaysia, 81310 Skudai, Johor, Malaysia

ARTICLE INFO

Article history:
Received 5 July 2011
Received in revised form 19 October 2011
Accepted 21 October 2011
Available online 29 October 2011

Keywords:
Palm oil
Waste treatment
Life cycle assessment
Bioconversion
Thermochemical conversion

ABSTRACT

This study identifies the potential greenhouse gas (GHG) reductions, which can be achieved by optimizing the use of residues in the life cycle of palm oil derived biodiesel. This is done through compilation of data on existing and prospective treatment technologies as well as practical experiments on methane potentials from empty fruit bunches. Methane capture from the anaerobic digestion of palm oil mill effluent was found to result in the highest GHG reductions. Among the solid residues, energy extraction from shells was found to constitute the biggest GHG savings per ton of residue, whereas energy extraction from empty fruit bunches was found to be the most significant in the biodiesel production life cycle. All the studied waste treatment technologies performed significantly better than the conventional practices and with dedicated efforts of optimized use in the palm oil industry, the production of palm oil derived biodiesel can be almost carbon neutral.

1. Introduction

Palm oil is the biggest vegetable oil in the world with a 2009 market share of 31.7%, which increases to 35.4% with the inclusion of the co-product palm kernel oil (MPOB, 2010). In Malaysia oil palm plantations take up 14.3% of the total land area with an average and relatively constant growth rate of 3.9% from 2005 to 2009 (MPOB, 2010). The production of 17.6 million tons of crude palm oil (CPO) and 2.1 million ton crude palm kernel oil, CPKO, in 2009 (MPOB, 2010) makes the palm oil industry the fourth largest revenue sector in Malaysia in 2009 with a gross national income (GNI) contribution of USD 17 billion after oil and gas (USD 36 billion), financial services (19 billion) and wholesale and retail (19 billion) (PEMANDU, 2011). In 2009 Malaysia exported 227,457 tons palm oil derived biodiesel (MPOB, 2010). Apart from ensuring sustainable land use change, the use of residues for optimal environmental performance in the life cycle of palm oil biodiesel production is one of the most important criteria in ensuring sustainable palm oil.

The aim of this paper is to evaluate the significance of technological improvements on the greenhouse gas (GHG) balance in handling of residues from palm oil and biodiesel production compared to conventional practices. This is done through application of life cycle assessment (LCA) tools. A brief background literature review is given in Appendix 1 of the Supplementary data.

Among the various waste treatments available, this study focuses on technologies, which are available for full scale implementation and that provide energy recovery (electricity, steam, etc.) or carbon sequestration. The chosen technologies, hereafter termed 'prospective technologies' are thus: (1) incineration with energy recovery, (2) pyrolysis, (3) biogas. As such it is not the aim to create a utopian best case scenario, but rather to assess the conventional residue use and disposal as well as realistic improvements to these conventional practices. A flow diagram identifying the conventional practices, prospective technologies and qualitative emissions/benefits of the various treatments is provided in Fig. 1 in Section 3. It should be noted that all four technologies have already been implemented full scale in the Malaysian palm oil industry, but only in very few cases as of primo 2011. The conventional practices are not a worst case scenario. Except for the palm oil mill effluent, POME, all residues are generally used, thus creating very little actual waste through low-tech application. In a worst case scenario, all residues would be landfilled in open dump sites. The implementation of the prospective technologies is unlikely to be a best case scenario. It is likely that some residues can be refined to replace products, which are very energy intensive to produce and thus create larger GHG savings than the three relatively low-tech prospective technologies included in this study.

* Corresponding author at: DTU Management Engineering, Technical University of Denmark, Produktionstorvet Building 424, 2800 Kgs. Lyngby, Denmark. Tel.: +45 4525 4660.

E-mail addresses: sbal@man.dtu.dk, suneballe@yahoo.dk (S.B. Hansen).

[1] Tel.: +60 12 219 9441.

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doi:10.1016/j.biortech.2011.10.069

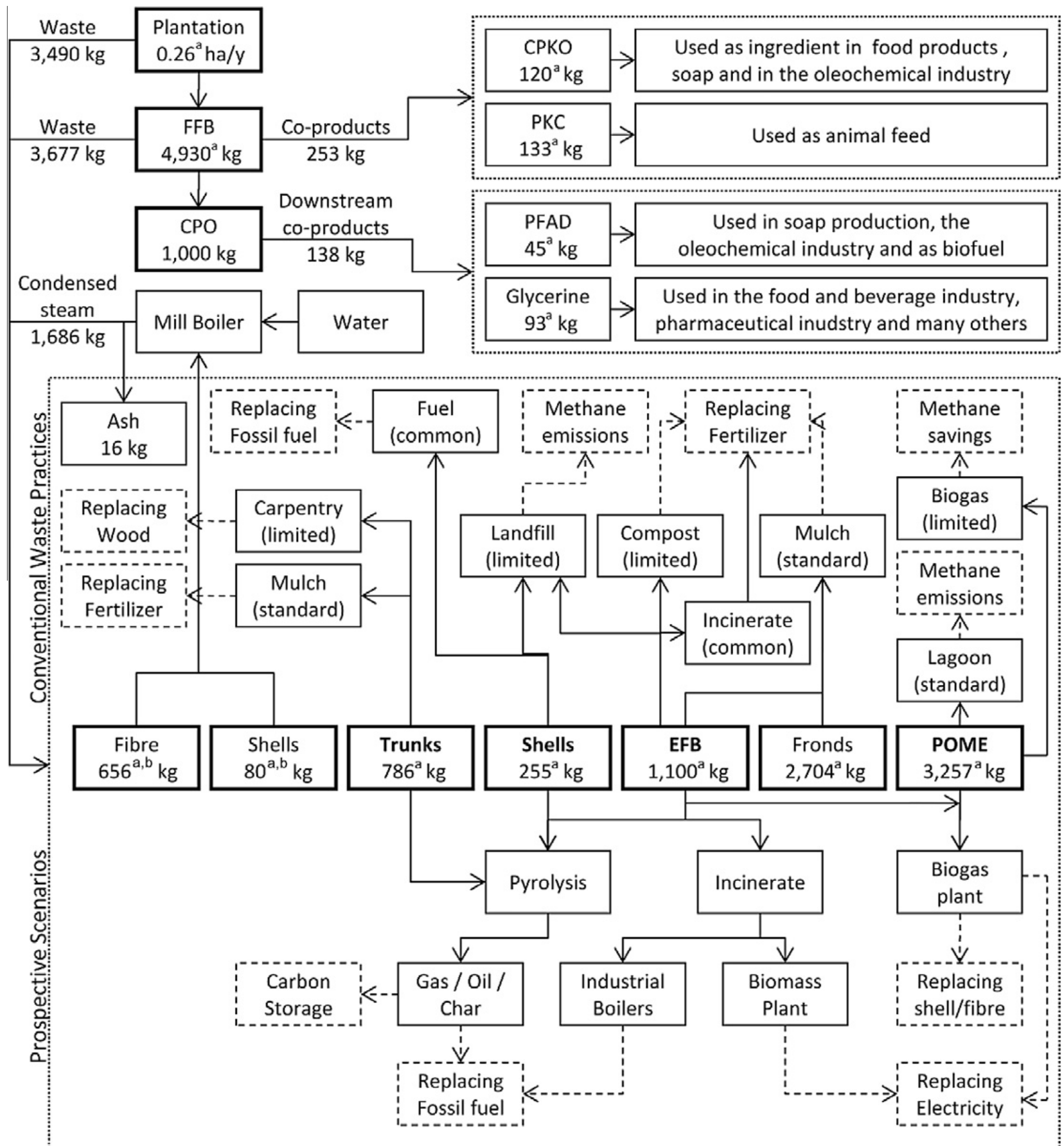

Fig. 1. Conventional practices and prospective technologies. (a) All quantities are wet weight averages from MPOB (2010), Felda (2010), Schmidt (2007), Subramaniam et al. (2008), Wicke et al. (2008), Yusoff (2006). Please find references for the uses in the following sections on the respective treatment technologies. For details from the individual studies and for an easy overview of the residue quantities, please refer to Appendix 2 of the Supplementary data. (b) Fiber is depicted as being fully utilized in the mill boiler. That is not conventional practice, but it is applied in this study. Also, approximately half of the shells are currently used in the boilers, not only 80 kg. See Section 3.1 for explanation.

In order to quantify the scale of the benefits from residue utilization in relation to the overall GHG emissions from palm oil derived biodiesel, the GHG emissions/reductions from the conventional and prospective treatment technologies are identified and compared to life cycle emissions for palm oil derived biodiesel. A scenario of the conventional practices is created and compared to a scenario of prospective treatment technologies thus presenting the actual benefits of the prospective residue utilization. In order to assess the sensitivity and uncertainty of the findings, the results and assumptions for each treatment technology (conventional and prospective) and the full scenarios as well as worst and best case scenarios will be assessed and a potential bandwidth for GHG emissions/reductions will be established. The sensitivity for the prospective scenario is given special attention.

Capturing the vast amounts of methane from the anaerobic digestion of palm oil mill effluent (POME) through the construction of biogas plants is recognized as one of the most important environmental challenges in the production of palm oil. It is hypothesized that adding solid residues, e.g. from empty fruit bunches (EFB), to the POME would boost the methane production in the biogas plant thus allowing for increased electricity production from combustion of the methane in gas engines at little extra cost. Experimental studies of biogas production from EFB were performed to test this hypothesis.

To the knowledge of the authors, the present study is the first to attempt to quantify and compare GHG emissions/reductions of various palm oil waste treatment technologies in a life cycle perspective. Industry specific data for this kind of studies are sparse and to some extent inconsistent as of primo 2011. As such, this study should be seen as an introduction to life cycle assessments of waste treatment in the palm oil industry and a platform on which to extend further studies on the topic.

2. Methods

Data collection and generation for the study has been conducted through literature reviews, discussions with palm oil industries and research institutions and through experimental analysis in the case of biogas generation from EFB. The results focus quantitatively on greenhouse gas emissions with qualitative discussions on other impacts.

2.1. Life cycle assessment

The life cycle assessment methodology applied is in accordance with standardized practices in ISO 14040 and ISO 14044 as described in the ILCD Handbook (ILCD, 2010). When assessing the transformation of residues into a new product or energy it can be done through allocation or substitution (ILCD, 2010). Substitution is used in this paper. This study focuses on greenhouse gas emissions and savings for which the denominator is CO_2-equivalents. One kg of methane corresponds to 25 kg CO_2-equivalents (IPCC, 2006). Lower heating (net calorific) values (LHV) are used in the calculations as per IPCC guidelines (IPCC, 2006). When substituting e.g. coal fired in an industrial boiler with a waste product it is done on a MJ–MJ basis with a correction factor to adjust for possible pretreatment of the residue, i.e. 1 MJ residue = 0.9 MJ coal. For transportation emission calculations, CO_2 emissions per ton $*$ km using a 22 ton truck (PE International, 2006a) are applied.

2.2. Data collection

Data was collected mainly through literature studies for the various waste treatment technologies translated into life cycle data. Where possible, data is specific to palm oil residues and based on experimental studies, however, for pyrolysis and gasification some generic data is included.

2.3. Experimental set-up

This section provides an overview of the experimental set-up. A full description can be found in Appendix 2 in the Supplementary data.

The experiments were designed to provide indications of the biogas potential in fibrous solid palm oil residues. The shredded EFB from a palm oil mill were digested in a batch process, fully mixed, 52 °C thermophilic digester for 21 days at a loading of 5% w/w. On day one of the experiments, 200 g shredded EFB were added to 4 L thermophilic anaerobic bacteria solution in an insulated 5 L glass bottle. The bottle (hereafter 'digester') was sealed to allow only for a gas tube and a thermometer and placed on a combined heater/magnetic stirrer. Produced gas volumes were measured continuously and recorded daily to study degradation of the fibers as a function of the hydraulic retention time, which is crucial for estimating the potential loading of fibers into a full scale biogas plant. The methane content of the biogas was analysed twice weekly. After the 21 days the digester was opened and the digestate was analysed for nutrient values in order to assess its potential in application as a fertilizer.

3. Results and discussions

This section quantifies the GHG emissions and savings from conventional waste treatments and prospective technologies. A summary of the potential GHG savings in relation to the life cycle emissions from palm oil derived biodiesel production is given along with a quantification of the GHG savings between a scenario of the conventional practices and a scenario of prospective waste treatment technologies. Fig. 1 depicts the residue quantities along with conventional practices, prospective technologies and the liabilities/benefits. For the conventional practices it is indicated whether it is a standard, common or limited practice. The various current and potential utilization options for the palm residues have several varieties. In order to present a concise overview, some generalization and simplifications have been made in the following sections. These are dealt with in a quantitative uncertainty analysis in Appendix 7 in the Supplementary data and the calculated bandwidth of the GHG data for each treatment technology is presented in the respective sections. An overall sensitivity and uncertainty analysis for the scenarios is presented in Section 3.8.

3.1. Boiler fuel

Palm oil mill boilers produce steam for sterilization and softening of the incoming fresh bruit bunches (FFB). The boilers are fired exclusively with press fiber and shells from the mill. The third solid residue from the mills, EFB, has high moisture content and is not well suited as boiler fuel. Without sufficient amounts of fibers and shells available, the steam generation would have to be based on external, possibly fossil fuels. For environmental and economic reasons the availability of fibers and shells for other applications is thus limited due to onsite demand for steam generation. The average fuel ratio was approximately 60% fiber and 40% shells in the early 2000s (Husain et al., 2002), but has changed to approximately 75% fiber and 25% shells (Subramaniam et al., 2008) and the trend is to utilize more fiber in the boilers and add shells as needed. There are mainly two drivers for this trend: (1) the shells produce undesirable black smoke with a lot of particulate matter and the palm oil mill boiler stacks do not have particle filters, (2) with their higher energy content (see Table 1) and density, the shells have a higher market value and lower transportation costs per energy unit and can be sold as boiler fuel to other industries. The 16 kg boiler ash generated per ton CPO can be used for various applications such as road filling, concrete production and adsorbent or as fertilizer in the plantations. This study assumes that the manner in which the boiler ash is used is of low significance relative to the other residues and the overall life cycle impacts for palm oil due to the small quantities, so further quantitative studies on ash are omitted from this paper.

3.1.1. GHG data for boil fuel

Assuming the above 75:25 fuel ratio; 170 kg shells and 520 kg fibers are used for steam generation per ton CPO (Subramaniam et al., 2008) resulting in an energy input to the boiler of 8.7 GJ/ton CPO. Thus, a total of 165 kg shells and 136 kg fibers are available for other uses. If the mills decide to use all their fiber in the boilers to make as much shell as possible available for revenue generation, they would on average need to supplement with 80 kg shells to meet the energy requirements, thus leaving 255 kg shells (75%) for other applications per ton of CPO. Assuming that 255 kg shells will be available for the prospective scenarios thus seems reasonable and the value is used in the following sections.

The mill boilers in Malaysia are generally inefficient as efficiency is not prioritized with the surplus availability of fibers and shells, which until recently did not have market value. The uncertainty analysis tests a 20% increase in boiler efficiency in the prospective scenario, which will make the fiber alone able to meet the energy requirements, thus making the remaining 80 kg shells available for other applications.

3.2. Mulch

All the fronds from the oil palms and some of the EFB from the mill are spread out between the oil palms as mulch to retain

Table 1
Mill residue energy contents.

	Moisture (%)	LHV (MJ/kg) dry weight	LHV (MJ/kg) wet weight	LHV (MJ/ton CPO)	Pot. electricity[a] (kWh/ton CPO)
EFB	66	17.9	6.1	6690	390
Press fiber	39	18.1	11.1	7290	–
Shell (75%)	11	19.1	17.0	4330	250
Total	–	–	–	18,310	1070

All values are based on averages from Chow et al. (2008).
[a] At 21% combined boiler and steam turbine efficiency.

moisture in the soil and provide nutrients through the degradation of the organic matter. The practice has proven to improve the root proliferation and the yield of the oil palms. The total nutrient requirements at the oil palm plantations are on average 264, 30 and 395 kg/ha/year for N, P and K, respectively on coastal soils in Malaysia including losses due to leaching (Henson and Chang, 2007). It should, however, be noted that significant variations exist depending on soil type. The mulched fronds contribute 126, 12 and 158 kg/ha of N, P and K, respectively (Henson and Chang, 2007). With 0.26 ha needed to produce 1 ton CPO per year, the remaining nutrient demands to be covered by EFB mulching and fertilizer translate to 36, 5 and 62 kg/ton CPO for N, P and K, respectively. The available EFB will only be able to contribute 3, 1 and 16 kg/ton CPO of N, P and K based on the nutrient content presented in Abdullah and Gerhauser (2008). EFB may not be appropriate as a fertilizer on its own, but when used in combination with industrial fertilizer, approximately 15% increase in FFB yield has been demonstrated compared to fertilizer alone (Singh et al., 1989). Although this increase is very likely to depend on other factors such as soil type and general plantation management as well, 15% increase is used as an example in the following. However, approximately 150 kg EFB is required per palm to achieve the 15% increase (Singh et al., 1989) under controlled circumstances. This paper estimates approximately 200 kg EFB per palm.

At replanting, the felled oil palm trunks are most often chipped and spread out as mulch or buried in the soil when the soil is tilled prior to planting of the new generation of oil palms. The trunks provide nutrients and carbon to the soil while degrading, however, the young palms can only utilize a fraction of the released nutrients, so most are leached to the groundwater. The method of burying the stems is thus convenient, but provides poor GHG reductions.

It is assumed that trucks bringing the FFB to the mill will bring back EFB instead of going back empty, so no transport emissions are allocated to EFB.

3.2.1. GHG data for mulching

The 200 kg EFB required per palm corresponds to over 7500 kg EFB per ton CPO. Only 15% of this is available. The increase in production due to EFB mulching on a national level is thus 15% of 15%. The areas with EFB mulching will not need P and K fertilizer and only two thirds of the N fertilizer. Thus, fertilizer savings due to EFB mulching are 5% N, 15% P and 15% K. 2% higher yield translates to 2% less fertilizer per ton CPO, so the net fertilizer savings are thus 7% N, 17% P and 17% K on a national level assuming all EFB is used as mulch. Effectively 2.5 kg N, 0.8 kg P and 10 kg K are potentially substituted per ton CPO. Using the Ecoinvent database in LCA software Gabi (PE International, 2006b) to calculate CO_2 emissions from fertilizer production gives a total saving of 14 kg CO_2/ton CPO.

In accordance with the IPCC guidelines (IPCC, 2006), composting emits some methane as well as N_2O, which makes it probable that mulching has similar emissions. IPCC (2006) provides emission ranges of 0.03–8 g CH_4/kg wet waste, 4 being the default value and 0.06–0.6 g N_2O/kg wet waste, 0.3 being the default value. As EFBs are not dense and are spread in a single layer, thus minimizing anaerobic conditions and as EFB has a lower nitrogen content than assumed in the IPCC calculation and it is only slowly released during degradation, the low ends of the ranges are used in the present study. Thus 0.4 g CH_4/kg waste (10% of the default value) corresponding to 11 kg CO_2-eq/ton CPO and 0.06 g N_2O/kg waste corresponding to 20 kg CO_2-eq/ton CPO are assumed emitted from the degrading EFB. On the other hand, N_2O emissions from mineral N fertilizer would be saved. Again using the low end of the range from fertilizer application on land in IPCC (2006), 0.003 kg N_2O–N is released per kg N of industrial fertilizer amounting to a saving of 4 kg CO_2-eq/ton CPO for replacing mineral fertilizer.

The total GHG balance for applying EFB as mulch is thus an emission of 13 kg CO_2-eq/ton CPO. The uncertainty analysis revealed that depending on whether the actual methane and N_2O emissions are in fact negligible or possibly as high as the IPCC (2006) default values, the bandwidth of the GHG data varies from a net GHG reduction of 14 kg CO_2-eq/ton CPO to emissions of 180 kg CO_2-eq/ton CPO when EFBs are applied as mulch.

3.3. Open lagoons and landfilling

Nearly all palm oil mills in Malaysia treat the palm oil mill effluent (POME) in a series of open lagoons. The first lagoons will be anaerobic, followed by facultative lagoons and finally algae ponds to meet the stringent effluent requirements. The lagoons have no bottom liner thus resulting in leakage to groundwater and methane emissions to the atmosphere from the anaerobic ponds. No studies have been published on the quantities and environmental impacts of leakage, however, Yacob et al. (2006) measured methane emissions from open lagoons to be 12.36 kg CH_4/ton POME at an average methane concentration in the biogas of 54%.

Landfilling of excess residues is becoming rarer, as the residues have monetary market values, which can give the mills a side income. However, it is estimated that 5% of the EFB is still landfilled in Malaysia although no official reference exists.

3.3.1. GHG data for open lagoons and landfilling

At 3.25 tons POME per ton CPO, the methane emission per ton CPO is 40 kg, corresponding to 1000 kg CO_2-equivalents. The methane values in Yacob et al. (2006) seem high as the methane production in an average POME biogas plant is also 40 kg/ton CPO at a methane content in the biogas of 65% (unpublished data). However, the high values could be due to the fact that with the long retention time of 40 days in the lagoon, COD is reduced to a level of 1200 mg/L (Yacob et al., 2006) whereas the average POME biogas plant (hydraulic retention time (HRT) < 20 days) only removes COD down to 4–6000 mg/L and thus do not harvest the full gas potential.

When landfilling EFB, apart from leachate, the anaerobic degradation would be responsible for significant methane emissions. At 16% C content (wet weight) (Chow et al., 2008) and an estimated 20% C conversion to methane for this type of organic residue in a landfill, an estimated 47 kg of methane or 1180 kg CO_2-equivalents is emitted per ton CPO if all EFB were landfilled.

There is little uncertainty in the methane emissions from POME, which are well documented. However, for the landfilled EFB, a bandwidth was established assuming 15% and 25% C conversion to methane resulting in an emission range from 890 to 1480 kg CO_2-eq/ton CPO.

3.4. Biomass power

Incineration of palm oil residues can produce significant amounts of steam for electricity production or industrial processes thus replacing grid electricity or fossil boiler fuels. The incinerated biomass also has a value as a fertilizer. Rosnah et al. (2006) reports that at the time 65% of EFB were incinerated at the mills without energy recovery in order to generate ash for fertilizer. Stack emissions can be considered CO_2 neutral. Other environmental impacts will be discussed qualitatively in Section 3.8. The ash remains are about 7% of the dry weight from incoming EFB leaving 9 kg K per ton CPO equivalent to 6 kg CO_2 in accordance with (PE International, 2006b). It is assumed that ash from Shells has the same properties.

A biomass incineration plant producing electricity would also be able to dispose of the ash as fertilizer thus saving 6 kg CO_2/ton CPO (as per above) on top of the CO_2 savings from the biomass power output. Biomass used in industry boilers is often co-fired with fossil fuels making the ash less suitable for fertilizer.

It is assumed that biomass plants will be constructed in areas with easy access from the mills supplying the feedstock. An average of 50 km is estimated with the trucks driving empty one way giving a total of 100 km. If shells or EFB are sold for use in industrial boilers, the industries capable of handling biomass in their boilers are estimated to be on average 200 km from the palm oil mills thus giving a total distance of 400 km with one way empty driving.

3.4.1. GHG data for biomass power

Table 1 in Section 3.1 lists the energy contents of EFB, press fiber and shells. From a 50 tons/h palm oil mill (average size), a biomass power plant could produce 2.5 MW electricity from just the shells not used in the mill boiler and this could be almost tripled to 6.5 MW by including all the EFB. With a placement adjacent to the mill, no significant transportation of the residues would be needed. The potential CO_2 savings from replacing current Malaysian electricity mix emitting 0.75 kg CO_2-eq/kWh (PE International, 2006c) are 190 kg CO_2/ton CPO for Shells and 290 kg CO_2/ton CPO for EFB including fertilizer contribution from the ash. If residues from one ton of CPO are instead substituting coal in industry boilers, shells could replace 146 kg coal equivalent to 380 kg CO_2 and briquetted EFB could replace 225 kg coal equivalent to 590 kg CO_2.

7 kg CO_2/ton CPO for EFB and 2 kg CO_2/ton CPO for shells are emitted from transportation to biomass plants and 29 and 7 kg CO_2/ton CPO for EFB and shells respectively from transportation to industry boilers given the above assumptions.

The GHG reductions calculated above can be considered as best case scenario for power production from the residues. IPCC (2006) suggests that approximately 5 g CH_4/ton waste and 50 g N_2O/ton waste is likely to be emitted during incineration. This would reduce the GHG reductions from power production from EFB by 4% and shells by 1%.

3.5. Biogas

Biogas capture from the anaerobic digestion of POME can be done by (1) simply covering the lagoon with a flexible membrane, (2) constructing covered tanks for ambient temperature operation (~30 °C) or (3) constructing covered tanks for thermophilic temperature operation (~50 °C). As POME is easily degradable, the anaerobic technology used has little influence on the methane quantities produced as long as the required hydraulic retention time and general operation and maintenance are in place. Approximately 12 kg methane is produced per ton POME resulting in 40 kg methane per on CPO. The captured gas can be: (a) flared off thus converting the methane to CO_2 thus making the POME treatment CO_2 neutral, assuming a closed flare with close to 100% combustion efficiency is used, (b) burned in a gas burner installed at the mill boiler (co-generation) for steam production or (c) burned in a gas engine for electricity production. All three types of biogas plants and all three gas utilization techniques are in operation in Malaysia as of end 2010.

3.5.1. GHG data for biogas

At a calorific value of 50 MJ/kg, the methane from POME from producing one ton CPO can produce 220 kWh electricity at 40% gas engine efficiency. 5 kWh are required to operate the biogas plant leaving 215 kWh for export equivalent to 160 kg CO_2. Or it could replace 180 kg of press fiber or 120 kg of shells in the boiler through co-generation.

As treating the POME in a biogas plant to avoid methane emissions is the highest priority for mills in ensuring sustainable palm oil, ensuring that the biogas plant is designed to digest EFB can generate a relatively low-cost boost to gas production. Thermophilic anaerobic digestion has the advantage of improved ability to digest solid residues. Converti et al. (1999) showed a 60% increase in gas yields from solids residues under thermophilic conditions compared to mesophilic conditions. The results of the experiments undertaken in this study are shown in Fig. 2 depicting the methane production over time from EFB digestion at thermophilic conditions. The degradation of the EFB as depicted by the methane production followed a logarithmic curve with the methane potential depleted after 21 days and a total methane production of 75 g/kg EFB. In comparison, it took (Paepatung et al., 2009) 90 days to produce 78 g methane per kg EFB under mesophilic conditions, which shows that methane potentials from EFB are similar under thermophilic and mesophilic conditions, but the time scales are very different. In a full scale, fully mixed thermophilic digester the practical experience has shown that optimal hydraulic retention time is 10–12 days for stabile POME digestion and gas production (unpublished data). As EFB is meant as a supplement to the POME, the methane produced at 12 days, namely 65 g/kg EFB or 86% of the total methane per kg EFB, is used in the following calculations. In a full scale biogas plant the mixing and pumping can be affected at suspended solid contents above 10% (unpublished data). With the existing 2–4% suspended solids in POME it is thus recommended to add shredded EFB at about 5% of the POME quantity or 160 kg per ton CPO. The added EFB would produce 10.5 kg methane, which is an increase of 26% compared to POME alone. 60 kWh of electricity can be produced from the EFB methane replacing 45 kg of CO_2. It should be added that there are only relatively low expenses involved in adding EFB to a thermophilic biogas plant, thus making it a cost effective solution. As the POME from the mills is 70–80 °C and the ambient temperature is app. 30 °C in Malaysia, thermophilic conditions can be maintained in an insulated tank with little or no auxiliary heating. It must, however, be mentioned that the methane potential of the EFB was determined at batch feeding, laboratory conditions. More studies are needed to determine actual EFB degradation and methane potential when mixed with POME under full scale, continuous flow conditions.

After biogasification, 70% (dry weight) of the EFB remains as nondigestible fiber. The LHV of the remaining fiber has not been measured; however, it may be an option to use them in the mill boiler

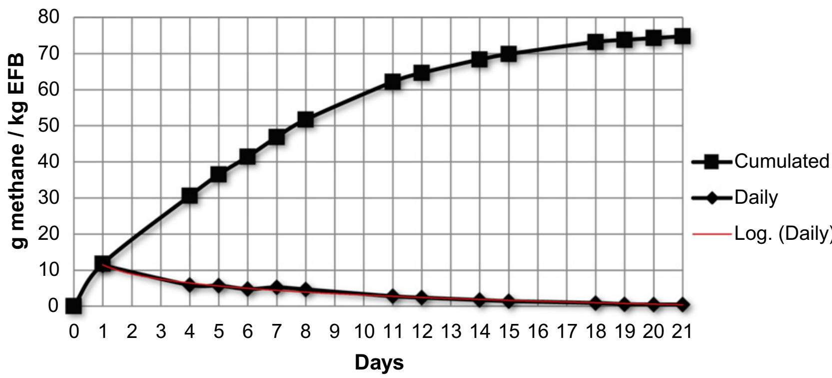

Fig. 2. Methane production from thermophilic digestion of EFB.

or in an incineration/pyrolysis plant. This could significantly improve the environmental profile of bio-gasification of EFB. Biogas plants are assumed to be constructed adjacent to the mills, so POME and EFB used for biogas do not have transportation emissions.

The anaerobic digestate retains considerable amounts of nutrients, which can be applied to the plantations as fertilizer. The fertilizer value is, however, assumed identical whether the digestate is from a biogas plant or open lagoons, so the industrial fertilizer savings are not included in the calculations. If EFB is added to the biogas plant, this study showed that 80% N, 50% P and 10% K are still present in the EFB after digestion. It is expected that the 'lost' nutrients are available in the liquid phase. There is thus an improved fertilizer value in the effluent digestate if EFB is added to the biogas plant. It is expected that this fertilizer value may be equal to that of mulched EFB, which would equal 2 kg CO_2/ton CPO at 160 kg EFB. These additional benefits are not included in the results as the potential GHG savings from use as fertilizer are uncertain and seem insignificant.

Energy recovery from the remaining digested EFB has not been scientifically quantified, but preliminary calculations in the uncertainty analysis showed that by substituting shells in the mill boiler (and use these shells in other applications), the GHG reductions from producing biogas from EFB could be doubled to a best case value of 89 kg CO_2eq/ton CPO. Conversely, it is not unlikely that a poorly managed biogas plant may have methane leakages of up to 10%, which would create a worst case GHG reduction value of 13 kg CO_2/ton CPO.

3.6. Pyrolysis and gasification

Pyrolysis is thermal treatment of organic material at anoxic conditions. Pyrolysis produces bio-oil, syngas and bio-char. With increasing temperatures more gas is produces as the carbon from the bio-char is released and the bio-oil is cracked into gaseous compounds. The ratios of the three products at various temperatures depend on the feedstock. In the case of EFB, as the temperature approaches 900 °C and beyond, the process is known as gasification, in which the output is solely gas and a few percent of ash. For Pyrolysis, three set-ups will be analyzed: Optimal bio-char production, optimal bio-oil production and optimal gas production. Bio-oil and gas can be cracked or synthesised into various products. However, for sake of simplification, in Table 2 bio-oil replaces diesel in an industrial boiler and the gas is used for electricity production in a gas engine with a standard 40% electrical efficiency. Additional data background for the values can be found in Appendix 4 of the Supplementary data.

3.6.1. GHG data for pyrolysis and gasification

The CO_2 savings from the three pyrolysis set-ups (optimal bio-char/bio-oil/gas) for the respective residues in Table 2 are not statistically different, so in Section 3.7 the average values for EFB, shells and trunks respectively are used. As for the biomass plants, pyrolysis plants are assumed to be placed at locations easily accessible for the feedstock. However, as transportation of the pyrolysis products to the final destinations have to be taken into account, 100 km distance is estimated. With empty driving one way this results in 200 km equivalent to 10, 14 and 3 kg CO_2/ton CPO for trunks, EFB and shells respectively.

In the uncertainty analysis, the double standard variations of the mean values for EFB, shells and trunks respectively have been used to create a potential bandwidth for the three residues: 362–433 kg CO_2-eq/ton CPO for EFB 253–323 kg CO_2-eq/ton CPO for shells and 180–239 kg CO_2-eq/ton CPO for trunks.

3.7. Scenarios and life cycle perspective

This section presents scenarios of the conventional and prospective waste treatment in the Malaysian palm oil industry. GHG reductions from the prospective scenario are held against the conventional scenario and the total life cycle GHG emissions from palm oil derived biodiesel in Table 3. A summary table of the GHG emissions and savings derived in Sections 3.1–3.6 can be found in Appendix 4 of the Supplementary data. According to Choo et al., 2011 it takes 1.09 ton CPO to produce 1 ton biodiesel, so the results from Sections 3.1–3.6 are multiplied by 1.09 in the following.

In order to compare the relative benefits of implementing improved waste treatment, a scenario of the conventional waste treatment is created in Table 3. No statistics currently exist, which quantify the actual distribution of residues on the various treatment technologies. The scenario is thus created through estimations based on various discussions and indirect information and may vary from actual conditions. It should be noted that other uses/treatments are currently being practiced on small scale, such as incineration with energy recovery. However, these currently constitute a small percentage and are considered under 'industrial use' (see Appendix 6 of the Supplementary data for further details).

It is unlikely that any one of the prospective treatment technologies will capture the entire Malaysian market, so rather than aiming to identify an unlikely optimal residue utilization scenario, the potential overall savings are calculated on the basis of the prospective scenario in Table 3, which assumes equal distribution within the waste treatment technologies. Only biogasification of EFB is given a smaller share as not all EFB from a mill can be used in a biogas plant (see Section 3.5.1). It is evident from Table 3 that the conventional low-tech practices such as mulching, incineration without energy recovery, open lagoon treatment of POME and landfilling compare poorly to the prospective treatments. Whereas the conventional scenario is responsible for large net emissions, the use of residues forms a carbon sink in the prospective scenario.

Table 2
CO_2 savings from pyrolysis per ton CPO.

	Bio-char		Bio-oil		Gas		Total
	Sequestered C (kg)	CO_2 equivalent[b] (kg)	Replaced diesel (kg)	CO_2 equivalent (kg)	Replaced electricity[a] (kWh)	CO_2 equivalent (kg)	CO_2 equivalent (kg)
Optimal bio-char							
EFB	45	180	55	200	31	25	405
Shells	41	160	38	140	0	0	300
Trunk	26	110	32	110	5	5	225
Optimal bio-oil							
EFB	47	180	63	230	31	25	435
Shells	37	150	43	150	6	5	305
Trunk	28	110	32	110	10	10	230
Optimal gas							
EFB	11	40	16	60	437	300	400
Shells	16	60	19	70	189	140	270
Trunk	6	20	8	30	220	150	200

[a] Including fertilizer savings.
[b] At 40% gas engine efficiency.

Thus, significant CO_2 savings can be achieved by applying advanced waste treatment.

The results show that without allocation to co-products 1125 kg CO_2-eq can potentially be saved per ton of biodiesel produced compared to a hypothetical carbon neutral disposal scenario where all carbon in the residues is simply converted to CO_2. 2000 kg CO_2-eq/ton biodiesel can be saved compared to the conventional practices. With 20% mass allocation of the savings to co-products generated at the mill (see Appendix 3 in the Supplementary data), the values are 700 kg CO_2-eq/ton biodiesel and 1595 kg CO_2-eq/ton biodiesel respectively.

In 2010, Choo et al. (2011) completed an LCA on palm oil derived biodiesel for the Malaysian Palm Oil Board (MPOB) through an extensive study of 21 nurseries, 102 plantations, 12 mills, 11 refineries and 2 biodiesel plants. The study concluded that the production of palm oil derived biodiesel emits 33.2 g CO_2-eq/MJ biodiesel without capture of methane from the anaerobic ponds and 21.2 g CO_2-eq/MJ biodiesel with capture of methane. This translates to 1340 kg CO_2-eq/ton biodiesel and 855 kg CO_2-eq/ton CPO respectively. The study is based on mass allocation for co-products and excess shells not used in the mill boiler. The allocation for shells is 14% of the life cycle emissions generated up until and including the mill (830 kg CO_2-eq/ton CPO with methane capture and without allocation). The fertilizer savings from mulching of EFB (all EFB is considered mulched) was not quantified but indirectly included as the inorganic fertilizer input would have been higher without the mulched EFB. No other residues were considered.

In order to be able to present the full conventional life cycle GHG emissions using the production emissions from the MPO study and the emissions/reductions from the conventional residue treatment scenario in Table 3, it must be ensured that there is no double counting between the MPOB study and the present study. Thus the GHG emissions from the MOPB study not including methane emissions from anaerobic digestion are used with the 14% allocation for excess shells removed and the fertilizer value from the EFB (as presented in Section 3.2.1) subtracted. The mulch emissions for methane and N_2O are not included in the MPOB study. The emissions from the MPOB study excluding emissions/reductions from any of the residues but including allocation to co-products thus amounts to $855 + 116 - (-14) = 985$ kg CO_2-eq/ton biodiesel. The emissions from the conventional residue use scenario in Table 3, minus 20% mass allocation are then added resulting in a total emission of $985 + (875 * (1–20\%)) = 1680$ kg CO_2-eq/ton biodiesel in the MPOB study when subjected to the conventional residue treatment of the present study. After subjecting the results of the present study to co-product allocation it is evident from Table 3 that 95% of the total life cycle GHG emissions from the production of biodiesel can be off-set against the GHG reductions by using the residues thus making the production of biodiesel close to carbon neutral. It is also worth noticing from the results that the shells have the highest emission reductions per ton residue, but that EFB due to the large quantities can provide the largest GHG emission savings in a life cycle perspective.

3.8. Sensitivity and uncertainty

This section focuses on a quantitative sensitivity analysis of the conventional and prospective scenario based on the GHG emission/reduction bandwidths presented in Section 3.1–3.6 and qualitative considerations regarding other impacts than global warming as well as consequential LCA.

The prospective scenario in Table 3 shows that improved residue utilization can make production of palm oil derived biodiesel close to carbon neutral. However, this scenario requires 100% use of the residues and significant investments from the industry itself or from external investors and may thus be achievable for some mills/estates, but not for all as some do not have the financial means and some are too remote and difficult to access to make residue transportation feasible. It must also be stressed that more research is required to generate a stronger scientific platform for life cycle data on palm oil waste treatment technologies and that other environmental benefits from e.g. using treated residues as soil enhancement and fertiliser are not regarded here.

Fig. 3 shows the cumulative bandwidths of the conventional and the prospective scenarios from the uncertainty analysis in Appendix 7 as well as the potential net GHG reductions of the prospective scenario is implemented with 25%, 50% and 75% success. It should be noted that 'best case' and 'worst case' values are realistic estimations not including extreme circumstances. The worst case scenarios are highly impacted by the potential N_2O emissions from mulch as per the IPCC (2006) default emission values (see Appendix 7 in the Supplementary data).

Based on the default emissions and reductions from the two scenarios, even if the prospective scenario is only implemented within 50% of the Malaysian palm oil industry – which is likely more realistic than 100% at least in the short term – the GHG reductions can still off-set 27% of the life cycle GHG emissions from palm oil production. It takes 30% implementation of the prospective scenario to create net GHG reductions from the use of residues generated in the production of Malaysian palm oil derived biodiesel.

The results presented in Table 3 consider only GHG emissions. A full environmental assessment would need to include factors such

Table 3
GHG balances for conventional and prospective Malaysian palm oil waste treatment scenarios.

	Trunks	Fronds	EFB	Shells	Fiber	POME	Total
Conventional scenario							
Boiler fuel	–	–	–	50%	80%	–	
Mulch	100%	100%	75%	–	–	–	
Incineration	–	–	10%	–	–	–	
Industrial use	–	–	5%	35%	20%	–	
Landfill	–	–	5%	15%	–	–	
Compost	–	–	5%	–	–	–	
Open lagoons	–	–	–	–	–	95%	
Biogas	–	–	–	–	–	5%	
Total GHG							
g/kg residue	−12	−12	−51	517	102	−292	
kg/ton CPO	−10	−35	−55	175	65	−950	−811
kg/ton biodiesel	−10	−35	−60	190	75	−1035	−875
Prospective scenario							
Boiler fuel				25%	100%		
Mulch		100%					
Incineration[a]			30%	25%			
Incineration[b]			30%	25%			
Pyrolysis	50%		30%	25%			
Biogas[c]			10%			100%	
Total GHG							
g/kg residue	267	−12	369	1121	–	50	
kg/ton CPO	210	−35	405	285	–	165	1050
kg/ton biodiesel	230	−35	440	310	–	180	1125
Total GHG savings without allocation to co-products (kg/ton biodiesel)							2000
Allocation (mass) of savings to co-products[d] (see Appendix 3)							20%
Net GHG reductions from improved residue utilization (kg/ton biodiesel)							1595
Biodiesel production life cycle							
Current net life cycle GHG balance (MPOB)							−1680
Net GHG balance with improved residue utilization							−85
Potential life cycle GHG emission reductions							95%

Positive values are GHG savings. Negative values are GHG emissions.
Explanations to the values presented in the table are available in Appendix 5 of the Supplementary data.
[a] Incineration with energy recovery (electricity).
[b] Incineration in industrial boilers.
[c] With energy recovery.
[d] Up until and including milling as all the considered residues are generated in the plantations and mills.

as stack emissions, leachate from landfilling, lagoons and mulching, transportation emissions, impacts due to possible soil erosion when removing EFB mulch and (indirect) land use change. The various forms of biomass incineration for electricity production or in industry boilers would likely generate more particulate matter than the equivalent fossil fuels, thus setting higher demands for flue-gas filters. Transportation of the residues would also be likely to play a bigger role when other impacts are considered, as the general condition of trucks in Malaysia is poor, often emitting dark exhaust. On the other hand, eutrophication due to leachate would be greatly reduced compared to the conventional scenario. If EFB is not used as mulch, increased surface soil erosion in the oil palm plantations may occur. This could, however, be countered with a cover crop such as legumes. If erosion was to occur it would lead

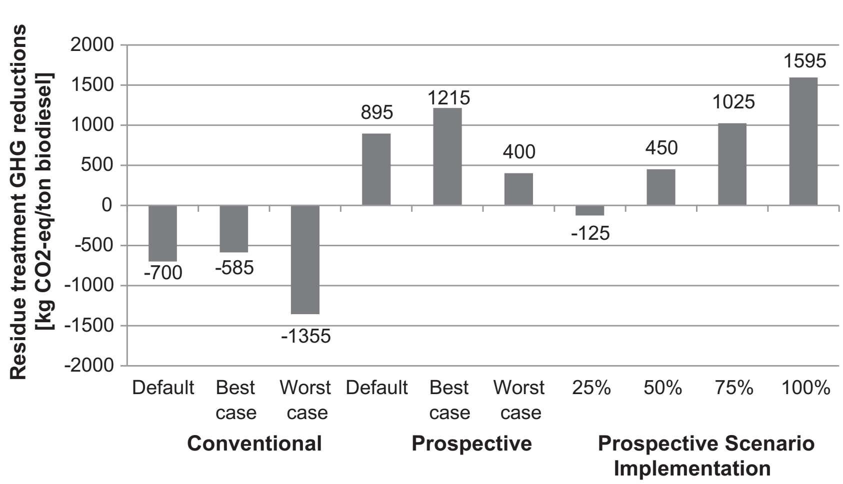

Fig. 3. GHG bandwidths of the scenarios and net effects of prospective scenario of implementation.

to eutrophication of streams and lakes and increased fertilizer use and/or reduced yields, which could have significant impacts on the life cycle impacts. The general nutrient balance and soil conditions can play a much more significant role in a holistic perspective than when considering GHG only. As such, the tradeoffs of removing biomass/nutrients from the system must be closely investigated. For example the benefits of bio-char on soil conditions may make pyrolysis an even more attractive technology than indicated in the results of this study.

Studying how decisions and actions in the life cycle of one product impacts the life cycle itself as well as the life cycles of other products is known as consequential LCA. When the residues from biodiesel production are used and thus substitute another product, the said product will either decrease in demand or the extra stock available will again substitute another product. Thus it can ultimately be very difficult to identify exactly what is substituted. It can even be argued that replacing e.g. coal with a biomass may lower the demand of coal, which will lower the price, which will ultimately result in increased use of coal. As such, the life cycles of each possible waste treatment technology should be studied carefully to obtain better decision support.

4. Conclusions

Methane capture from the anaerobic digestion of POME is the highest priority in the pursuit of sustainable palm oil derived biodiesel. If the methane is used for steam or electricity production, adding EFB to the POME can significantly increase the gas production under thermophilic conditions. The implementation of solid waste treatment technologies such as waste incineration with energy recovery and pyrolysis also result in significant GHG reductions. The use of all residues in an optimized manner can make the production of biodiesel from palm oil close to CO_2-neutral with a reduction of 95% of the current 1680 kg CO_2-eq/ton biodiesel.

Acknowledgements

The authors would like to express gratitude to palm oil corporation Felda Holdings Bhd and their fully owned subsidiary Felda Palm Industries Sdn Bhd for allowing access to their mills for collection of POME and EFB for the practical experiments of this study and for providing comparative data for the residue quantities. The authors would also like to thank Malaysian biogas contractor CST Engineering Sdn Bhd for access to, and use of, biogas testing facilities. It is stressed that neither Felda Palm Industries nor CST Engineering has had any subjective influence on the results of this study.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biortech.2011.10.069.

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Appendix 1a – Supplementary Data

Supplementary data for Residue use paper

Supplementary Data for

Greenhouse Gas Reductions through Enhanced Use of Residues in the Life Cycle of Malaysian Palm Oil derived Biodiesel

Sune Balle Hansen, Stig Irving Olsen, Zaini Ujang

Appendix 1

Brief background literature review

Studies carried out on environmental impacts from the production of palm oil and palm oil derived biodiesel have solely been focusing on the current practices in the production process without investigating the potential benefits of environmental improvements in the system, e.g. Schmidt (2007) and Choo et al., (2011). The current debate focuses largely on land use change, however, whereas land use change is a very significant focus area, it is not the only area, which can lead the way to sustainable palm oil.

Several studies exist on the waste quantities produced (e.g. Yusoff (2006)) and the various recycling technologies. Apart from the technologies described in Sections 3.1 – 3.6 in the main article, reuse of palm oil residues have been researched e.g. within bioethanol from EFB (Tan et al., 2010), citric acid from EFB (Bari et al., 2009) and POME (Alam et al., 2008), plywood/fibreboards from EFB and trunks (Khalil et al., 2010), and cellulose enzyme from EFB (Alam et al., 2009). However, only few of these mention the quantitative environmental impacts and benefits from the technology and none have investigated the actual benefits in a life cycle perspective. Thus, this study has chosen to focus on the existing technologies listed in Section 1 in the main article.

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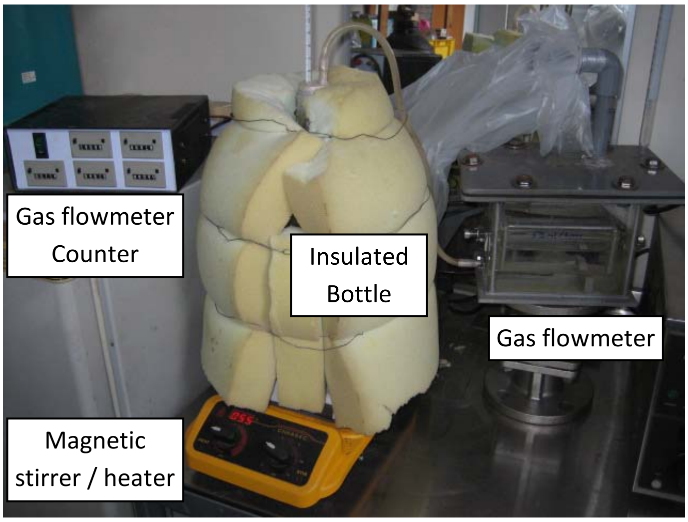
Appendix 2

Experimental set-up – Anaerobic digestion of EFB

The experiments were designed to provide indications of the biogas potential in fibrous solid palm oil residues. The shredded EFB from a palm oil mill were digested in a batch process, fully mixed, 52°C thermophilic digester for 21 days at a loading of 5% w/w. On day one of the experiments, 200 g shredded EFB were added to 4 L of thermophilic anaerobic bacteria solution ($MLSS_{bacteria} \approx 4,000$ mg/L) in an insulated 5 L glass bottle. The insulation was 5 cm thick sponge material. The anaerobic bacteria solution, which was retrieved from a Malaysian full scale batch process, fully mixed, thermophilic digester using POME as a feedstock, had been left to degrade all remaining organics for 5 days to ensure that gas produced during the experiments was from the EFB only. Using bacteria from a POME fed digester is considered the most representative solution, as the EFB will be co-digested with POME in a full scale scenario. The bottle (hereafter 'digester') was sealed to allow only for a gas tube and a thermometer and placed on a combined heater/magnetic stirrer. The temperature was maintained at a constant 52°C in the digester. Produced gas volumes were measured continuously using an unnamed flowmeter developed by Chiang Mai University for small gas volumes. The gas volumes were recorded daily to determine the degradation rate of the fibres (as depicted by the gas production) as a function of the hydraulic retention time, which is crucial for estimating the potential loading of fibres into a full scale biogas plant. The methane content of the biogas was analysed twice weekly using a Dräger X-am 7000 methane meter. After the 21 days the digester was opened and the digestate was analysed for nutrient values in order to assess potentials in application as fertilizer. The digestate and the remaining fibres were separated and the liquid was analysed for total N , P and K using Standard Methods APHA[1] 4500-N_{org} B & 4500-NO_3^- H for total N, APHA 4500-P B&F for total P and APHA 3120 B for total P. The fibers were rinsed clear of bacteria sludge and analysed for Total N, P and K as well using APHA 4500-N_{org} B & 4500-NO_3^- H for total N, and Acid digest / IPC for Total P and K.



[1] Standard Methods for Examination of Water and Wastewater, 21st Edition 2005, American Public Health Association

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Appendix 3

Overview of the waste quantities

Table A1 – Co-products and waste products in the biodiesel life cycle [kg (wet weight)/ton CPO]

	Stage	a	b	c	d	e	f	Average
Raw material								
Land	Plantation	0.26 ha	-	-	-	-	-	0.26 ha
Fresh Fruit Bunch, FFB	Plantation	4885	-	-	-	-	-	4885
Co-products								
Crude Palm Kernel Oil	Milling	120	-	-	-	-	-	120
Palm Kernel Cake	Milling	133	-	-	-	-	-	133
Palm Fatty Acid Distillate	Refining	45	-	-	-	-	-	45
Glycerine	Biodiesel	-	-	-	-	93	-	93
Total co-products								391
Waste Products								
Fronds	Plantation	-	-	2835	-	-	2573	2,700
Stems	Plantation	-	-	759	-	-	812	786
Empty Fruit Bunch, EFB	Milling	-	1014	1125	1168	884	1094	1,100
Press fibre	Milling	-	673	650	629	716	671	656
Boiler Ash	Milling	-	-	-	16	-	-	16
Palm Oil Mill Effluent , POME (liquid)	Milling	-	3290	3365	3045	3116	3328	3,250
Shells (palm kernel)	Milling	-	359	350	358	307	272	335
Spent Bleaching Earth	Refining	-	-	7	-	-	-	7

a. (MPOB, 2010)
b. (Felda, 2010)
c. (Schmidt, 2007)
d. (Subramaniam et al., 2008)
e. (Wicke et al., 2008)
f. (Yusoff, 2006)

MPOB (Malaysian Palm Oil Board) is the research body for the Malaysian palm oil industry. Their values for national production and co-products is considered as reliable. The waste products are not part of the annual statistics from MPOB, so external studies have been used. It is not possible to disqualify the values for the waste products from any of the studies above, so average values have been used.

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Spent bleaching earth is rich in oil residues and could potentially be added to a biogas plant. However, due to the small quantities and lack of available data, it was not included in this study.

Wastewater from the refineries and biodiesel plants is also relatively high in oil residues, however, the amounts are not expected to be high enough to have any significant impact on the GHG balance even if the wastewater is treated anaerobically with biogas capture and combustion in a gas engine.

Co-product allocation by mass

Products at mill: 1,000 kg CPO + 253 kg palm kernels ➔ 80% for CPO, 20% for Palm Kernels

Products at refinery: 1,000 kg CPO + 45 kg PFAD ➔ 96% for CPO, 4% for PFAD

Products at biodiesel plant: 1,000 kg CPO + 93 kg glycerine ➔ 91% for CPO, 9% for glycerine

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Appendix 4

Introduction to bio-char and yields from pyrolysis

Lim and Lim (1992) measured 30% volatile carbon in char from palm oil trunk at 400°C and 20% at 500°C, based on which this paper assumed 10% at 900°C. Since no such measurements are available for EFB and shells, the same values are assumed for these. In Table A2 it is assumed that all the volatile carbon degrades in the first few years. The volatile carbon has thus been subtracted from the total carbon of the char to get the fixed carbon. Quantitative studies on the improvement in yields due to application of bio-char in tropical soils have not been conducted. In the following it is assumed that the fertilizer savings and soil properties benefits are equal to those of EFB mulching. So at 10 g bio-char produced per kg EFB, 1 kg bio-char has the fertilizer value of 10 kg EFB equal to 140 g CO_2 in accordance with (PE International, 2006b).

Bio-char could be applied to the oil palm plantations at re-planting. This would ensure no char is lost due to surface run-off and it would require no additional man-power for application.

Studies on pyrolysis of oil palm residues and the use of the pyrolysis products are few and deliver inconsistent results. No data is available on energy input vs. output and on the feasibility of constructing and operating pyrolysis plants. In its Economic Transformation Programme initiated in 2010, the Malaysian government is emphasizing bio-oil as a desired product from the palm oil residues and targets a yearly production of 3.8 million tons bio-oil by 2020. Thus significantly more research can be expected within the area in the coming years. Since bio-char is co-produced with bio-oil, more research should be done within pyrolysis conditions, which can favour both bio-oil production and bio-char with a high degree of fixed carbon as well as research on bio-char application to soil.

Supplementary Data for

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Table A2 – Yields from pyrolysis of palm oil wastes at various temperatures

	Temp.	Bio-char Yield		Bio-oil Yield		Net Gas Yields[g]	
	[°C]	[% of dry input]	C Content	[% of dry input]	LHV[e] [MJ/kg]	[% of dry input]	LHV[f] [MJ/kg]
Optimal Bio-char							
EFB[a]	~400	30%	40%	35%	20	15%	5
Shells[b]		40%	45%	40%	20	0%	5
Trunk[c]		35%	40%	40%	20	5%	5
Optimal Bio-oil							
EFB[a]	~500	25%	50%	40%	20	15%	5
Shells[b]		30%	55%	45%	20	5%	5
Trunk[c]		30%	50%	40%	20	10%	5
Optimal Gas							
EFB[a]	>900	5%	60%	10%	20	65%	15
Shells[b]		10%	70%	20%	20	50%	15
Trunk[c, d]		5%	60%	10%	20	65%	15

Data in the literature varies greatly due to various methods and assumptions. Data given is based on averages and may vary significantly from individual references.

a) based on (Sukiran et al., 2009); (Abdullah et al., 2010); (Abdullah and Gerhauser, 2008); (Sulaiman and Abdullah, 2011); (Li et al., 2007)

b) based on (Khor et al.,, 2010); (Li et al., 2007)

c) based on (Kim et al., 2010); (Lim and Lim, 1992);

d) no data available in literature. Data for EFB is used.

e) Inconsistent data in literature. 20 MJ/kg (Abdullah and Gerhauser, 2008) is used, which is consistent with (Mullen et al., 2010)

f) Calculated from gas composition in (Li et al., 2007) No data for palm oil wastes available in literature. Low temperature LHV corresponds to (Mullen et al., 2010) (pyrolysis of corn).

g) A gas quantity corresponding to 20% of the total yield is assumed for pyrolysis operation. The figures given are thus actual percentages minus 20.

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Appendix 5

Table 3 –GHG balances for the various wastes and technologies compared to hypothetical carbon neutral disposal

Waste Technology	Replaced Product(s)	Saved CO2-eq [g CO2/kg waste]	Waste Quantity Available [kg waste/ ton CPO]	Saved CO_2-eq [kg CO2/ ton biodiesel]
Stems				
Pyrolysis	C seq./diesel/elec.	260	786	230
EFB				
Mulch	Fertilizer	15	1100	-15
Incineration	Fertilizer	5		5
Incineration	Electricity / fertilizer	260		315
Incineration	Coal	510		615
Pyrolysis	C seq./diesel/elec.	360		435
Landfilling	-	-1,080		-1,290
Biogas	Elec. / fertilizer	280	160	50
Shells				
Incineration	Electricity	760	255	210
Incineration	Coal	1,480		410
Pyrolysis	C seq./diesel/elec.	1,130		315
POME				
Open lagoon	-	-310	3257	-1,090
Biogas plant	Electricity	50		175
Biogas plant	Shells - 100 kg	50		180

The contributions from fronds, fibres and the shells used in the mill boilers are not included as they do not constitute savings or emissions outside the boundaries of the palm oil mill. The 'Saved CO_2 eq.' values are savings compared a no-impact scenario in which all the carbon in the wastes simply turn to CO_2.

Appendix 6

Background for setup of the conventional scenario

Table A3 (first part of Table 4 in the main article)

	Trunks	Fronds	EFB	Shells	Fibre	POME	Total
Boiler Fuel	-	-	-	50%	80%	-	
Mulch	100%	100%	75%	-	-	-	
Incineration	-	-	10%	-	-	-	
Industrial Use	-	-	5%	35%	15%	-	
Landfill	-	-	5%	15%	5%	-	
Compost	-	-	5%	-	-	-	
Open lagoons	-	-	-	-	-	95%	
Biogas	-	-	-	-	-	5%	

Boiler Fuel

In accordance with (Subramaniam et al., 2008) 520 kg of fibre and 170 kg shells are used in the mill boilers per ton CPO. Comparing these to the total quantities in Table A1 gives 80% and 50% respectively.

Mulch

Almost all trunks are still buried at the plantations. In order to limit the number of entries in the scenario, it has been listed as mulch and the benefits (fertilizer savings and soil improvement) are assumed to be similar to mulch from EFB (1 kg trunks = 1 kg EFB). This simplification does not have significant impact on the overall emissions from the current scenario.

All fronds are currently used as mulch (frond stacks) in the plantations. The benefits (fertilizer savings and soil improvement) are assumed to be equal to mulch from EFB (1 kg fronds = 1 kg EFB).

Incineration

Incineration of EFB without energy recovery is practiced at the mills in order to limit the weight and volume of EFB before applying as fertiliser. The practice is declining due to increased focus on air pollution from the simple incinerators.

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Industrial Use

A small amount of EFB is use in industrial applications such as fibre boards and for incineration with energy recovery. In the quantification of GHG savings all 5% was allocated to Incineration with energy.

There is a rising trend in use of shells in industry boilers and in concrete production. All shells for industrial use have been allocated for use in industry boilers in the GHG calculations.

Some fibres are currently used in industry boilers or as a source of fibres in e.g. fibre boards. In the calculations, values for EFB incineration in industry boilers have been used.

Landfill

Only very limited landfilling of EFB is taking place and the practice can be expected to decrease further.

Excess Shells from remote mills are still landfilled as there are no uses for them on site and transportation to industries is not feasible. However, the hard shells are considered inert in a landfill.

As for the shells, some fibres at remote mills are landfilled. GHG emissions are assumed equal to EFB (1 kg fibre = 1 kg EFB).

Compost

Composting is practiced at some mills and is getting more common. It ensures that the nutrients in the EFB are made available to the palms, so in the calculations the benefits of compost is assumed double that of mulch (1 kg EFB for composting = 2 kg EFB for mulching).

Open lagoons and biogas

More and more biogas plants are being constructed. However, most of them flare off the biogas without energy recovery. Thus, in the conventional scenario, ‘Biogas’ is considered CO_2-neutral.

Supplementary Data for

Greenhouse Gas Reductions through Enhanced Use of Residues in the Life Cycle of Malaysian Palm Oil derived Biodiesel

Sune Balle Hansen, Stig Irving Olsen, Zaini Ujang

Appendix 7

Sensitivity & Uncertainty

The uncertainty/sensitivity analysis is performed qualitatively in the following and presented quantitatively in Table A4.

Mill boilers

The mill boilers in Malaysia are generally inefficient as efficiency is not prioritized with the surplus availability of fibres and shells, which until recently did not have market value. With the growing market value for shells it is very likely that some mills will upgrade their boiler systems. The uncertainty analysis tests a realistic 20% increase in boiler efficiency in the prospective scenario, which will make the fibre alone able to meet the energy requirements, thus making the remaining 80 kg shells available for other applications. In the best case prospective scenario in Figure 3 in the main article, these 80 kg shells are treated as per the prospective scenario in Table 3 in the main article.

Mulch

The uncertainty analysis investigates the potential situation that the actual methane and N_2O emissions from mulch are negligible and the potential situation that the N_2O emissions are as per the (IPCC, 2006) default values for composting. Both situations are borderline realistic. Unpublished studies claim that N_2O emissions from Malaysian agricultural soil is significantly lower than the IPCC values, so the same could apply to the degrading EFB and the single layer EFB mulch is not unlikely to retain aerobic conditions. On the other hand, as the actual emissions have not been studied, it is also relevant to relate to the IPCC default values. Thus, the bandwidth of the GHG data when EFBs are applied as mulch varies from a net GHG reduction of 14 kg CO_2-eq/ton CPO due to the industrial fertilizer savings if the methane and N_2O emissions are negligible to emissions of 180 kg CO_2-eq/ton CPO if the IPCC default emissions apply. In this context any variations in the actual amount of industrial fertilizer replaced becomes insignificant as it would only contribute by a few kg CO_2-eq/ton CPO.

The sensitivity analysis also assumes that the fronds and the chipped trunks behave similarly to the EFB when it comes to methane and N_2O emission. The fronds and stems actually have higher nitrogen content than the EFB (Chow et al., 2008), so the emissions from these could be even larger than for EFB. Due to the large quantity of fronds, these become a major contributor of emissions in the worst case scenarios with over 400 kg CO_2-eq/ton biodiesel after allocation. Thus, especially the N_2O emissions from degrading fronds are important to study. It must, however, also me taken into consideration, that the mulch increases soil carbon (carbon sequestration) and soil fertility, which can give significant counter weight to the N_2O emissions. This must be researched further as well in order to achieve a balanced assessment.

Anaerobic treatment

There is little uncertainty in the methane emissions from POME, which are well documented.

However, for the landfilled EFB, it is not unlikely that the percentage of C being converted to methane could differ. A bandwidth was established assuming 15% and 25% C conversion to methane resulting in an emission range from 890-1480 kg CO_2-eq/ton CPO.

Biomass power

The GHG reductions can be considered as best case scenario for power production from the residues. IPCC (2006) suggests that app. 5 g CH_4/ton waste and 50 g N_2O/ton waste is likely to be emitted during incineration. This would reduce the GHG reductions from power production from EFB by just 4% and shells by 1%.

Biogas

Energy recovery from the remaining digested EFB has not been scientifically quantified, but preliminary calculations assuming that the dry weight calorific value of the digested EFB is the same as for fresh EFB have been made for the uncertainty analysis. These show that by substituting shells in the mill boiler and use these shells as per the prospective scenario in Table 3 in the main article, the GHG reductions from producing biogas from EFB could be doubled to a best case value of 89 kg CO_2eq/ton CPO. Conversely, it is not unlikely that a poorly managed biogas plant may have methane leakages of up to 10%, which would create a worst case GHG reduction value of 13 kg CO_2/ton CPO.

Pyrolysis

The three pyrolysis set-ups all give similar GHG reduction, which is to be expected since they are variations of the same process and using the same feedstock. Using the average value is likely to be a deviation from actual conditions, so in the uncertainty analysis, the double standard variations of the mean values for EFB, shells and trunks respectively have been used to create a potential bandwidth for the three residues: 362-433 kg CO_2-eq/ton CPO for EFB 253-323 kg CO_2-

eq/ton CPO for shells and 180-239 kg CO_2-eq/ton CPO for trunks. Using the double standard deviation takes into consideration that there are uncertainties in the mean value as well as in the individual set-ups.

Scenarios

The values in Table A4 are computed into the conventional and prospective scenarios in Table 3 in the main article to create best case and worst case scenarios.

Supplementary Data for

Greenhouse Gas Reductions through Enhanced Use of Residues in the Life Cycle of Malaysian Palm Oil derived Biodiesel

Sune Balle Hansen, Stig Irving Olsen, Zaini Ujang

Table A4 – Quantitative uncertainty/sensitivity values

	New emission/reduction		Comment	Change
	kg CO2-eq/ton CPO	g CO2-eq/kg residue		
Mill boiler	255 kg shells available		default	
15% increased efficiency	335 kg shells available		best case	131%
Mulch (EFB)	-14	-12	default	
No CH_4 and N_2O emissions from mulching	14	13	best case	NA
IPCC default CH_4 and N_2O emissions from mulching	-198	-180	worst case	-1447%
EFB landfilling	-1184	-1077	default	-
25% c conversion to methane	-1480	-1346	worst case	125%
15% C conversion to methane	-888	-808	best case	-25%
Power production (EFB)	427	388	default / best case	-
5g/ton CH_4 emissions and 50g/ton N_2O emissions	410	372	worst case	-4%
Power production (shells)	285	1117	default / best case	-
5g/ton CH_4 emissions and 50g/ton N_2O emissions	281	1101	worst case	-1%
Biogas (POME)	163	50	default / best case	-
5% CH_4 leakage	105	32	-	-36%
10% CH_4 leakage	47	14	worst case	-55%
Biogas (EFB)	44	275	default	-
5% CH_4 leakage	29	179	-	-35%
10% CH_4 leakage	13	83	worst case	-54%
Digested fibre substituting shells in mill boiler	89	556	best case	202%
Pyrolysis (EFB)	398	362	default	-
+ 2 Standard deviations	433	394	best case	109%
- 2 Standard deviations	362	329	worst case	9%
Pyrolysis (shells)	288	1129	default	-
+ 2 Standard deviations	323	1267	best case	112%
- 2 Standard deviations	253	991	worst case	12%
Pyrolysis (trunks)	210	267	default	-
+ 2 Standard deviations	239	304	best case	114%
- 2 Standard deviations	180	229	worst case	14%

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Appendix 2 – Land Use Change Paper

Carbon Balance Impacts of Land Use Changes related to the Life Cycle of Malaysian Palm Oil derived Biodiesel

Sune Balle Hansen, Stig Irving Olsen

Submitted to International Journal of Life Cycle Assessment in 2012

References to appendices A-C made in the paper are for the supplementary data submitted to the journal for online access. The supplementary data can be found in Appendix 2a

Carbon Balance Impacts of Land Use Changes related to the Life Cycle of Malaysian Palm Oil derived Biodiesel

Sune Balle Hansen[a*], Stig Irving Olsen[a]

[a] DTU Management Engineering, Technical University of Denmark, Produktionstorvet building 424, 2800 Kgs. Lyngby, Denmark

Abstract

Purpose The area of oil palm plantations in Malaysia is expanding by approximately 0.14 million hectare per year and with the increasing demand for palm oil worldwide there is no sign of the expansions slowing down. This study aims to identify the greenhouse gas emissions associated with land conversion to oil palm in a life cycle perspective.

Method LCA methodology is applied to existing land use change data. The assessment includes the issue of temporary carbon storage in the plantations. Through quantification of emissions from state forest and rubber plantation conversions, the average Malaysian palm oil related land use changes are calculated.

Results The results show that there are high emissions associated with the conversion of Malaysian state forest to oil palm, whereas the conversion of rubber leaves a less significant carbon dept when indirect land use change is not included. Looking at the average Malaysian land use changes associated with oil palm shows that land use change emissions are responsible for approximately 1/3 of the total conventional biodiesel production emissions. The sensitivity analysis shows that the results could be significantly influenced by data variations in indirect land use changes, peat soils and state forest carbon stock.

Conclusions The relatively extensive conversions of state forest must be reversed and preferably with a shift towards conversion of degraded land in order for the average Malaysian land use changes to have less impact on the production life cycle of palm oil and biodiesel.

Keywords: Land use change, Palm oil, Biodiesel, Temporary carbon storage, Forest, Rubber, Plantations

1 Introduction

Oil palm plantations cover 4.98 million hectares (ha) in Malaysia in 2011, which is 15% of the total land area. In the past 25 years, which is the length of an oil palm cycle, the area has increased by 3.4 million ha at a relatively consistent 0.14 million ha per year (MPOB 2012). Palm methyl ester (PME) is biodiesel produced from palm oil and the production is on the rise thus furthering the expansion of oil palm plantations. The conversion of land to oil palm plantations can result in significant greenhouse gas (GHG) emissions, especially if forest is converted to plantation, which can negate the benefits of PME produced from palm oil (Kim et al. 2009). Some studies exist, which quantify the emissions from land use change in relation to palm oil. Reijnders and Huijbregts (2008) used land use change (LUC) data in their environmental assessment of palm oil while arguably the most comprehensive review on palm oil related

* Corresponding Author. Tel: +60 12 219 9441 (Malaysia), +45 4525 4660 (Denmark)
E-mail address: sunebh@utm.my (primary), suneballe@yahoo.dk (secondary)

LUC is conducted by Germer and Sauerborn (2008) who include biomass as well as soil carbon estimates. In the data discussions in sections 3.2.1-3.2.3 more palm oil related LUC references are presented. The existing studies have all considered the results of converting a single previous land use to oil palm (e.g. Wicke et al. 2008). A study of the Malaysian average (LUC) GHG emissions related to palm oil has not previously been published.

Fig. 1 illustrates that oil palm has primarily been planted on state forest and rubber plantations in the past 25 years (from FAO 2010; MPOB 2012; MRB 2011). State forest is forest earmarked by the Malaysian Government for development (Woon and Norini 2002), from which large trees have been or will be harvested for timber, but with smaller trees and undergrowth still standing until the land is cultivated. As land from other land uses such as yearly crops and coconut has become sparser, conversion from state forest has become more dominant in the past 10 years. Thus, this study focuses primarily on conversion from state forest and from rubber plantations with other land uses included qualitatively.

In this study, the GHG emissions related to LUC from conversion of state forest, rubber and the Malaysian average LUC emissions are put in a life cycle perspective for PME production, and related to the PME production emissions presented in Hansen et al. (2012), which does not include LUC. In order to relate the total GHG emissions from PME production to a tangible reference, the final emissions are compared to the emission requirements of the European Union Renewable Energy Directive (EU-RED), which dictates that renewable energy must provide at least 35% reduction in GHG emissions compared to its fossil counterpart (European Parliament 2009).

Hansen et al. (2012) allocates emissions by mass to four co-products; PME, palm kernels, palm fatty acid distillate (PFAD) and glycerin, resulting in a total mass allocation of 33% to non-PME co-products. In order to be able to compare the results in this study with the results in EU-RED, allocation should be done by energy content, whereby only 26% is allocated to non-PME co-products in accordance with Appendix A in the Online Resource. The land use change emissions presented in this study will follow the same 26% energy allocation. However, in order for this study to comply with state-of-the-art LCA methodology (see section 2.2), some variations occur compared to the methodology of EU-RED. Hansen et al. (2012) takes the substitution of fossil fuels by the residue use into consideration. EU-RED does not recognize residue use benefits unless the residues have a market value, in which case they are considered co-products and dealt with through allocation. EU-RED also does not recognize other consequential LCA methods such as indirect land use change (ILUC) or induced emissions, nor the distinction between fossil and biogenic carbon. Appendix B in the Online Resource describes a scenario and derived results of this study adhering to the EU-RED methodology.

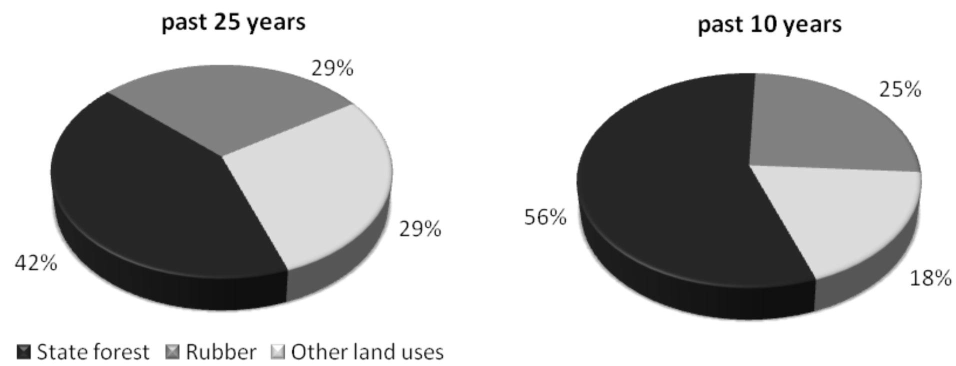

Fig. 1 Conversion of land to oil palm plantations

2 Methods

2.1 Life Cycle Methodology

The life cycle methodologies used in the study follows or are derived from ISO 14040 as presented in the ILCD Handbook (European Commission 2010). The methodological choices are listed below.

- *Impact time horizon*: 100 years.
- *Biogenic carbon and temporary carbon storage*: In LCA the temporary uptake of biogenic carbon in biomaterials and plants (e.g. plantations) is by default not credited as it is insignificant in the infinite impact time horizon applied in conventional LCA (European Commission 2010). However, when applying a 100 year impact horizon, which is commonly done for global warming impacts, the temporary storage can be significant and temporary carbon storage may be included as is done in this study. In such cases the ILCD Handbook (European Commission 2010) credits 1% of the total stored carbon per year of storage (i.e. full credit is given if the carbon is stored for 100 years or more).
- *Fossil carbon*: As carbon in virgin forests has been in equilibrium for thousands or millions of years, the carbon stored in these forests is considered permanently stored and is termed as fossil carbon. The fraction of carbon left in the logged-over state forest after timber harvest and thus the emissions from the conversion to oil palm are considered fossil carbon emissions as well. The emissions from the biomass added during the potential recovery of the forest and in the oil palm plantations are considered biogenic.
- *System time horizon*: All emissions from land conversion to a plantation are allocated to the first generation of the plantation use. So in this study only plantations established within the past 25 years are considered as contributing to land use change impacts. Soil carbon takes more than 25 years to establish a new equilibrium, but the estimated total emissions are allocated to the first generation of plantation. By including emissions for all 1st generation plantations, LUC emissions, which happened up to 25 years ago are included in the average Malaysian LUC emissions. From a legislative point of view such emissions cannot be included as the awareness of the impacts had not surfaced at the time and palm oil producers cannot be held responsible. However, from a strictly scientific point of view, the emissions have occurred and it is argued that the palm oil/PME produced on the land has to pay off the incurred carbon dept. The impact of only including LUC since 2008 as done in EU-RED (European Parliament 2009) is tested in the sensitivity analysis.
- This study focuses on describing the LUC impacts from the average Malaysian scenario. However, individual LUC data for Malaysian state forest and rubber plantations are presented as well in order to determine the main sources of emissions.

3 Results & Discussion

3.1 Land Use Change Emissions

Land use change data used in this study are presented briefly in sections 3.2.1 – 3.2.5. Additional details and references can be found in Appendix C in the Online Resource.

3.1.1 Oil palm plantation

A fully grown oil palm plantation holds app. 90 ton biomass per ha (derived from Germer and Sauerborn 2008; Khalid et al. 1999a; Khalid et al. 1999b) equalling sequestration of 140 ton $CO_{2,b}$-eq/ha. As the biomass builds up approximately linearly over 25 years, the average storage time is 12,5 years, which in accordance with section 2.2 justifies a credit of 12.5% of the sequestered CO_2. The credit for an oil palm plantation is thus 17 ton $CO_{2,b}$-eq/ha per plantation cycle. If plantation residues are used in a manner, which stores the carbon or replaces fossil fuels, then carbon credits should be given for the use, but such credits do not belong under LUC. See e.g. Hansen et al. (2012) for residue use calculations.

In accordance with Germer and Sauerborn (2008) and Mathews et al. (2010), the soil carbon content in an oil palm plantation on mineral soil is set to 80 ton C/ha.

3.1.2 Malaysian State Forest

Forest conversions to oil palm plantations in Malaysia only take place on state forest land, which is always logged for timber prior to land conversion. When logged through selective logging, a tropical forest of app. 340 ton biomass/ha (Germer and Sauerborn 2008) looses about 45% of the standing biomass (Lasco 2002) bringing it down to a total of app. 190 ton biomass. The carbon loss, which is equivalent to 280 ton $CO_{2,f}$-eq/ha is allocated to the timber. Clearing the logged forest to establish an oil palm plantation emits 350 ton fossil CO_2 equivalents ($CO_{2,f}$-eq) per hectare. Had the logged forest been left idle, it could on average likely have recovered to app. 240 ton biomass/ha within the 25 year system time horizon of this study (derived from Silver et al. 2000). By clearing the forest, the 50 ton biomass equalling 90 ton biogenic CO_2 equivalents ($CO_{2,b}$-eq) per hectare that would have been sequestered thus stay in the atmosphere and are allocated to the land use change. Some logged forest will be cleared shortly after logging, while other may stand (and recover) for decades. The 25 years time horizon of this study is assumed to be a suitable average. Thus the 'missed' temporary carbon storage credit is 12.5% credit as for the oil palm plantation resulting in an indirect emission of 12 ton $CO_{2,b}$-eq/ha.

No studies have been identified, which quantify the soil carbon in a logged forest. This study assumes that the soil carbon is somewhere between the 120 ton C/ha in a virgin forest (Germer and Sauerborn 2008) and an oil palm plantation. In lack of better data, the soil carbon in state forest is estimated at 100 ton/ha. The conversion to oil palm thus results in a loss of 20 ton soil carbon per ha. The sensitivity of this assumption is tested in the sensitivity analysis.

The net emissions from the conversion of Malaysian state forest to oil palm are thus 350 ton $CO_{2,f}$-eq plus 70 ton $CO_{2,f}$-eq/ha from soil carbon depletion equalling 420 ton $CO_{2,f}$-eq. The net temporary carbon storage is plantation sequestration of 17 ton $CO_{2,b}$-eq minus the missed recovery storage of 12 ton $CO_{2,b}$-eq equalling 5 ton $CO_{2,b}$-eq/ha.

The variation in the literature data are accounted for in Appendix C in the Online Resource and the sensitivity is quantified in the sensitivity analysis.

3.1.3 Rubber Plantations

The sequestered biogenic CO_2 in biomass in a rubber plantation just before felling is app. 260 ton C/ha (Yew 2001) or almost double the amount of carbon in an oil palm plantation. Rubber plantations have a planting cycle of 25 years, which as for oil palm gives a temporary biogenic carbon storage credit of 12.5% resulting in 35 ton $CO_{2,b}$-eq/ha. Thus, the loss from conversion to oil palm is 18 ton $CO_{2,b}$-eq/ha. The literature suggests that soil carbon content in rubber and oil palm plantations is similar (e.g. Lai 2004) so the loss/gain in conversion from rubber to oil palm is set to 0.

When converting a rubber plantation to an oil palm plantation, the rubber that was produced at that plantation must be produced somewhere else assuming that the world rubber demand is unchanged. In this study it is assumed that the rubber is produced synthetically from fossil oil, thus creating induced emissions. Patel (2003) reported cradle to gate emissions from production of synthetic rubber of 1.38 ton CO_2-eq/ton rubber in Germany. As comparison Jawjit et al. (2010) reported an average of 0.65 ton CO_2-eq/ton natural rubber produced in Thailand. With 0.9 ton rubber produced per hectare per year in Malaysia (MRB 2011), the net additional emission is thus 0.67 ton CO_2/ha/year by producing the rubber synthetically. Over a 25 year plantation cycle that amounts to app. 17 ton CO_2/ha, which are assumed fossil.

In summary there are net emissions of 17 ton $CO_{2,f}$/ha and 18 ton $CO_{2,b}$-eq/ha from conversion of rubber to oil palm.

3.1.4 Other Land Uses

Other land uses include other plantations such as coconut, perennial crops such as sugar cane or areas like degraded land. Planting oil palm on some of these lands can result in net carbon sequestration as the oil palms bind more carbon than the previous land use. However, the sequestration is only temporary and the credit given is thus small. Additionally there is the matter of indirect land use change (ILUC) when a crop is replaced. ILUC is not included in the scope of this study, but has been included in the sensitivity analysis. Due to lack of data availability on LUC emissions from these other land uses, which may or may not be significant, the quantitative sequestration and emissions have been omitted from this study.

3.1.5 Peat

7-8% of Malaysia is covered by peatlands and just below 15% of the oil palm plantations in Malaysia are planted on peat, mainly in Sarawak (Wahid et al. 2010). Peatlands are perhaps the most controversial of the land uses and numerous studies have highlighted that draining peatlands for agricultural development will lead to very large soil CO_2 emissions through oxidation of the exposed peat (e.g. Page et al. 2011; Couwenberg et al. 2010). However, some recent studies have indicated that the models used to calculate these emissions are not representative for tropical peat and that emissions from well managed plantations on peat soils may not be significant. Melling et al. (2005) and Melling et al. (2012) has shown that soil CO_2 emissions can even be higher in tropical virgin peat swamp soils than in drained and compacted plantation peat soil. Although the additional emissions are likely from higher biogenic litter degradation and root respiration in the virgin peat (Melling et al., 2012) it shows that compacted cultivated peat is not necessarily a higher carbon emitter than virgin peat swamps. Melling et al. (2012) highlights that due to the heterogeneous characteristics of tropical peatland, further studies on e.g. environmental factors, peat properties and microbial activities are necessary to reach firm conclusions. Thus, due to insufficient data and understanding of peat, this study has chosen to omit peat from the assessment. Conventional peat emission estimations have been included in the sensitivity analysis in section 3.5.

3.1.6 Malaysian average LUC emissions

Figure 2 presents the GHG emissions for land conversion to oil palm plantation in Malaysia derived in sections 3.2.1-3.2.4. For the ‘National oil palm land use change emissions’, the relative land use change contributions from Fig. 1 for the past 25 years are used with the inclusion of the fraction of plantations planted more than 25 year ago (second generation or older). In order to simplify the presentation and further use of the results, no distinction is made between biogenic and fossil carbon in the total values for each LUC and for the national average.

Each generation of oil palms collects temporary carbon credits. Thus, the plantations of second generation and older receive the credit without having LUC emissions. It is clear from Fig. 2 that state forest conversion is in fact the only significant LUC as the temporary carbon storage in the rubber plantations only counts little in the overall carbon balance. ILUC from rubber or other crops could, however, be significant as will be shown the sensitivity analysis.

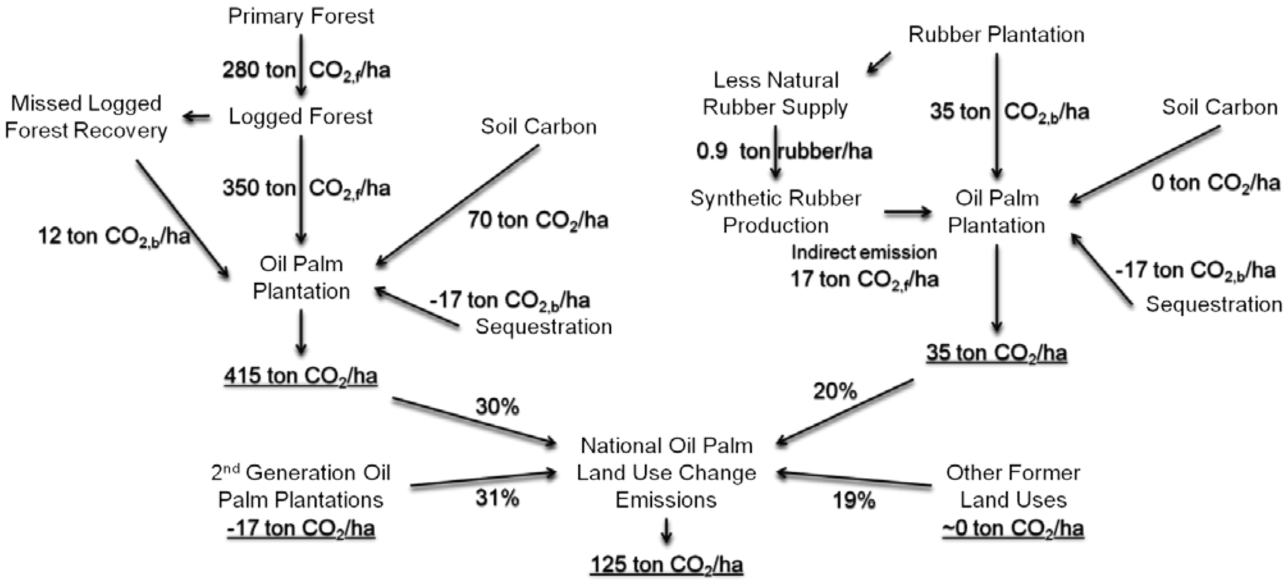

Fig. 2 GHG emissions for land conversion to oil palm plantation. CO_2 values given are CO_2-eq.

3.2 Land use change impacts in relation to biodiesel life cycle

It takes 0.26 ha to produce one ton crude palm oil based on average Malaysian yield for 2007-2011 (MPOB, 2012) and 1.09 ton crude palm oil to produce one ton PME (Choo et al. 2011) thus resulting in 0.28 ha to produce one ton PME. In order to be able to compare the impacts from land conversion to oil palm with the impacts from PME production, the impacts are multiplied by 0.011, which is the land area used to produce one ton palm oil over 25 years.

In Table 1, the land use change emissions presented in Figure 2 are subjected to the 26% energy allocation to non-PME co-products and added to the PME production emissions. It is evident that for conversion of Malaysian State forest, the emissions are so large that PME production on such lands will result in emissions larger than emissions from fossil diesel throughout the first plantation generation. In fact, with conventional PME production it will take the most of a century before the PME has net greenhouse benefits. Even with improved/optimized production, almost 40 years will pass before a net reduction in emissions can be seen. On the contrary, conversion from rubber plantations has very limited impacts. The national average emissions for PME production including LUC can meet the EU-RED criteria of 55 g CO_2/MJ (European Parliament 2009), but the success depends on the manner in which the PME is produced.

With the conventional waste treatment presented in Hansen et al (2012), a 90% reduction in the Malaysian average LUC emissions is required to meet the EU-RED requirements whereas an increase of 25% in LUC is permitted if the improved waste treatment from Hansen et al. (2012) is implemented nationwide. With the improved waste scenario in Hansen et al (2012) 50% implemented, a 33% reduction in the LUC emissions are needed whereas 80% nationwide implementation of the improved waste scenario is required for PME to be labeled renewable if the current LUC emissions are maintained.

The updated LCA methodology used in this paper makes it difficult to compare the LUC results with conventional studies. Wicke et al. (2008) also assesses LUC from logged-over forest. Whereas the emissions from the felling of the logged-over forest are similar in the two studies, Wicke et al. (2008) arrives at a lower net LUC impact of 50 g CO_2-eq/MJ as full credits are given to sequestration in the oil palms. On top of that, Wicke et al. (2008) uses carbon stock data for the oil palm plantation, which are significantly higher than the ones used in this study by Germer and Sauerborn (2008) and Khalid et al. (1999a,b). It is argued that previous studies such as Wicke et al. (2008) are underestimating the LUC impacts by disregarding the temporary nature of the oil palm sequestration. On the other hand the study by Reijnders and Huijbregts (2006) does not take into consideration that the forest is logged prior to oil palm conversion, which, at an equivalent of 160 g CO_2/MJ, overestimates the LUC emissions for the Malaysian scenario. Thus, the

Table 1 – CO_2-eq emissions from LUC and PME production emissions

	OP on state forest[1]	OP on rubber plantation[2]	Malaysian average emissions[3]	
LUC emissions	413	33	126	ton CO_2/ha
	126	10	39	g CO_2/MJ
LUC emissions with 26% energy allocation to co-products	304	24	90	ton CO_2/ha
	92	7	28	g CO_2/MJ
Conventional PME (no LUC emissions)[4]	-	-	42	g CO_2/MJ
Improved PME (no LUC emissions)[4]	-	-	6	g CO_2/MJ
Conventional PME incl. LUC emissions[4]	142	57	70	g CO_2/MJ
Improved PME incl. LUC emissions[4]	99	13	34	g CO_2/MJ
LUC emission payback time (conventional PME)	55	4	17	years
LUC emission payback time (improved PME)	30	2	9	years

[1] Emissions for PME derived from plantations planted on Malaysian State forest
[2] Emissions for PME derived from plantations planted on former rubber plantation
[3] Malaysian average emissions for PME production as per land use distribution in Figure 3
[4] With 26% energy allocation to LUC and PME production

accounting methodology is of utmost importance. Targeting degraded (low carbon) land for oil palm plantations means that there will be a net carbon sequestration and that no ILUC occurs. Planting oil palm on degraded land will result in net carbon sequestration of 135 ton CO_2/ha including biomass and soil carbon (Germer and Sauerborn 2008), which, when applying the 12.5% temporary carbon storage credits amount to 17 ton $CO_{2,b}$-eq/ha. This corresponds to a net sequestration of only 5 g CO_2/MJ PME produced, on top of which degraded land is likely to result in lower oil yield. Degraded land should thus not be targeted because of the prospects of carbon sequestration, but rather because the alternatives – forest or other agricultural crops – can result in large emissions through direct and indirect LUC.

Aside from the quantitative emissions associated with palm oil related LUC there are ongoing debates on the rights of e.g. Malaysia and Indonesia to develop their land and boost their economies (e.g. Padfield et al. 2011). It could be argued that a certain leeway on the LUC emissions could be given from a political and social point of view, however, from a scientific and environmental standpoint the impacts of state forest clearings remain as presented in this paper.

3.3 Sensitivity

A sensitivity analysis has been prepared by quantifying impacts on the Malaysian national oil palm LUC emissions from variations in the data and assumptions made in this study. The results are presented in Fig. 3 along with potential future scenarios. The biggest sensitivity variable is plantations on peat. Assuming that 75% of the plantations planted on peat are planted in the past 25 years and applying emissions of 800 ton CO_2/ha over 25 years (Germer and Sauerborn 2008), the national oil palm LUC emissions are increased by more than 70%. It is thus of very high importance that the actual emissions from oil palm plantations on peat are quantified by representative experimental data.

Another significant variable is the inclusion of ILUC in the conversion of rubber plantations. In Fig. 3 half of the rubber from plantations which have been converted to oil palm is replenished by establishing new rubber plantations through directly or indirectly converting an equivalent to Malaysian state forest in other tropical countries. The actual consequences of replacing rubber plantations should thus be investigated. Such significant impacts could occur in relation to replacement of other crops than rubber as well.

The assumption that all forest converted to oil palm is state forest and would be logged, i.e. large trees being taken out in any case whether or not the oil palm plantation is established, should stand firm. The sensitivity analysis shows that if a small part of the forest (here 10%) is in fact not harvested for timber, e.g. because it is too far from civilization to make timber transport feasible then although it does have significant site specific impacts it does not have much influence on the national average LUC emissions. The accuracy of data on biomass in the state forests and the biomass removal through logging does, however, have high impact. More data on site/regional ranges of biomass and the influence of logging are thus much needed.

The three future scenarios in Fig. 3 are all based on the LUC ratios presented in Fig. 1 for the last 10 years. The increased forest conversion will result in higher emissions. However, two ways of curbing this development are by ensuring that the yield is increased thus limiting the need for oil palm expansion or by using biochar from oil palm residues to regenerate degraded land (Roberts et al. 2010) and use this land for oil palm expansion rather than converting state forest. Increasing the yield alone will reduce the increase in emissions, but it is not sufficient to reduce emissions to below the level of the current national average LUC emission in Fig. 2 and Table 1 unless other actions are taken as well. However, targeting the one million ha of degraded land in Malaysia (Wicke et al. 2011) rather than state forest does have huge potentials for reducing the LUC, even on its own. Action is required immediately as it will take several years of planting on degraded land rather than on forest before a significant relative reduction of oil palm plantations on former state forest can be seen in the Malaysian average land use picture.

Following the LUC methodology of EU-RED, which is also practiced by conventional LUC studies (e.g. Germer and Sauerborn 2008), the Malaysian average LUC emissions over 25 years decrease by 12%, mainly due to the full carbon storage credits in the oil palm plantations. However, as EU-RED only includes LUC after 2008, the reported average Malaysian LUC emissions actually decrease by 86%. In other aspects like residue use, the EU-RED methodology is, however, less favorable for palm oil. See Appendix B in the Online Resource for more details. If the Malaysian average LUC emissions presented in this study were subjected to the 2008 cut-off point, the emissions would be reduced by 88%, which highlights the impacts of political decisions on such results.

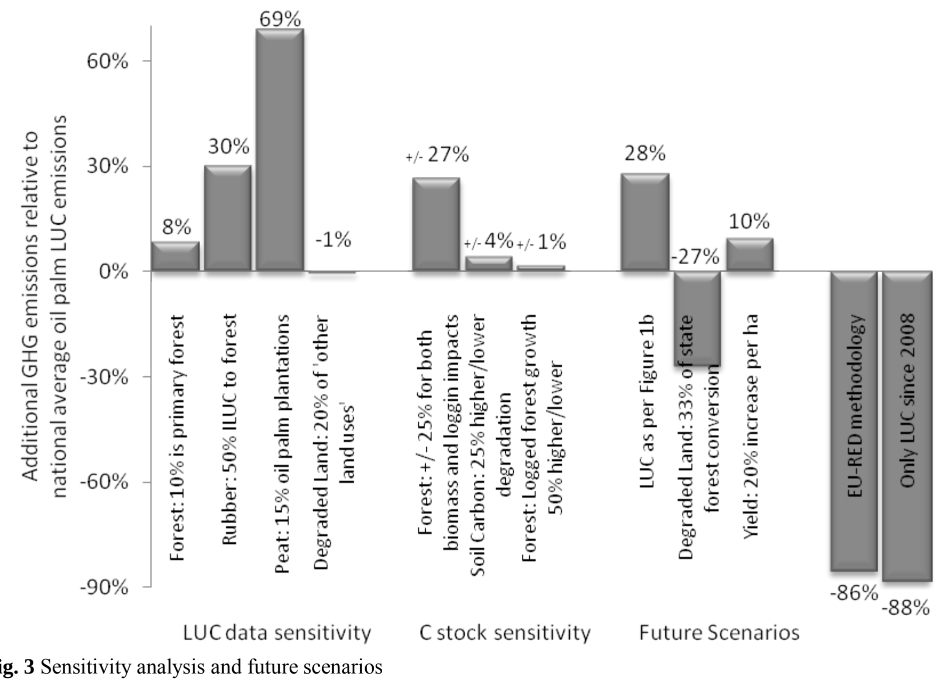

Fig. 3 Sensitivity analysis and future scenarios

4 Conclusions

Land use changes contribute significantly to the CO2 emissions from production of PME and result in long payback times if the previous land use is high carbon stock land like state forest. The average PME production is also significantly influenced by LUC. Due to the temporary nature of the biogenic carbon sequestered in oil palm plantations, these can only offset relatively few LUC emissions. Whereas the net emissions from rubber conversion to oil palm are relatively small, the emission can potentially increase significantly if ILUC is included in the assessment. Thus, although the sequestration benefits of converting degraded land are small, it is much preferable to the conversion of other land from an environmental perspective. The option of restoring and using degraded land should thus be investigated. It is clear that with a combination of avoiding forest conversion and implementing environmental optimization of the palm oil and PME the production, Malaysian palm oil can be environmentally sustainable from a global warming point of view.

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Appendix 2a – Supplementary Data

Supplementary data for the Land use change paper

Carbon Balance Impacts of Land Use Changes related to the Life Cycle of Malaysian Palm Oil derived Biodiesel

Electronic Supplementary Material

International Journal of Life Cycle Assessment

Sune Balle Hansen[a*], Stig Irving Olsen[a]

[a] DTU Management Engineering, Technical University of Denmark, Produktionstorvet building 424, 2800 Kgs. Lyngby, Denmark

Appendix A – Allocation

In Hansen et al. (2012) mass-based co-product allocation is given to crude palm kernel oil (CPKO), palm kernel cake (PKC), palm fatty acid distillate (PFAD) and Glycerine. In Table A1 the allocation details and the energy-based allocation, which is used in the main paper are presented.

The allocation to co-products takes into consideration the allocation, which has been made to co-products in previous phases. Thus it as e.g. been included in the allocation ratio to PFAD that some emissions have already been allocated to CPKO and PKC.

Table A1 Allocation to co-products

	Process phase	**Dry Weight [kg/ton PME]**	**LHV [MJ/kg residue]**	**LHV [MJ/kg PME]**	**Allocation to non-CPO/PME co-products**	
					Weight	Energy
PME[1]		1000	-	37		
Conventional co-products						
CPKO+PKC	Milling	276	28	7.7	22%	17%
PFAD	Refining	49	39	1.9	4%	4%
Glycerine	Biodiesel	101	24	2.4	7%	5%
Total		427	-	12.1	33%	26%

All values are taken or derived from Hansen et al. (2012)
[1] PME: Palm Methyl Ester (biodiesel)

* Corresponding Author. Tel: +60 12 219 9441 (Malaysia), +45 4525 4660 (Denmark)
E-mail address: sunebh@utm.my (primary), suneballe@yahoo.dk (secondary)

Appendix B – EU-RED Methodology

As benefits from residue use is not recognized by EU-RED, this section applies the production emissions from Choo et al. (2011), which does not include residue use. Choo et al. (2011), however, allocates emissions to shells, which is not allowed in EU-RED methodology. Removing this allocation, the production emissions from Choo et al. (2011) are 24.4 g CO_2/MJ assuming capture and flaring of methane from the anaerobic lagoons. With only 5-10 percent of mills in Malaysia currently capturing biogas, the national average production emissions are 42.0 g CO_2/MJ.

Like other existing studies, EU.RED LUC methodology does not distinguish between fossil and biogenic carbon and does not include indirect impacts like recovery of logged forest or induced emissions. The full carbon credit is thus given to carbon sequestration in oil palm plantations. Full emissions are, however, also assigned to carbon stored in rubber plantations. EU-RED only includes LUC emissions taking place after 2008, so in the Malaysian average emissions only areas converted after 2008 are included resulting in very low LUC emissions. Applying these conditions to section 3.2 in the main paper, the results come out as in Table B1.

The simplified methodology of EU-RED results in LUC emissions 30% lower for state forest conversion, 280% higher for rubber conversion and almost 90% lower for the Malaysian average compared to the methodology applied in this study. The potentials for reducing the emissions from the biodiesel production are, however, diminished as the benefits of using residues is not accounted for.

Table B1 GHG emissions using EU-RED methodology

	OP on state forest[1]	OP on rubber plantation[2]	Malaysian average emissions	
LUC emissions	280	127	18	ton CO_2/ha
	85	39	6	g CO_2/MJ
LUC emissions with 26% energy allocation to co-products	206	93	13	ton CO_2/ha
	63	28	4	g CO_2/MJ
National average PME[3] (no LUC emissions)[4]	-	-	**42**	g CO_2/MJ
PME[4] with no CH_4 emissions (no LUC emissions)[4]	-	-	**24**	g CO_2/MJ
Conventional PME[3] incl. LUC emissions[4]	*109*	75	**50**	g CO_2/MJ
PME[3] with no CH_4 emissions incl. LUC emissions[4]	*90*	55	**31**	g CO_2/MJ
LUC emission payback time (national average PME[3])	37	17	2.5	years
LUC emission payback time (no CH4 emission PME[3])	26	12	1.5	years

[1] Emissions for biodiesel derived from plantations planted on Malaysian State forest
[2] Emissions for biodiesel derived from plantations planted on former rubber plantation
[3] PME: Palm methyl ester (Biodiesel). Production as per Choo et al. (2011)
[4] With 26% energy allocation to LUC and Biodiesel production
'Bold': value passes the 35% emission reduction requirement of the EU-RED, i.e.below 55 g CO_2/MJ
'Italic': value is higher than the emissions for fossil diesel, i.e. higher than 84 g CO_2/MJ

Appendix C – Additional background for LUC Emissions data

Oil Palm Plantation

Oil palm plantations sequester carbon while growing. Germer and Sauerborn (2008) report 83 ton biomass per ha, which is slightly lower than the 101 ton per ha reported by Khalid et al. (1999a) and Khalid et al. (1999b) for Malaysian plantations. This study applies an average value of 90 ton/ha, resulting in 140 ton biogenic CO_2 sequestered per ha at the end of a 25 year growth cycle at 42% C in palms (Chow et al. 2008).

Due to a general lack of studies on soil carbon in Malaysian forests, Germer and Sauerborn (2008) report 120 ton soil carbon (0-100 cm) in a hectar of primary forest on mineral soil based on IPCC (1997). In accordance with IPCC (1997) and other studies, Germer and Sauerborn (2008) estimates 33% reduction in the soil carbon upon conversion of forest to oil palm plantation resulting in 80 ton soil carbon in the oil palm plantations. (Mathews et al. 2010) performed soil C measurements on oil palm plantations in Malaysia in 0-45 cm depth and found 55 ton C/ha in first generation plantations, app. 70 ton C/ha in second generation and app. 80 ton in the third generation thus indicating a significant build-up over time in the plantations. It is difficult to compare the results of Germer and Sauerborn (2008) and Mathews et al. (2010) due to the difference in measured depth. With the vast majority of soil carbon being concentrated in the upper layers of the soil (Germer and Sauerborn 2008, Mathews et al. 2010), the quantities presented in Germer and Sauerborn could be in line with the second or third generation soil carbon quantities presented in Mathews et al. (2010) and thus comply with a long term soil carbon equilibrium in the plantations. The plantation soil carbon of 80 ton/ha from Germer and Sauerborn (2008) is thus used in this study.

State Forest

Germer and Sauerborn (2008) report that primary tropical forest contains an average of 342 ton biomass per ha, which is in line with the IPCC guidelines (IPCC 2006). Thus, average CO_2 emissions from biomass clearing of primary tropical forest reach 627 ton/ha (assuming land clearing without burning) at 50% carbon content in the biomass and 3.67 ton CO_2/ton carbon (Germer and Sauerborn 2008).

Silver et al. (2000) states that tropical wet logged-over forest of about 200 ton biomass per ha can grow to 300 ton biomass or more per ha within approximately 25 years if left idle. So even if the forest is logged-over, the 'lost' biomass by clearing the land is higher than the standing biomass in the logged-over forest. However, as some logging is done by clearing it could take significantly longer for the forest to recover or the land could even turn into degraded land. Thus, an average recovery potential of 50% is assumed equalling a total average biomass of 250 ton/ha after 25 years.

Open burning is illegal and not practiced in Malaysia. It is assumed that residues from land clearing are left to degrade aerobically at, or nearby, the cleared site. Accidental fires in forests or plantations are not included in the scope of the study.

It must be noted that data for biomass forests can vary significantly. Germer and Sauerborn (2008) indicate variations of app. +/- 50% in tropical forest biomass and soil carbon in their review. Biomass loss during selective logging can also vary by app. +/- 50% depending specific vegetation and methods and equipment used (Lasco 2002). Forest recovery can vary significantly as well depending on impacts from the logging, soil fertility and local climate (Silver et al. 2000). Local LUC emissions can thus vary greatly from the averages presented here. In the sensitivity analysis (section 3.3 in the main paper) a scenario is given, in which the impacts of variations of +/- 25% for biomass in the state forest and +/- 25% carbon removal through logging are presented. A different scenario investigates the impacts of +/- 25% soil carbon loss in the conversion from state forest to oil palm plantation.

Rubber Plantations

The sequestered carbon in biomass in a rubber plantation just before felling is 72 ton C/ha (Yew 2001) or just about double the amount of carbon in an oil palm plantation. The literature on soil carbon in rubber plantations is very limited. Lai (2004) reported a 45% reduction in soil carbon after conversion from forest to rubber plantation in Malaysia, which can be considered similar to the carbon degradation at conversion from forest to oil palm. Thus, the soil carbon content for the two types of plantations is assumed similar and the loss/gain in conversion from rubber to oil palm is set to 0.

When converting a rubber plantation to an oil palm plantation, the rubber that was produced at that plantation must be produced somewhere else assuming that the world rubber demand is unchanged. This can be achieved either by establishing a rubber plantation somewhere else or by increasing the production of synthetic rubber. If it is assumed that another rubber plantation is established then it must be considered what land it is established on. This process is known as indirect land use change and is highly dependent of market forces, which makes the actual impacts very difficult to quantify. With the world production of synthetic rubber growing faster than natural rubber it is a valid assumption that the replaced rubber will be substituted by synthetic rubber. Synthetic rubber is produced from fossil oil and is more energy intensive than the production of natural rubber. By converting a rubber plantation, induced emissions are thus created.

Whereas Thailand as the biggest natural rubber producer in the world is likely to be representative for natural production of rubber, German rubber production may be more energy efficient that the world average. However, as no alternative studies have been found, the German values are used in this study. The net induced emissions from producing synthetic rather than natural rubber are thus 0.73 ton CO_2-eq per ton rubber.

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Appendix 3 – Management Paper

Environmental Management Options in Malaysian Palm Oil derived Biodiesel Production

Sune Balle Hansen, Stig Irving Olsen, Zaini Ujang

Submitted to Journal of Environmental Management in 2012

Environmental benefits of management choices in Malaysian palm oil derived biodiesel production

Sune Balle Hansen[a,b*], Stig Irving Olsen[a], Zaini Ujang[c]

[a] DTU Management Engineering, Technical University of Denmark, Produktionstorvet building 424, 2800 Kgs. Lyngby, Denmark
[b] UTM Razak school of Engineering and Advanced Technologies, University of Technology Malaysia, KL International Campus, Jalan Semarak, 50300 Kuala Lumpur, Selangor, Malaysia
[c] Faculty of Chemical Engineering, University of Technology Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

Abstract

This study aims to quantify the positive and negative environmental impacts of management choices in the production of palm oil derived biodiesel. Focus is on the plantation and milling stages where the main options for environmental improvements have been identified as residue use and yield improvement with a link to land use change impacts. The aspects of management differences between corporations and smallholders as well as an economic feasibility study of environmental improvements have been included. The life cycle assessment software GaBi was used to construct a model of the production system and test 14 different management scenarios. In terms of greenhouse gas emissions, the results show that there is little difference in the emissions between corporations and smallholders, unless plantations are planted on former state forest, in which case the lower yields and thus higher land use of some smallholders result in higher emissions. Looking at other impact categories, the smallholders are generally performing better than corporations because of lower fertilizer use. Scenarios depicting potential improvements in yields and residue use are all performing significantly better than the conventional scenario in terms of greenhouse gasses and moderately better in most other impact categories. No impact categories increase compared to the conventional scenario. Economically, the environmental improvements are a good investment for the palm oil companies although the income is small compared to the income from palm oil and biodiesel.

Keywords: Palm Oil, Biodiesel, Environmental Management, Residue use, Economic feasibility, Life Cycle Assessment

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* Corresponding Author. Tel: +60 12 219 9441 (Malaysia), +45 4525 4660 (Denmark)
E-mail address: sunebh@utm.my (primary), suneballe@yahoo.dk (secondary)

1 Introduction

Palm oil is the biggest and fastest growing vegetable oil on the world market with a market share of about 30%. Whereas the high yield per hectare (ha) of palm oil gives it certain economic and environmental advantages over other vegetable oils, there are a number issues in the production, which compromises the environmental advantages unless the production is managed with environmental considerations in mind. With the growing biodiesel market, the need to map the environmental impacts of conventional palm oil production as well as potential improvements has never been bigger.

The main stages in the production of biodiesel from palm oil (Palm methyl ester – PME) are nursery, plantation (incl. land use change (LUC)), milling and transesterification including refining. Whereas the nursery impacts in a life cycle perspective are insignificant (Choo et al., 2011) and the refining and transesterification stages are limited mainly by technological state-of-the-art; the plantation and milling stages are subject to significant influence by management practices (Hansen, Personal observations).

This study discusses potential improved management practices and quantifies the environmental benefits of such improvements using life cycle assessment (LCA) tools with a focus on global warming potential (GWP) but with inclusion of other impact categories as well. The improvements are subjected to an economic feasibility assessment in order to evaluate the applicability.

The difference in environmental impacts due to the management practices observed by corporations and smallholders are assessed as well.

Three main categories of oil palm plantation owners are present in Malaysia:

1. Private or Government-linked corporations (60%)
2. Organized smallholders (29%)
3. Independent smallholders (11%)

The organized smallholders follow management practices set by the umbrella organization like the Government-linked Federal Land Development Authority (FELDA) and as such the management practices are similar to the private or government-linked corporations (Felda, Unpublished). The independent smallholders may, however, have very diverse management practices depending on financial ability and general commitment to the plantation. Whereas some take pride in a well-managed estate, which can be better maintained than most corporate owned estates, other smallholders only attend to the plantations during harvesting (Hansen, Personal observations).

For simplicity purposes, the limit of 55 g CO_2-eq/MJ for biofuels to be labeled renewable in the EU Renewable Energy Directive (EU-RED) (European Parliament, 2009) is used in this study to describe environmental sustainability.

2 Materials and Methods

2.1 LCA details/choices

The LCA methodology follows the guidelines of the ILCD Handbook (European Commission, 2010). Some specific methodological choices have been made to include substitution rather than allocation for residues as per Hansen et al. (2012) and energy allocation for co-products. For LUC, a distinction between temporary and permanent carbon storage as described in Hansen et al. (Submitted 2012).

2.2 Data collection

The study included collaboration with Malaysian palm oil producer Felda from whom some unpublished data has been collected (Felda, Unpublished) as well as personal observations made during the field work and interviews (Hansen, Personal observations).

The data collected from smallholders had higher variation than expected, resulting in statistical insignificance of the data. The results are thus used only to provide indications and show the potential ranges of data. Firm conclusions on the difference between corporations and smallholders cannot be derived.

2.3 The model

A PME production model was generated in the LCA software GaBi 4 using processes from the EcoInvent 2.0 database. The model includes nursery, plantation (incl. LUC), milling and PME refining.

Data input to the model is mainly as presented in Choo et al. (2011) with waste emissions included as per Hansen et al. (2012) and LUC emissions included as per Hansen et al. (Submitted 2012). The FFB yield of 20.7 ton/ha given in Choo et al. (2011) has been replaced by the national average yield for Malaysia for 2007-2011, which was 19.2 ton/ha (MPOB, 2012) without adjusting other input/output from Choo et al. (2011). The rationale for doing this is that most plantation activities are the same whether the yield is high or low. The one process, which has a direct correlation with yield, is the fertilizer application. However, Choo et al. (2011) recognizes that the fertilizer use presented in their study is already low compared to other studies, so it is not lowered further in this study. Even with the adjusted FFB yield by this study, only about 800 kg fertilizer (~350 kg NPK) is applied per ha, whereas Basri and Arif (2009) reported an estimated 4.3 million tons fertilizer use in Malaysia in 2007, applied to a total planted area of 4.3 million ha (MPOB, 2012) equaling 1,000 kg/ha (~430 kg NPK/ha). Choo et al. (2011) argues that one reason contributing to the low fertilizer use in their study is the fact that it is taken into consideration that no fertilizer is applied in the last three years of the plantation cycle. This has also been applied in this study in all scenarios involving fertilizer use.

Characterization of the system was done using ReCiPe Midpoint as included in the GaBi 4 software.

2.4 Economic feasibility

The economic feasibility of environmental improvements in the PME production through the use of residues is based on the capital costs, loan interests and operation of biomass plants, biogas plants and mill boilers from the point of view of the palm oil industry based in data from Felda (Unpublished). The option of simply selling residues to traders is not associated with any cost. The income from sale of residues or residue derived products like electricity is included in the assessment using 2012 market prices. As no pyrolysis plants are yet in operation in Malaysia, no economic data has been retrieved for pyrolysis/biochar. Costs and income from pyrolysis has been assumed similar to a biomass plant producing electricity.

3 Results and Discussion

Based on the management options in the oil palm plantations and the palm oil mills presented in section 3.1, a number of scenarios are identified in section 3.2, which describe current and potential results of management strategies. The scenarios in section 3.2 have been chosen to best describe the conventional production, the improvement options and the expected future reality. The GWP impacts of each scenario are given in section 3.3 along with other impact categories results for chosen scenarios. The economic feasibility study follows in section 3.4.

3.1 Management options

The management options described below depict the conventional Malaysian management system for corporations as well as for smallholders. Changes in some or all of the management options are explored in the scenarios in section 3.2

3.1.1 Plantation

Fertilizer and Pesticides

The use of fertilizer and pesticides in the plantations is ideally subject to a cost-benefit analysis, which determines the optimal fertilizer-yield ratio. In practice, many corporations conduct general cost-benefit analyses, which are incorporated in the management practices without site-specific considerations (Hansen, personal observations). Whereas the fertilizer quantities are fitting in most cases, this practice can in some cases result in over- or (in rare cases) under-fertilization.

Smallholders are generally prone to letting their fertilizer use be guided by financial limitations thus most often resulting in under-fertilization. The resulting lower yield starts a vicious circle in which the lower income means less capital for new fertilizer thus maintaining the low yield (Hansen, personal observations).

Although there are big variations in the amounts of fertilizer used by smallholders, this study found that on average the use is approximately 20% lower than for corporations. This can to some extend be compensated for by the manner of application. Whereas corporate estates use machinery or plantation laborers with a minimum of training, the smallholders are often knowledgeable farmers and do the application under personal supervision (Hansen, personal observations). Maximum benefits from the fertilizer can be achieved by mixing the fertilizer into the soil to avoid surface run-off. This practice is time consuming and not applied by corporations, but some smallholders achieve good yields while keeping fertilizer expenses low this way.

From an environmental point of view, the trade-off between fertilizer use and higher yield is interesting as well and is being explored in the scenarios in section 3.2.

Mulch

Fronds cut from palms during harvesting are applied as mulch in long rows on the plantation. Mulching has the advantage of diminishing soil erosion and moisture evaporation and well as providing carbon and nutrients to the soil. All of this with a minimum of labor and transportation involved. Without the mulching of fronds, soil fertility would drop and more industrial fertilizer would be needed. However, the gains are small in relation to the amount of organic material applied as most of the carbon is lost as CO_2 and potentially a smaller fraction as methane from the center of the frond piles. Also, it is expected that some N_2O emissions take place during the organic degradation. The emissions of this high-strength greenhouse gas could be enough to create a negative GHG balance for mulching (Hansen et al., 2012).

During replanting, trunks are for the most part sliced and applied as mulch around the new palms. Same pros and cons apply as for the mulch.

Thoughts must be given to the benefits of mulching as well as the logistic complications of transporting the vast amounts of organic material out of the plantations before considering trunks and especially fronds for other applications. One option to overcome these issues is mobile pyrolysis units, which can create biochar on-site for direct field application as an alternative to the mulch (see section 3.2.8).

Transportation

As mills are most often located at the oil palm estates, transportation distances for FFB are on average approximately 5 km (Felda, Unpublished). Thus, environmental impacts from the FFB transportation are low compared to other plantation impacts and the potential gains from optimization of the transport are negligible in a life cycle perspective.

Harvesting

Ripeness of the FFB is determined by the number of fruits, which have fallen to the ground. However, some smallholders are eager to sell their produce and harvest earlier, which results in a lower oil extraction rate and lower pay from the mills per ton FFB (Donough et al., 2010). In order to increase the overall oil yield in the palm oil sector, it is thus important that these smallholders are educated not to prematurely harvest the FFB.

Replanting

Smallholders face problems during replanting, at which they have expenses to clear the land and buy and plant new seedlings on top of which they do not get an income from the land for three years while the palms mature enough to start bearing fruits. Due to this, many smallholders leave the palms for more than 25 years resulting in decreasing yield. It is also not uncommon that new seedlings are planted in the inter-rows between the existing palms. The old palms are poisoned and left to rot once the new palms are fruit bearing. This will shorten the no-income period, but it compromises the growth of the young palms due to lack of sunlight and additional risk of spreading of deceases and pests from the rotting palms to the young palms resulting in an overall yield loss (Ooi and Heriansyah, 2005; Bivi et al., 2010; Hansen, personal observations).

According to Felda (Unpublished), the optimal plantation cycle is 22 years of FFB production meaning a full plantation cycle of 25 years incl. the three years of maturing. Extending the production cycle from 25 to 30 years decreases the average annual production by 2% per ha and makes the harvest more difficult due to the taller palms.

Land Use Change, LUC

Before establishing a plantation, the decision of where to establish it can determine the potential sustainability of the palm oil produced. If planting on previously high carbon stock land, the emissions from the land use change will be enough to render the production unsustainable in a foreseeable future (Germer and Sauerborn, 2008; Hansen et al., Submitted 2012). The first and most important management choice thus lie before the plantation even exists.

3.1.2 Mill

Boiler

The conventional boilers at the palm oil mills are often highly inefficient as there have traditionally been no alternative use for the press fibre and shells, which are being used as fuel, nor any restrictions on stack emissions. There have thus been no incentives for mills to invest in high-efficiency boilers. On the contrary, the boilers have even been overfed in some cases to reduce the volumes of press fibre and shells before disposal (Hansen, Personal observations). With the increasing market value for the solid residues and the growing environmental focus, more efficient boilers may, however become more attractive.

Residues

The solid residues from the mill, which are not used in the mill boiler, amount to 600 kg dry weight EFB and kernel shells per ton of palm oil produced. Whereas the EFB are currently mostly used as mulch in the oil palm plantations, the shells are to a large extent sold off as fuel for industrial boilers. The residues have numerous alternative application potentials as feedstock for biomaterials and energy recovery. This study is limited to consider the conventional practices like mulching and potential applications to energy recovery and biochar production. Biochar is produced through pyrolysis with the co-products bio-oil and syngas. The high content of fixed (non-biodegrabable) carbon in the biochar makes it an ideal product for simultaneous soil fertility enhancement and carbon sequestration (Lehmann and Joseph, 2009).

Palm oil mill effluent (POME) is wastewater from the palm oil mills. The high organic content of the POME is removed through anaerobic digestion in open lagoons before discharge to the water ways. The resulting methane emissions are the single largest greenhouse gas contributor from the palm oil production life cycle only exceeded in some cases by carbon emissions from land use change. Substituting the open lagoons with a biogas plant with methane energy recovery (e.g. gas engine) turns the emissions into a resource substituting fossil fuels.

3.2 Management scenarios

The management scenarios in sections 3.2.1 to 3.2.14 quantify the results of various management strategies in terms of fertilizer input, FFB output etc. The yields presented in the scenarios are average yields over the 25-year plantation cycle incl. the immature phase.

3.2.1 Malaysian Average

The Malaysian average scenario depicts conventional palm oil production in Malaysia as presented in section 2.3, section 3.1 and Hansen et al. (2012).

3.2.2 Corporations

The 'Corporations' scenario takes its base in corporations adhering to best management practices (BMPs). 2011 Annual reports from some of the biggest palm oil producers in Malaysia (Felda, Sime Darby, IOI, KLK and UP) show an average yield of app. 21 ton FFB/ha/year from the plantation activities including immature plantations and an oil extraction rate of app. 21%, i.e. a CPO output of 4.4 ton/ha. Based on Hansen (Personal observations), the average fertilizer application is estimated at 3.9 kg N, 3.1 P_2O_5, and 11.0 K_2O totaling 18 kg NPK/ton FFB for corporations.

3.2.3 Smallholders1 – Knowledgeable farmers

Whereas some smallholders can achieve FFB yields as high as the corporations, these are few. This scenario estimates a yield of 20 ton FFB/ha/year, which is higher than the national average, but lower than the corporations running BMPs. Fertilizer use per ha is assumed equal to the national average based on the interviews carried out in this study. Default emissions are assumed for the milling.

3.2.4 Smallholders2- Neglected plantations

This scenario depicts the smallholder plantations subjected to underplanting and/or neglected weeding and general maintenance. These smallholders are also assumed not to have the financial means to purchase adequate amounts of fertilizer. Based on Ayat et al. (2008) and the observations made during this study, it is estimated that these factors result in a yield of only 15 ton FFB/ha/year with a fertilizer use of 13 kg NPK/ton FFB. Default emissions are assumed for the milling.

3.2.5 With methane capture at POME lagoons

This scenario assumes that all methane from the anaerobic digestion of POME is captured and used for electricity production in a gas engine. Default emissions are assumed for the plantation stage.

3.2.6 Without methane capture at POME lagoons

This scenario assumes that the anaerobic digestion of POME is done in open lagoons with methane emissions directly to the atmosphere. Default emissions are assumed for the plantation stage.

3.2.7 Energy recovery of residues

This scenario is based on Hansen et al. (2012) and assumes all available residues from the mill and the trunks from the plantation are used for energy recovery in biomass plants, industrial boilers or pyrolysis. POME is treated in biogas plant with methane capture. This is a purely hypothetical scenario to show the potential environmental benefits of residue use. All other processes in the plantations and mills are considered default.

3.2.8 Biochar from wastes

The assumed yields of biochar, bio-oil and syngas from pyrolysis of palm oil residues as well as the expected fixed carbon content in the biochar are described in Hansen et al. (2012)

The biochar scenario assumes all available solid wastes from the mills used for biochar production through pyrolysis. Half of the fronds are used for biochar as well whereas the other half is retained as mulch in the plantations. Transferring plantation residues away from the plantations presents a logistic problem. Mobile pyrolysis units, which can be moved to replanting areas to create biochar from the trunks will resolve this problem and make the biochar easily accessible for field application during replanting. Fronds from nearby plantation areas could then be utilized simultaneously. Thus, only some of the fronds are feasible to use. The increased soil fertility from adding the biochar to the plantation soil will likely result in yield increases. As no field data exist, only a minor yield increase to 20 ton FFB/ha due to soil fertility enhancement is assumed here. This scenario as well is purely hypothetical to show the potentials of biochar.

3.2.9 Yield improvement

Despite an overall stagnation in the FFB yields in the past decade (MPOB, 2012), yields improvements are expected in the near future with the increasing focus on BMPs and improved oil palm genome entering the estates (PIPOC, 2011). This scenario depicts a 30% yield increase to 25 ton FFB/ha. The 30% increase in FFB yield equals a 20% increase in the overall biomass production at the plantation, which is assumed to result in 10% increased fertilizer need per ha as increased plant uptake lowers fertilizer losses. The fertilizer use per ton FFB decreases to 15 NPK kg due to the increased yield. Default emissions are assumed for the milling stage.

3.2.10 Vision 35/25

Vision 35/25 aims for a FFB yield of 35 ton/ha and an oil extraction rate (OER) of 25% by 2020 (Basri and Arif, 2009). Some R&D plantations are currently achieving 30-35 ton FFB/year yields during the prime production years of the palms and OERs close to 25% have been reached as well (Basri and Arif, 2009). So although the vision is unlikely to come through as a Malaysian average by 2020, some pioneering mills and estates may achieve such average yields. Records of fertilizer needs at such high productivity estates have not been found. It is assumed here that fertilizer use is 33% higher than the current default. More fertilizer is thus used per ha, but with the higher yield, the fertilizer use decreases to 13 kg NPK/ton FFB.

3.2.11 Boiler efficiency improvements

A relative improvement in boiler efficiency of just 18% is sufficient to let the boiler run on residue press fiber alone and make all the kernel shells currently used as boiler fuel available for other applications. Further improvements could release a fraction of the press fiber as well. Alternatively the biogas from POME treatment can produce sufficient amounts of steam in a high-efficiency gas-fired boiler to release all shells and fiber for other applications. Due to data shortage only the first option of 18% boiler efficiency improvement is considered here. The 18% improvement may be possible to achieve through modifications of the boiler units and pipes as well as more efficient operation, but the feasibility study tests the scenario of installing a new boiler. Improving boiler efficiency is only logical if the residues have alternative uses. Thus, this scenario is combined with the Energy recovery of residues scenario.

3.2.12 Optimal scenario

The optimal scenario combines the various improvements proposed in the other scenarios to present the ideal environmental conditions for palm oil production; i.e. the full residue use, the yield and OER of the 35/25 scenario and the improved mill boiler.

3.2.13 2015 scenario

The 2015 scenario aims to present a realistic scenario for 2015. As no official projections have been found for 2015, the scenario is based on observations made by the authors during this study.

The trend line of FFB yield development for 2002-2011 points towards a yield of 21 ton/ha in 2015 if the sudden decreases in 2009 and 2010 are omitted (MPOB, 2012). The poor yields in these years have been explained by unfortunate weather conditions (PIPOC, 2011). Whereas some future years may also produce low yields, the technology and knowhow is present to assume 21 ton/ha by 2015, which is done in this scenario. This yield increase can be reached with negligible increases in fertilizer use through the presently ongoing and continuous introduction of more productive oil palm breeds. The use of plantation residues will still be mainly mulch as the application of pyrolysis is still in its infancy. A negligible quantity of fronds will thus be used for pyrolysis and only 1% of the trunks.

At the mills, the OER is likely to increase marginally to app. 21% based on the trend of the last 10 years (MPOB, 2012) and the increasing market for residues will make mills strive to operate their boilers more efficiently to release more shells. An average 5% increase in boiler efficiency is estimated. EFB will still to a large extent be used as mulch, but the use in biomass plants and industrial boilers is likely to increase to 25%. Only remote mills will not be able to sell their shells. 80% of these will be used on biomass plants and industrial boilers. 20% of mills will have biogas plants.

3.2.14 2020 scenario

Further improvements will happen by 2020 although the FFB yield is not expected to reach the Vision 35/25 goal. Yield is expected to follow the Yield improvement scenario. Mobile pyrolysis units are becoming more wide-spread resulting in 30% of trunks being used, but only 5% of the fronds due to the logistics.

In the mills, the OER increases to 23% and average mill boiler efficiency increases by 10% compared to the current level. Most EFB are now used for energy recovery or biochemical purposes (this paper only includes energy recovery) and the market value of shells is ensuring that all shells are used. All mills will have biogas plants.

3.2.15 Land use change

Land use changes related to the founding of a plantation have potentially large impacts on the life cycle of palm oil production. All scenarios above will be subjected to LUC impacts from the previous land uses State Forest and Rubber Plantation as they are presented in Hansen et al. (Submitted 2012).

3.2.16 Scenarios summaries

In Table 1 and Table 2 default (Malaysian average) values apply to all scenarios unless other values are stated.

Table 1 – Scenario data for the plantations

Management options	FFB Yield ton/ha/yr	NPK Kg/ton FFB	Pesticide kg/ton FFB	Under planting	Fronds		Trunks	
					mulch	pyro.	mulch	pyro.
Conventional								
Malaysian avg. **(default)**	19.2	18	2.8	neg.	100%	0%	100%	0%
Corporations	21	18	3	No	d	d	d	d
Smallholders 1	20	15	2	No	d	d	d	d
Smallholders 2	15	14	1	Yes	d	d	d	d
Waste								
Biochar	20	d	d	d	50%	50%	0%	100%
Production								
Yield improvement	25	15	d	d	d	d	d	d
Vision 35/25	35	13	d	d	d	d	d	d
Future								
Optimal	35	13	d	d	50%	50%	0%	100%
2015	21	16	d	d	100%	0%	99%	1%
2020	25	15	d	d	95%	5%	70%	30%

d: same value as default scenario

Table 2 – Scenario data for the mills

Management options	OER	Boiler eff. improv.	EFB			Shells			POME	
			mulch	power	pyro.	landf.	power	pyro.	open	b.g.p.
Conventional										
Malaysian avg. **(default)**	20%	-	85%	15%	0%	30%	70%	0%	90%	10%
Corporations	21%	d	d	d	d	d	d	d	d	d
With CH_4 capture	d	d	d	d	d	d	d	d	0%	100%
Without CH_4 capture	d	d	d	d	d	d	d	d	100%	0%
Waste										
Energy recovery	d	d	0%	100%	0%	0%	100%	0%	0%	100%
Biochar	d	d	0%	0%	100%	0%	0%	100%	0%	100%
Production										
Boiler efficiency	d	18%	0%	67%	33%	0%	67%	33%	0%	100%
Vision 35/25	25%	d	d	d	d	d	d	d	d	d
Future										
Optimal	25%	18%	0%	67%	33%	0%	67%	33%	0%	100%
2015	21%	5%	75%	25%	0%	20%	80%	0%	80%	20%
2020	23%	10%	10%	70%	20%	0%	80%	20%	5%	95%

d: same value as default scenario

3.3 Results

3.3.1 GHG emissions

Figure 1 shows GHG emission results of the 14 scenarios with no LUC impacts, with impacts from state forest conversion to oil palm and with impacts from rubber to oil palm conversion. The value axis has been cut at 84 g CO_2-eq/MJ, which is the GHG emission value for fossil diesel. All scenario emissions exceeding this value are thus emitting more GHG than fossil diesel. PME from a plantation planted on state forest is clearly unsustainable for all scenarios except the utopic Optimal scenario thus making the plantation and milling management decisions less influential from a sustainability point of view. With less prominent emissions from LUC as in the case of replacing rubber plantations, the management decisions, however, become highly relevant. It is worth noticing that all scenarios including the average Malaysian scenario are meeting the sustainability criteria in section 1 when plantations are not planted on previous high carbon stock land.

With no land use change impacts, the differences between the impacts from corporations and smallholders are small. However, due to the low yields, the less productive smallholders fall significantly behind when conversion of State forest is assumed as more land is needed. There could, however, be lessons to be learned by the corporations when it comes to lower their impacts through more efficient means of fertilizer application.

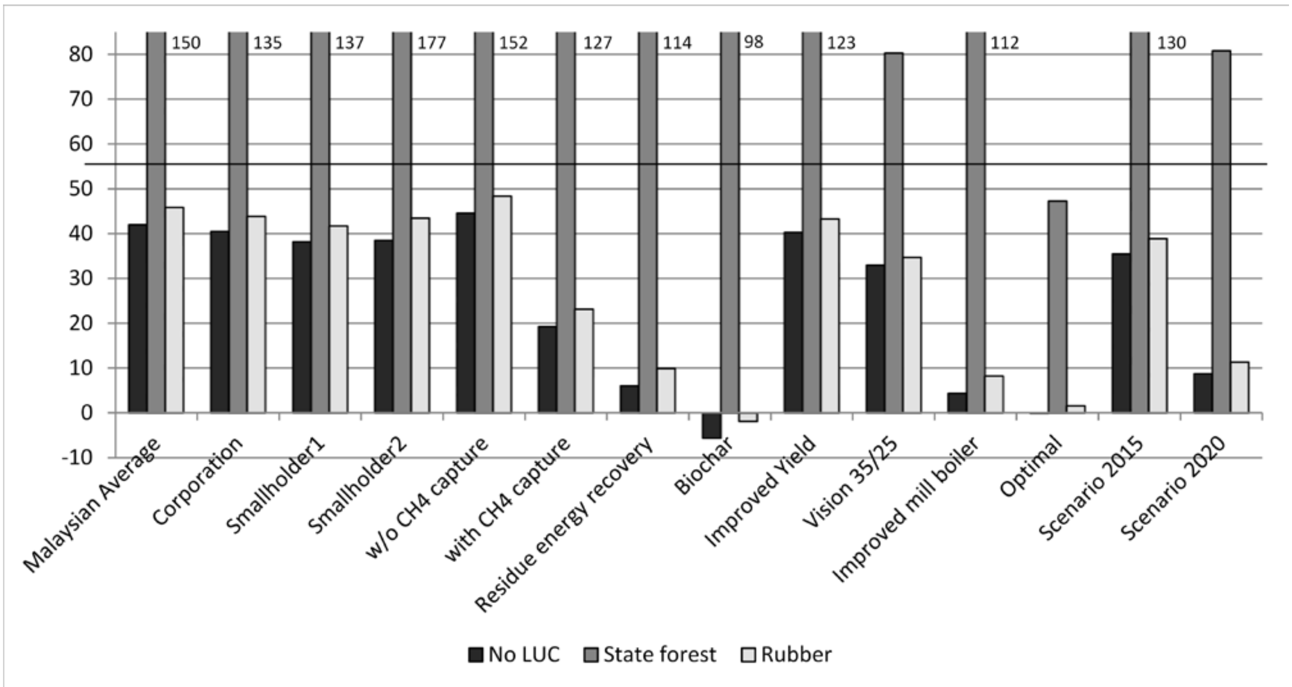

Figure 1 – Life cycle GHG emissions (g CO_2-eq/MJ PME) with and without LUC contribution for each scenario
The cut-off at 84 g CO_2-eq/MJ symbolizes the GHG emissions equivalent to fossil diesel emissions. The horizontal line at 55 g CO_2-eq/MJ symbolizes the sustainability limit as defined in section 1.

In general, the main motivator for improving the yield is to reduce the LUC, thus avoiding having to convert forest of any kind. However, the use of residues for energy recovery and substitution of fossil based energy can result in equally important emissions reductions and even potentially turn PME production into a carbon sink if no high carbon stock land is converted.

The biochar and the optimal scenarios are the only scenarios assuming that significant amounts of fronds are used for other applications than mulch, which is why the benefits are so immense in these scenarios. The carbon savings in the biochar scenario are larger than the optimal scenario for low carbon stock land use change as the higher yield in the optimal scenario makes fewer residues available for biochar thus reducing the benefits.

The 2015 and 2020 scenarios show that PME production from palm oil can be expected to improve considerably over the next decade, but that PME is still dependent on LUC decisions to be sustainable.

3.3.2 Other impacts

In Figure 2 and Figure 3 some selected scenarios have been subjected to other impact categories than GWP. GWP has, however, also been included for comparative purposes. As land use changes are only quantified for GWP in this study, the No LUC GWP results from Figure 1 are applied in Figure 2 and Figure 3. Only non-GWP impact categories with results pointing in different directions than the GWP impacts are included in Figure 2 and Figure 3. The impacts have not been normalized as GaBi 4.0 does not include Malaysian normalization values and different impact categories can thus not be compared to each other.

Whereas the GWP impacts show higher impacts for the less productive smallholders, the other impact categories in general suggest lower impacts due to the lower consumption of fertilizer and pesticides per ton FFB produced. Especially freshwater eutrophication potentials are significantly lower. This indicates that the environmental performance of PME should not be made based on GWP impacts alone. This is supported by the results in Figure 3, which show that especially freshwater eutrophication and to some extend also freshwater ecotoxicity and human toxicity do not necessarily improve much when GWP targeted improvements are made to the production system. It should, however, be noted that no category experience increased impacts in any of the scenarios compared to the conventional average Malaysian scenario. But in a holistic environmental management strategy for palm oil and PME it is necessary to assess whether a strategy aimed at GWP impacts is necessarily the best for the environment as a whole.

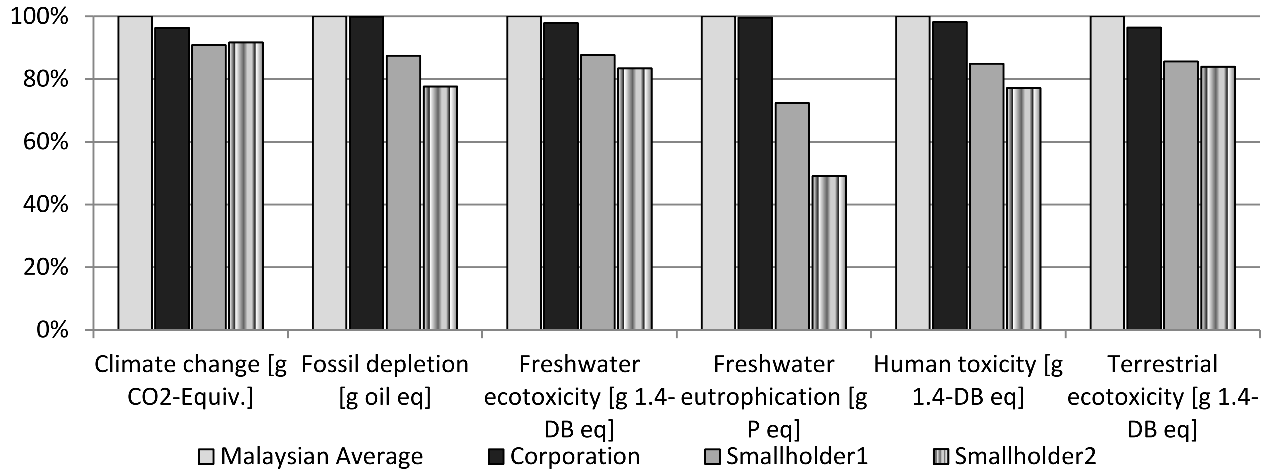

Figure 2 – Selected impact categories for corporations and smallholders

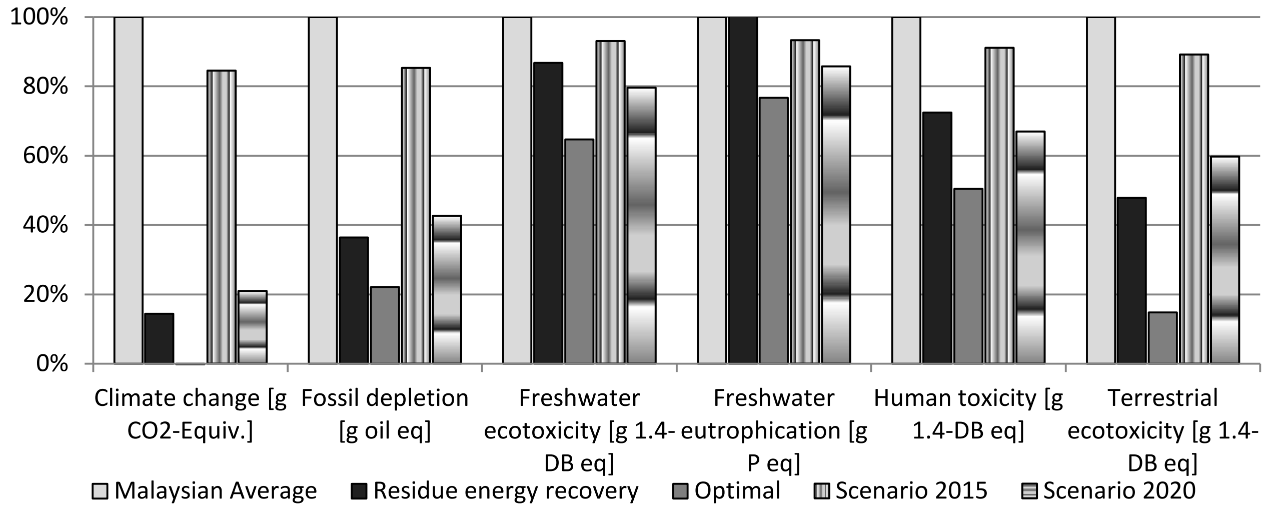

Figure 3 – Relative impacts of chosen impact categories in chosen scenarios

3.4 Economic Feasibility

This section identifies the costs and potential incomes associated with management practices in plantations and the investments associated with improved residue use.

3.4.1 Plantation management costs – Smallholders vs. Corporations

Management costs in the plantations are incurred through purchase of fertilizer and pesticides, transportation, equipment maintenance and labor for general up-keeping, harvesting and fertilizer/pesticide application. On top of this, corporations have expenses for office buildings and staff. Table 3 shows general plantation expenses and income for corporations and smallholders (as defined in section 3.2) based on Basri and Arif (2009) and field data collected during the present study (Hansen, personal observations). Note that although Smallholders2 have a relatively high net income per ton FFB their low yield give them a lower income per ha per year. This indicates that e.g. Governmental development programs could turn the vicious circle of low yield-low income-low fertilizer application-low yield around by providing small loans to the smallholders for a few seasons until the yield has improved and more income can be generated per ha.

As the results of this study show that the smallholder practices do have environmental advantages in some impact categories, it is important that the palm oil industry as a whole puts increased focus on optimized fertilizer application to ensure an optimal yield-fertilizer ratio.

Table 3 – Plantation expenses and income

	Corporations	Smallholders1	Smallholders2	
Costs				
Fertilizer and Pesticides	550	450	300	USD/ha/year over 19 years
All other	950	550	400	USD/ha/year over 22 years
Replanting	2,000	2,000	2,000	USD/ha for 3 years
Total	1,500	1,050	800	USD/ha/year over 25 years
Total	70	55	55	USD/ton FFB
Income				
Mill FFB price	200	200	200	USD/ton FFB
Average income	3,700	3,500	2,650	USD/ha/year over 25 years
Average income	175	175	175	USD/ton FFB
Net income	2,200	2,450	1,850	USD/ha/year over 25 years
Net income	105	125	120	USD/ton FFB

All values are from Basri and Arif (2009) and Hansen (personal observations)

3.4.2 Income from residues

The scenarios, which include a change in the use of residues compared to the default scenario, have been subjected to a simple economic feasibility assessment using the methodology described in section 2.4. The input costs and income for the feasibility study listed below have been collected from the palm oil industry and residue traders in Malaysia (Hansen, personal observations)

- 7 MW Biomass power plant
  - Capital cost: 23 mill. USD, interest rate: 5% over 15 years, operation cost: 5% of capital cost per year, operation: average 90% capacity for 20 years
  - Feedstock: 170,000 ton EFB per year
  - Product: Electricity, Income: 0.11 USD/kWh
- 2 MW biogas plant
  - Capital cost: 4 mill. USD, interest rate: 5% over 10 years, operation cost: 5% of capital cost per year, operation: average 90% capacity for 10 years
  - Feedstock: 250,000 ton POME per year
  - Product: Electricity, Income: 0.11 USD/kWh
- New mill boiler (40 ton)
  - Capital cost: 1.5 mill. USD, interest rate: 5% over 5 years, operation cost: no additional cost, operation: 20 years
  - Feedstock: press fibre
  - Product: shells, Income: 60 USD/ton
- Sale to traders
  - No expenses
  - Income: EFB: 8 USD/ton, Shells: 60 USD/ton

Figure 4 presents the results as the marginal costs per ton CO_2-eq saved, i.e. the costs of bringing the system from the default standard to the respective improved scenario standards and not including expenses, which are not affected by the change. Income is presented as negative values in Figure 4.

It is common for all the scenarios that the income from selling the residues, or the products derived from the residues, is higher than the expenses. In general, the more residues, which are used, the higher the net income is. Despite full residue use in the optimal scenario, the income is lower than some of the other scenarios as the increased FFB yields and oil extraction rates results in less residues per ton PME. It is just barely feasible to replace the mill boiler if the efficiency of the new boiler is only enough to make the shells available for other applications. A higher efficiency, which would also release some of the press fiber, would increase the investment potentials. The biochar scenario has not been included in Figure 4 as it would be based purely on the assumption that pyrolysis and biomass plants are similar in costs and product income. As such, the uncertainly of that scenario is higher than the other scenarios and presenting them in the same figure could lead to confusion. Qualitatively it can be mentioned that costs, income as well as net income are higher for the biochar scenario than for any of the other scenarios.

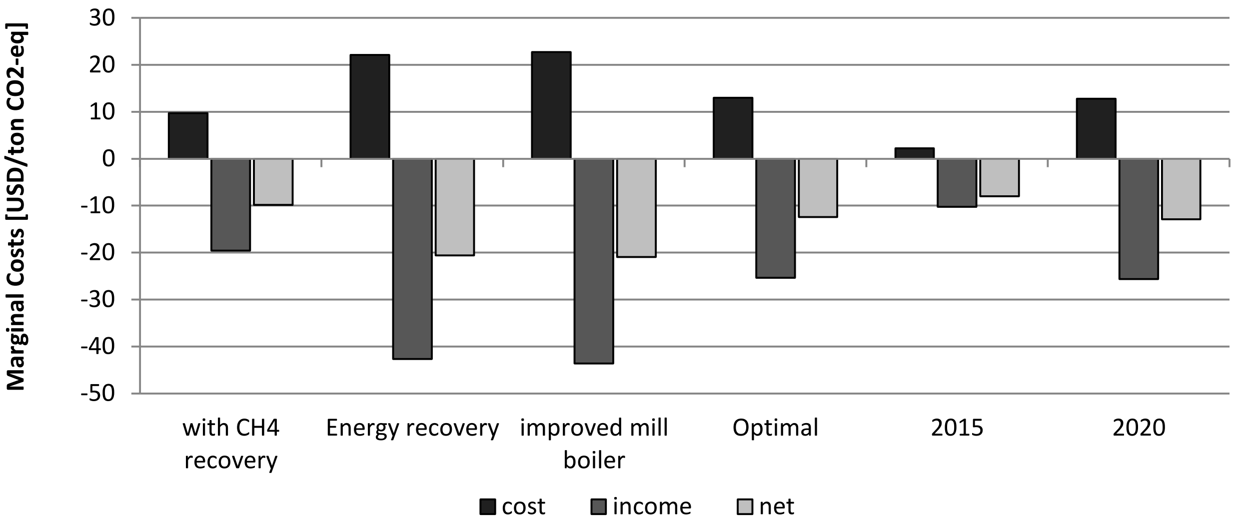

Figure 4 – Costs, income and net income of residue use related scenarios
Costs are given in positive values and income as negative in order to make a clear distinction

In relation to the price of CPO, which has been fluctuating around an average of app. 1,000 USD in 2012, the potential income generation from the residues is minimal. The potential for especially the smallholders to supplement their FFB income with a residue income is thus very limited. It should, however, be noted that the net income in Figure 4 can be added directly to the bottom line as no additional expenses are required. Also, as higher value bioproducts from palm oil residues are being developed, market prices and thus potential income generation for plantations and mills are likely to increase. The potential of biomass from the palm oil industry has been acknowledged by the Malaysian Government in e.g. the National Biomass Strategy 2020 (AIM, 2011) and the Economic Transformation Program (PEMANDU, 2012). In order to ensure the progress as per the strategies, the Government will push for and oversee the development of biomass use, which will only increase the market demands and thus prices for palm oil residues.

In absolute terms, the income from residues is not negligible. A 60 ton mill adhering to the Residue energy recovery scenario would be able to generate app. 2.5 mill. USD/year from its EFB, shells, which are not used in the mill boiler, and POME and a smallholder with a 5 ha plantation could get an equivalent income of up to 600 USD/year from trunks and fronds, which is equivalent to the monthly salary of a low-ranking office staff in Malaysia. This is assuming that the trunks and half of the fronds are sold for pyrolysis. Government programs could also ensure that mobile pyrolysis units could be rented by smallholders during replanting. If the biochar is added to the soil on the smallholder plantation, the expected yield increase may provide an even bigger additional income. An added benefit is that if the biochar is sold, the income would come during replanting when the farmer needs it the most.

The potential additional income from carbon credits for the residues are not included here, but can boost the income.

4 Conclusions

Significant GHG emission reduction potentials are available through management choices of yield improvement and residue use. Other impact categories are reduced as well although it is important to increase both the yield to fertilizer ratio and the residue use in order to achieve reductions in all categories. Smallholders with neglected plantations are generally responsible for the highest GHG emissions as the low yields cause more LUC to meet market demands for palm oil. However, for other impact categories, in particular eutrophication, the smallholders cause less impacts due to the lower use of fertilizers and pesticides.

It makes good economic sense to ensure that residues are used. Palm oil producers can either invest in e.g. biomass plants to generate electricity or sell the residues to traders, who again sell them for energy recovery applications in other industries. There are still only relatively small incomes to be made from the residues, but with higher value biochemical applications potentials in the near future, residues may become a considerable side income and improve socio-economic conditions for smallholders as well.

Acknowledgements

The authors of this study would like to thank Malaysian palm oil producer Felda and their subsidiary Felda Plantations Sdn. Bhd. for providing background data, granting access to plantations and mediating contact to plantation smallholders.

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Appendix 4 – Fieldwork in Malaysia

A total of 20 months of the study was spent on data collection in Malaysia.

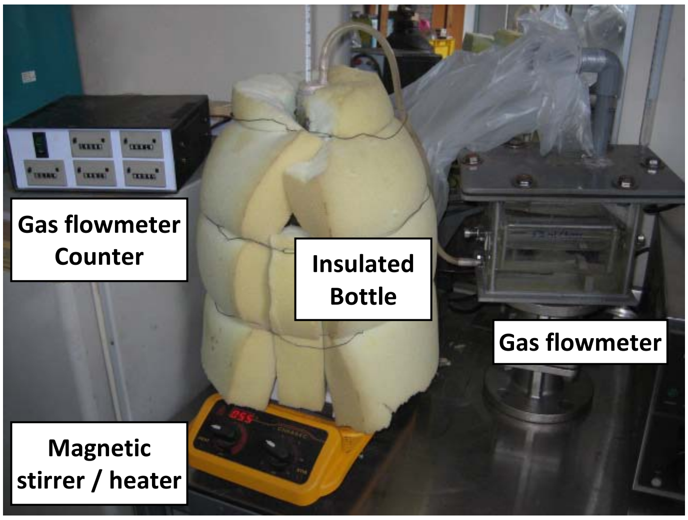
The local base was University of Technology Malaysia under supervision of Prof. Zaini Ujang, Faculty of Chemical Engineering.

Main activities in Malaysia were:

- Networking to establish collaboration partners, identify data holders and gain access to said data
    - A collaboration agreement was established with Government-linked palm oil producer Felda, who provided access to mills and plantations for data collection
    - Key contacts were established within a number of palm oil related research institutions
- Data collection from research institutions and the palm oil industry
    - Meetings and site visits at mills and plantations
    - Interviews with plantation smallholders
- Experimental data generation (see Experimental setups)
    - Biogas potentials from EFB
    - Soil carbon determination

Experimental setups – Biogas from EFB

The experiments were designed to provide indications of the biogas potential in fibrous solid palm oil residues. The shredded EFB from a palm oil mill were digested in a batch process, fully mixed, 52°C thermophilic digester for 21 days at a loading of 5% w/w. On day one of the experiments, 200 g shredded EFB were added to 4 L of thermophilic anaerobic bacteria solution ($MLSS_{bacteria} \approx 4{,}000$ mg/L) in an insulated 5 L glass bottle. The insulation was 5 cm thick sponge material. The anaerobic bacteria solution, which was retrieved from a Malaysian full scale batch process, fully mixed, thermophilic digester using POME as a feedstock, had been left to degrade all remaining organics for 5 days to ensure that gas produced during the experiments was from the EFB only. Using bacteria from a POME fed digester is considered the most representative solution, as the EFB will be co-digested with POME in a full scale scenario. The bottle (hereafter 'digester') was sealed to allow only for a gas tube and a thermometer and placed on a combined heater/magnetic stirrer. The temperature was maintained at a constant 52°C in the digester. Produced gas volumes were measured continuously using an unnamed flowmeter developed by Chiang Mai University for small gas volumes. The gas volumes were recorded daily to determine the degradation rate of the fibres (as depicted by the gas production) as a function of the hydraulic retention time, which is crucial for estimating the potential loading of fibres into a full scale biogas plant. The methane content of the biogas was analysed



twice weekly using a Dräger X-am 7000 methane meter. After the 21 days the digester was opened and the digestate was analysed for nutrient values in order to assess potentials in application as fertilizer. The digestate and the remaining fibres were separated and the liquid was analysed for total N , P and K using Standard Methods APHA[1] 4500-N_{org} B & 4500-NO_3^- H for total N, APHA 4500-P B&F for total P and APHA 3120 B for total P. The fibers were rinsed clear of bacteria sludge and analysed for Total N, P and K as well using APHA 4500-N_{org} B & 4500-NO_3^- H for total N, and Acid digest / IPC for Total P and K.

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Appendix 5 – Additional Papers

a. Feature article (The Environmentalist, UK): *Striking a balance in the palm oil debate* (Padfield and Hansen, 2010)
b. Conference paper (ICESE2011[2], Indonesia): *Exploring opportunities for sustainability in the Malaysian palm oil industry*, (Padfield et al., 2011)
c. Conference paper (PIPOC2011[2], Malaysia): *Oil palm plantations and biodiesel – Land use change impacts on the carbon balance*, (Hansen et al., 2011)

[2] See Appendix 6

Appendix 5a

Striking a balance in the palm oil debate

Rory Padfield, Sune Balle Hansen

The Environmentalist, 2011

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Striking a balance in the palm oil debate

*The environmental impact of palm oil is a subject that has stirred considerable interest and opinion in recent years. **Rory Padfield** and **Sune Hansen** attempt to provide some much-needed balance and perspective to recent debates*

The ever-increasing global thirst for vegetable oil can be regarded as one of the greatest environmental challenges of the 21st Century; interest has intensified with the prospect of biofuels. Palm oil has risen to become the dominant player on the vegetable oil market – and the main recipient of environmental scrutiny. But balance is rarely found in current debate where too often there is unscientific and excessive hyperbole. Malaysia, which is one of the biggest producers, has found that moving towards a less polarised version of the palm oil narrative to one based more on scientific evidence is more likely to lead to a sustainable outcome.

In 2008, world consumption of vegetable oils was estimated at 132 million tonnes, the largest contributor being palm oil (39 million tonnes) followed by soyabean oil (38 million tonnes). World production of palm oil derived biodiesel is expected to rise and Malaysia has aspirations to take advantage of this emerging market; production capacity of biodiesel could reach six million tonnes in Malaysia in the future. However, more recent scrutiny over palm oil production has brought a number of negative perceptions to the surface.

Run a quick straw poll with friends and colleagues on the topic of palm oil and you are likely to be inundated with predominantly negative comments: 'deforestation', 'environmental destruction', and 'biodiversity losses' are some of the expected responses. Although palm oil has been grown on a large scale for well over 50 years, it appears negative perceptions have gathered pace in recent years. Driven predominantly by a number of high-profile NGO campaigns and increased media coverage, palm oil seems to be perceived alongside the likes of GM crops and nuclear technology as one of the latest in a line of environmental scare stories.

So how well founded are the negative perceptions of palm oil? Let's start with the claims of deforestation and biodiversity losses. There is no doubt that both have occurred in Malaysia and that this is partially due to the growth of palm oil plantations. Latest reports suggest orangutan numbers have declined by 50 per cent since the mid 1980s, the number of remaining Sumatran rhinos in Malaysia and Indonesia are as low as 250 and during the period 2000 to 2007, Malaysia lost an average of 140,200 hectares – 0.65 per cent of its forest area – per year. But these impacts are also attributable to other development activities such as logging, urbanisation and other crops. But given the vast scale of palm oil plantations in Malaysia, estimated at 13.7 per cent of total land area, the palm oil industry must take some responsibility for the documented environmental destruction.

The related impacts on climate change, from the damage and loss of 'carbon sinks' and subsequent release of carbon dioxide from deforestation to the planting on peat lands, is a fact the palm oil industry cannot – or should not – deny. Encouragingly, the Malaysian Government has banned the conversion of primary forest and peatland into palm oil plantations and is, in collaboration with various NGOs, striving to provide wildlife corridors between patches of forest isolated by palm oil plantations.

Plus points

Examining why palm oil has grown so rapidly over such a short period of time points towards some of the lesser known benefits. Most importantly, palm oil yields by far exceed those of other vegetable oils making it the most efficient oil crop on the market. Figures from 2009 show that the average oil palm yield is 4.25 tonnes/hectare/year which compares extremely favourably against rapeseed (1.3), sunflower (0.46) and soyabean (0.4). Furthermore palm oil plantations often double as grazing areas for cattle.

A point often overlooked is the 'opportunity cost' of replacing palm oil; in other words, assuming the global demand for oil and fats remains the same, what would be the cost – environmental or other – of replacing palm oil with another oil crop? Meeting global demand for oils and fats by replacing palm oil with an alternative oil crop would lead to a much greater area of land than is currently required. Such expansions are likely to lead to deforestation elsewhere in the world.

Recent research suggests that palm oil is environmentally preferable to other oils assuming that new oil palm plantations are not replacing primary forest or peat land. The conclusions can, however, go both ways depending on assumptions and data sources. A call must therefore be made for scientifically and internationally recognised databases for environmental palm oil data.

The 'economic development versus resource use' dilemma also casts a different light on the debate. The Malaysian Government has made a commitment to maintain 50 per cent of its primary rainforests; this lies in stark contrast to many developed countries where significantly fewer natural woodlands remain. Moreover, the industry employs close to one million people making it the second largest employer after the government. Unsurprisingly, the Malaysian palm oil industry is less than happy with the apparent double standards held by many European views in this argument: why should emerging economies compromise their growth by not making use of their natural resources when developed countries did not? When urban and rural poverty is still an everyday reality for many, it is hard not to feel sympathy with the Malaysian position for continued economic growth and prosperity.

In terms of the documented deforestation and biodiversity losses, the Malaysian authorities and palm oil sector have shown a willingness to engage in the broader sustainability agenda. Alongside stand alone efforts such as the creation of the Malaysian Palm Oil Wildlife Fund, an initiative to pay for the protection of wildlife habitats and biodiversity, Malaysia is heavily involved in the Roundtable for Sustainable Palm Oil (RSPO). The RSPO is made up of a range of palm oil stakeholders, including NGOs such as WWF, with a goal to develop and implement global standards for sustainable palm oil. Malaysia has actively supported this process as demonstrated by the growing number of palm oil growers and processors achieving certification. Sadly, there is a general unwillingness amongst palm oil importers to pay the slight increase in cost that inevitably applies when production is being made sustainable and so unsustainable palm oil is still preferred by most European importers.

"Why should emerging economies compromise their growth by not making use of their natural resources when developed countries did not?"

Environmental improvements

Despite the initiatives taken, there are still measures the industry can take to improve the environmental profile of palm oil. Methane capture from the anaerobic digestion of palm oil mill effluent with subsequent energy recovery and state-of-the-art recycling of solid wastes is scarcely practised at the moment, although it is gaining momentum. Adopting methane capture and recycling with greater vigour is likely to lead to greater acceptance into the European biofuels market and, crucially, help achieve the increasingly stringent GHG performance indicators in the European Renewable Energy Directive.

Unless there is a dramatic turnaround in the global oil and fats market, rising demand for palm oil will continue into the future. Placing an embargo or an outright ban in Europe is unlikely to stem global production given that non-EU countries make up nearly 80 per cent of export destinations for Malaysian palm oil. And sourcing and producing an alternative to palm oil may have just as many undesirable environmental impacts.

A possible way forward is to help support the palm oil industry achieve high levels of sustainability through more sensible debate in the middle ground. Currently, there is a tendency for polarised discussions, moving from one extreme view to the other. This is not helpful in breeding trust and confidence between those with opposing and supporting views. With respect to certain associated environmental impacts, the palm oil sector has taken to a path of denial rather than engaging in scientific and academic dialogue. Greater transparency of palm oil impacts through academic studies might be a better approach.

Furthermore, instead of focusing solely on campaigning against palm oil, opposing NGOs could focus on ensuring the growth in sustainable palm oil whilst pressurising importers to choose certified sustainable palm oil. It is also important to remember that the Malaysian palm oil sector is carefully poised and needs to be wary not to drive planters to countries where there is far less scrutiny over operations.

Open and honest discussions between stakeholders may support this improved approach. Similar to the objectives of the RSPO, collaboration between stakeholders could help achieve common research agendas and methodologies, identify which areas of sustainability need to be addressed, and what can be done to achieve this. The hydropower sector is an example of where collaboration between stakeholders is having a positive outcome. A recent multi-stakeholder initiative has brought together hundreds of hydropower stakeholders with radically opposing views to contribute constructively towards the establishment of guidelines for sustainable hydropower. The time has come for a similar initiative in the palm oil sector, one that drives forward an agreed agenda for sustainable palm oil. ■

Rory Padfield is a visiting lecturer in the Razak School of Engineering & Advanced Technology at Universiti Teknologi, Malaysia (UTM)
rorypadfield@gmail.com
Sune Hansen is a PhD student at DTU Management at the Technical University of Denmark and Razak School of Engineering & Advanced Technology at Universiti Teknologi, Malaysia (UTM)
sbal@man.dtu.dk
A full list of references is available on request, editor@iema.net

Appendix 5b

Exploring opportunities for sustainability in the Malaysian palm oil industry

Rory Padfield, Sune Balle Hansen, Christopher Preece, Effie Papargyropoulou

Proceedings, 2011 International Conference on Environment Science and Engineering

2011 International Conference on Environment Science and Engineering
IPCBEE vol.8 (2011) © (2011) IACSIT Press, Singapore

Exploring Opportunities for Sustainability in the Malaysian Palm Oil Industry

Dr. Rory Padfield (1)
Department of Civil Engineering & Built Environment
RAZAK School of Engineering and Advanced Technology
Universiti Teknologi Malaysia (UTM)
Kuala Lumpur, Malaysia
rorypadfield@gmail.com

Sune Hansen (2)
Department of Civil Engineering & Built Environment
RAZAK School of Engineering and Advanced Technology
Universiti Teknologi Malaysia (UTM)
Kuala Lumpur, Malaysia
sbal@man.dtu.dk

Prof. Dr. Christopher Preece (3)
Department of Civil Engineering & Built Environment
RAZAK School of Engineering and Advanced Technology
Universiti Teknologi Malaysia (UTM)
Kuala Lumpur, Malaysia
dr.chris.preece@gmail.com

Effie Papargyropoulou (4)
Department of Civil Engineering & Built Environment
RAZAK School of Engineering and Advanced Technology
Universiti Teknologi Malaysia (UTM)
Kuala Lumpur, Malaysia
epapargyropoulou@yahoo.gr

***Abstract*—The global thirst for vegetable oil can be regarded as one of the greatest environmental challenges of the 21st Century and interest has intensified with the prospect of biofuels. Palm oil has risen to become the dominant player on the vegetable oil market – and the main recipient of environmental scrutiny. Focusing specifically on the Malaysian context, this paper analyses the major environmental, social and economic impacts associated with palm oil production. Drawing on recently published research, publicly available data and a comparison made with a recent sustainability initiative undertaken by the hydropower industry – an equally controversial and highly scrutinised sector – it is argued that the full extent of the impacts of palm oil should be acknowledged by those on both sides of the debate. Moreover, it is argued that by moving towards a less polarised version of the palm oil narrative and one based on scientific evidence is more likely to lead to greater opportunities for sustainable palm oil.**

Keywords-palm oil, sustainability, Malaysia, hydropower

I. INTRODUCTION

The environmental impact of palm oil is a subject that has stirred considerable interest and opinion in recent years. A number of high profile media and non-governmental organisation (NGO) campaigns have led to close scrutiny of the activities associated with palm oil production. In particular, reports of unscrupulous deforestation and the associated increase in greenhouse gas emissions, and a marked decline in rare wildlife species, such as the orangutan, have fuelled an anti-palm oil campaign in some parts of the world. In response, the palm oil industry in South East Asia has gone on the defensive to protect the future development of the industry.

Focusing specifically on palm oil production in Malaysia, this paper analyses a range of data sources in order to understand the extent of the environmental, social and economic impacts. It is hoped that by examining the impacts from these different perspectives it will lead to a balanced and fair analysis. Furthermore, the paper also draws on the experience of the hydropower industry; an industry under similar levels of scrutiny from environmental campaigners across the globe. It is argued that the approach taken by the hydropower sector may offer some lessons for the palm oil industry.

The paper is divided into four main sections; the first examines palm oil production in South East Asia; the second considers the negative environmental impacts; the third considers the positive social and economic aspects; and the forth considers options for a sustainable future followed by a brief conclusion.

II. PALM OIL PRODUCITON IN SOUTH EAST ASIA

In 2008, world consumption of vegetable oils was estimated at 136 million tonnes, the largest contributor being palm oil (43 million tonnes) followed by soyabean oil (37 million tonnes) [1]. In part due to the tropical climate and the suitable soil conditions, Malaysia and Indonesia are the worlds leading exporters of palm oil accounting for 86% of global palm oil production [1]. In 2008, the countries produced 17.7 million tonnes and 19.3 tonnes respectively, the combined production from other countries amounted to just 6 million tonnes [1]. Extrapolating the development in palm oil production from 2005-2009, the production can be expected to increase by 0.7 million tonnes per year [1] and significantly more with the prospects of biodiesel.

The global demand for biofuels is expected to drive increases in the consumption and production of palm oil. The production of palm oil derived biodiesel is expected to rise in the future with Malaysia and Indonesia aiming to take advantage of this emerging market; indeed, production capacity of biodiesel could reach 6 million tonnes per year in Malaysia in the future [2].

As the production of palm oil has grown exponentially in recent years, especially in South East Asia, there has been increasing scrutiny from a range of different stakeholders, both local to the region and international. The following section examines some of the negative environmental impacts of palm oil that have come to light following various studies and research.

III. Environmental Damage and Desturction

Although palm oil has been grown on a large scale for well over fifty years, it appears negative perceptions have gathered pace in recent years. Predominantly driven by a number of high profile NGO campaigns and increased media coverage, palm oil seems to be perceived alongside the likes of GM crops and nuclear technology as one of the latest in a line of environmental scare stories.

So how well founded are the negative perceptions of palm oil? Let's start with the claims of deforestation and biodiversity losses. There is no doubt that both have occurred in Malaysia partially due to the growth of palm oil plantations. Latest reports suggest orangutan numbers have declined by 50 per cent since the mid 1980's [3], the number of remaining Sumatran rhinos in Malaysia and Indonesia are as low as 250 [4] and during the period 2000 to 2007, Malaysia lost an average of 71,000 hectares of forest—0.36 percent of its forest area—per year [5]. These impacts are also partially attributable to other development activities such as logging and urbanisation. However, the FRA2010 forest resource country report for Malaysia prepared by various Malaysian governmental bodies states that urbanization only increased by 3 hectares per year from 2000 to 2007. Rubber and other crops declined by 32,000 and 23,000 ha/year respectively with oil palm plantations increasing by 123,000 ha/year [5]. Based on the report it can thus be concluded that the deforestation taking place in Malaysia is mainly due to oil palm expansion. However, the deforested areas are mainly secondary forest that has previously been logged for timber. From 2000 to 2007 a total of more than 800,000 hectares of primary and secondary forest was earmarked for national parks and wildlife sanctuaries [5].

The related impacts on climate change, by damage and loss of 'carbon sinks' such as forests and peat lands with subsequent release of CO_2 from deforestation is a fact the palm oil industry cannot – or should not – deny. Encouragingly, the Malaysian government has banned the conversion of primary forest and peatland into palm oil plantations and is in collaboration with various NGOs striving to provide wildlife corridors between patches of forest isolated by palm oil plantations.

Another significant source of greenhouse gas emissions related to palm oil production is from the anaerobic digestion of palm oil mill effluent in lagoons. Approximately 40 kg methane is released for every ton of palm oil produced [6] amounting to more than 700,000 tons methane per year from Malaysian palm oil mills. This corresponds to 16 million tons carbon dioxide (CO_2) equivalents with methane having a greenhouse gas potential 23 times higher than CO_2. Some biogas capture is currently taking place, but more action is needed. This will be discussed further in the following section.

IV. The Benefits of Palm Oil

Examining why palm oil has grown so rapidly over such a short period of time points towards some of the lesser known benefits. Most importantly, palm oil yields by far exceed those of other vegetable oils making it the most efficient oil crop on the market. Figures from 2009 show that the average oil palm yield is 3.9 (+ 1.0 ton palm kernel oil) [1] tonnes/hectare/year which compares extremely favourably against rapeseed (1.3), sunflower (0.46) and soyabean (0.4) [7]. Furthermore palm oil plantations often double as grazing areas for cattle.

A point often overlooked is the 'opportunity cost' or 'indirect land use' impacts of replacing palm oil; in other words, assuming the global demand for oil and fats remains the same, what would be the cost – environmental or other – of replacing palm oil with another oil crop? Meeting global demand for oils and fats by replacing palm oil with an alternative oil crop would lead to a much greater area of land than is currently required. Such expansions are likely to lead to deforestation elsewhere in the world.

Recent research suggests that palm oil is environmentally preferable to other oils assuming that new oil palm plantations are not replacing primary forest or peat land [8]. The conclusions can, however, go both ways depending on assumptions and data sources. A call must therefore be made for scientifically and internationally recognised databases for environmental palm oil data.

The 'economic development versus resource use' dilemma also casts a different light on the debate. The Malaysian government has made a commitment to maintain 50 per cent of its primary rainforests [9]; this lies in stark contrast to many developed countries where significantly less natural woodlands remain [10]. Moreover, the industry employs close to one million people making it the second largest employer after the government [1]. Unsurprisingly, the Malaysian palm oil industry is less than happy with the apparent double standards held by many European views in this argument: why should emerging economies compromise their growth by not making use of their natural resources when developed countries did not? When urban and rural poverty is still an everyday reality for many [11], it is hard not to feel sympathy with the Malaysian position for continued economic growth and prosperity.

In the terms of the documented deforestation and biodiversity losses, the Malaysian authorities and palm oil sector have shown a willingness to engage in the broader sustainability agenda. Alongside stand alone efforts such as the creation of the Malaysian Palm Oil Wildlife Fund, an initiative to pay for the protection of wildlife habitats and biodiversity, Malaysia is heavily involved in the Roundtable for Sustainable Palm Oil (RSPO). The RSPO is made up of a range of palm oil stakeholders, including NGOs such as WWF, with a goal to develop and implement global standards for sustainable palm oil. Malaysia has actively supported this process as demonstrated by the growing number of palm oil growers and processors achieving certification. Currently, there are eight certified sustainable palm oil growers in Malaysia which includes forty-one palm oil mills [12].

Unfortunately, there is a general unwillingness amongst palm oil importers to pay the slight increase in cost that inevitably applies when production is being made sustainable and so unsustainable palm oil is still preferred by most European importers. This is currently a major barrier to the adoption of sustainable palm oil practices in the industry and until there is evidence of greater interest in sustainable sources from buyers outside of Asia, especially EU and North America, certification rates are likely to remain low.

Despite the initiatives taken, there are still measures the industry can take to improve the environmental profile of palm oil. Methane capture from the anaerobic digestion of palm oil mill effluent with subsequent energy recovery and state-of-the-art recycling of solid wastes is presently scarcely practiced although it is gaining momentum. Adopting methane capture and recycling with greater vigour will significantly improve the global warming impacts from the palm oil production and is likely to lead to greater acceptance into the European biofuels market and crucially, help achieve the increasingly stringent GHG performance indicators in the European Renewable Energy Directive.

Unless there is an unprecedented turnaround in the global oil and fats market, rising demand for palm oil will continue into the future. Placing an embargo or an outright ban in Europe is unlikely to stem global production given that non-EU countries make up nearly 80 per cent of export destinations for Malaysian palm oil [1]. And sourcing and producing an alternative to palm oil may have just as many undesirable environmental impacts.

V. Moving Towards A More Sustainable Future

One way forward is to help support the palm oil industry achieve high levels of sustainability through more sensible debate in the middle ground. Currently, there is a tendency for polarised discussions, moving from one extreme view to the other. This is not helpful in breeding trust and confidence between those with opposing and supporting views. With respect to certain associated environmental impacts, the palm oil sector has taken to a path of denial rather than engaging in scientific and academic dialogue. Greater transparency of palm oil impacts through academic studies is likely to win the industry more goodwill and long term market benefits.

On the other hand, instead of focusing solely on campaigning against palm oil, opposing NGOs could focus on the implementation of internationally recognized sustainability criteria and ensuring the growth in sustainable palm oil following these criteria whilst pressurising importers to choose the certified sustainable palm oil. It is also important to remember that the Malaysian palm oil sector is carefully poised and needs to be wary not to drive planters to countries where there is far less scrutiny over operations. Open and honest discussions between stakeholders may support this improved approach.

Similar to the objectives of the RSPO, collaboration between stakeholders could help achieve common research agendas and methodologies, identify which areas of sustainability need to be addressed, and what can be done to achieve this.

The hydropower sector is an example where collaboration between stakeholders is having a positive outcome. A recent multi-stakeholder initiative, called the Hydropower Sustainability Assessment Forum (HSAF), has brought together hundreds of hydropower stakeholders with radically opposing views to contribute constructively towards the establishment of guidelines for sustainable hydropower [13]. These range from government agencies, private sector interests such as hydropower firms and investment banks, to non-governmental agencies and civil society stakeholders. Following a similar process to the World Commission on Dams in 2000, the proposed guidelines cover a host of environmental, social and economic issues that hydropower developers can examine before undertaking a new development. The guidelines will help to minimise the development of unsustainable hydropower and improve the sustainability of existing plants.

Whilst the guidelines have still to be fully agreed by all stakeholders, the initiative has led to open and frank discussions between various stakeholders and a platform for improved sustainability of the sector as a whole. The development of hydropower is unquestionably as controversial a topic as palm oil, especially when considering the environmental impacts, and yet this initiative is opening up opportunities for a more sustainable industry.

The time has come for a similar initiative in the palm oil sector, one that drives forward an agreed agenda for sustainable palm oil. This could be achieved by convening stakeholder workshops to discuss and agree a guideline for sustainable palm oil. Potential stakeholders include the palm oil industry, academia, the Roundtable for Sustainable Palm Oil, governmental agencies, international bodies such as the World Trade Organisation, NGOs as well as local community group and representation from consumer groups. Whilst disagreement between stakeholders is expected, opening up the discussions to all parties and ensuring a common ground for the debate through scientific and transparent data would allow an opportunity for methodologies and a process to be defined which ultimately, would lead to a more sustainable future for the palm oil industry in Malaysia.

VI. Conclusion

This paper has undertaken a critical analysis of the some of the major environmental, social and economic impacts of palm oil production in Malaysia. The analysis finds a range of impacts, both positive and negative, many of which are frequently overlooked by critical commentators and even the palm oil industry itself. Overall, it is argued that all impacts and benefits should be recognised and acknowledged by both sides of the palm oil debate and discussed openly and transparently. As shown by the hydropower sector, moving towards a less polarised version of the palm oil narrative and one more based on scientific evidence is more likely to lead to a sustainable outcome.

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Appendix 5c

Oil palm plantations and biodiesel – Land use change impacts on the carbon balance

Sune Balle Hansen, Stig Irving Olsen, Zaini Ujang

Proceedings, 2011 Malaysian Palm Oil Board International Palm Oil Congress

OIL PALM PLANTATIONS AND BIODIESEL – LAND USE CHANGE IMPACTS ON THE CARBON BALANCE

Sune Balle Hansen[* a,b], Stig Irving Olsen[a], Zaini Ujang[c]

[a] *DTU Management Engineering, Technical University of Denmark, Produktionstorvet building 424, 2800 Kgs. Lyngby, Denmark*
[b] *UTM Razak school of Engineering and Advanced Technologies, University of Technology Malaysia, KL International Campus, Jalan Semarak, 50300 Kuala Lumpur, Selangor, Malaysia*
[c] *Office of the Vice-Chancellor, University of Technology Malaysia, 81310 Skudai, Johor, Malaysia*

ABSTRACT

The topic of land use change impacts from palm oil production is heavily debated and often twisted by stakeholders. Thus academic objectivity is needed. This study provides a critical review on quantification of the GHG emissions conversion of secondary forest to oil palm plantation in Malaysia per ha in relation to biodiesel production. The results show a net emission of 560 kg CO_2/ha of land converted, which results in a land use change emission of 3.4 ton CO_2/ton biodiesel from first generation plantations on secondary forest. One national average ton of palm oil derived biodiesel has a land use change emission of 0.9 ton CO_2 resulting in total emissions of 1.7 or 2.1 ton CO_2/ton including the production stage depending on whether methane is captured from the POME digestion.

INTRODUCTION

Palm oil is the largest player on the global vegetable oil market and the production of palm oil is projected to increase in response to demands for the versatile oil and palm oil derived biodiesel. The expansions of oil palm plantations to accommodate the ever rising demands for palm oil have given rise to vicious campaigns from NGOs against palm oil claiming large scale impacts on biodiversity and natural carbon sinks. A review of the existing literature has shown that the accusations from NGOs as well as the counter-strikes from the palm oil industry are not purely based on scientific foundations but rather on biased assumptions. This study aims to provide an independent, academic exercise based on critical literature assessments as well as site specific field sampling of soil carbon. The assessment focuses on land use change on mineral soils.

First it is assessed whether land conversion to oil palm plantations is a current issue of significant magnitude: Malaysia is losing an average of 71,000 hectares of secondary forest – 0.36 percent of its forest area – per year (FAO, 2010). The FRA2010 forest resource country report for Malaysia (FAO, 2010), prepared by various Malaysian governmental bodies and reviewed by FAO and thus considered a reliable source, states that urbanization only increased by 3 hectares per year from 2000 to 2007. Rubber plantations and other crop areas are declining by 32,000 and 23,000 ha/year respectively with oil palm plantations increasing by 123,000 ha/year (FAO, 2010). Based on the report it can thus be concluded that the deforestation of secondary forest taking place in Malaysia is mainly due to oil palm expansion and that it is happening on a significant scale.

MATERIALS AND METHODS

Data collection is conducted through literature studies and experimental soil carbon sampling and analysis. The existing literature is thoroughly debated and assumptions are critically assessed to ensure that the present study remains focused on academically sound data. The study takes into consideration above and below ground biomass carbon and soil carbon in secondary forest and oil palm plantations. The focus is on direct land use change, however, indirect land use change is discussed qualitatively. It takes just over one ton CPO to produce 1 ton biodiesel. In the calculations the ratio is set at 1:1.

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[*] Corresponding Author. Tel: +60 12 219 9441 (Malaysia), +45 4525 4660 (Denmark)
E-mail address: sbal@man.dtu.dk (primary), suneballe@yahoo.dk (secondary)

The land use change impacts for greenhouse gasses are presented from a life cycle perspective following guidelines presented in ILCD (2010). It should, however, be noted that a final international consensus has not been reach on a framework for land use change in life cycle assessment (Finnweden et al., 2009).

The experimental data of the present study, which will be presented on the PIPOC2011 poster, focuses on the carbon balance in conjunction with the two most common land use changes occurring in Malaysia: Rubber plantation to oil palm plantation and logged forest to oil palm plantation. The sampling and analysis are restricted to plantations on mineral soil. Under each former land use scenario, a representative site for the former land use and plantations of various ages after conversion from the former land use (immature, 1-3 years; young, 3-7 years; prime, 7-13 years; mature, 13-25 years; and after replanting (second cycle)) are sampled and analysed for total carbon to determine the carbon content over time. This method is known as chrono-sequence. All sampling sites share similar characteristics such as soil classification, geographical area and topography. Ideally only the age of the plantation varies. Through random stratified sampling a total of 12 sampling points are randomly chosen per site – 3 from the palm circle, 2 from the harvesting path, 3 from inter-row and 4 from beneath the frond piles, which have the highest degree of heterogeneity. Three cores are taken per sampling point and each core is taken at depths of 0-15 cm, 15-30 cm and 30-100 cm as per IPCC guidelines (IPCC, 2006). Bulk density samples are taken and the soil temperature, moisture and pH are determined before final analysis of total organic carbon.

RESULTS AND DISCUSSIONS

Arguably the most thorough review of carbon stock studies in tropical forests and palm oil plantations was the study carried out by Germer and Sauerborn (2008), which includes several regional and industry specific references. Germer and Sauerborn (2008) report that primary tropical forest contains an average of 342 ton biomass per ha. Thus, average CO_2 emissions from biomass clearing of primary tropical forest reach 627 ton/ha (assuming land clearing without burning) at 50% carbon content in the biomass and 3.67 ton CO_2/ton carbon (Germer and Sauerborn, 2008).

In Malaysia, only logged over forest (secondary forest) is permitted for conversion to palm oil plantations, so it is argued that the full carbon loss from primary forest cannot be allocated to palm oil. Lasco (2002) reports an average decline in forest biomass of approximately 40% from logging in Indonesia, so it could be argued that the GHG emissions from biomass allocated to palm oil should be 205 ton biomass per ha equivalent to 376 ton CO_2-eq/ha. However, Silver et al. (2000) shows that tropical wet secondary forest can grow to 300 ton biomass or more per ha within approximately 30 years if left idle. So even if the forest is logged, the 'lost' biomass by clearing the land is 300 ton/ha equalling 550 ton CO_2/ha.

Another argument is that most of the logged timber is used in construction and other carpentry and the carbon is thus fixed in the material for decades and will not contribute to the acute GHG impacts. As this study has not dealt with the quantities of logged timber, which can be considered in such context, nor with the time frame, in which the carbon is fixed, no conclusion is made whether such contribution is significant and no quantifications are attempted.

Germer and Sauerborn (2008) state that 1/3 of the 120 ton soil carbon (0-100 cm) in a primary forest will be degraded upon conversion to oil palm plantation before a new equilibrium is reached. This amounts to 145 ton CO_2/ha. Mathews et al. (2010) showed that the soil carbon increases by as much as 50% from the first to the third generation of oil palms in Malaysian estates. However, Mathews et al. measured only the top 45 cm. Thus, the soil carbon values from Germer and Sauerborn (2008) will be used in the carbon balance of the present study.

Oil palm plantations sequester carbon while growing. Germer and Sauerborn (2008) report 83 ton biomass per ha, which is slightly lower than the 95 ton per ha reported by Khalid et al. (2009) for Malaysian plantations. This study applies an average value of 89 ton/ha, resulting in 37 ton carbon per ha at the end of a 25 year growth cycle at 42% C in palms (Chow at al., 2008). If the carbon in the felled oil palms is fixed through use in carpentry, which provides short term carbon fixation and substitutes virgin wood, or it is converted to bio-char (long term carbon fixation) then it can be argued that the carbon sequestration of the subsequent generation of palms should be accounted for as well.

However, the authors of this study argue that such carbon sequestration should instead be accounted for under the assessment of waste products in the palm oil life cycle. Thus, 37 ton carbon sequestration per ha in the oil plantations is used in the carbon balance.

The carbon balance for land conversion from secondary forest thus amounts to losses of 300 ton biomass equalling 150 ton carbon from biomass and 40 ton soil carbon totalling 190 ton carbon per ha. 37 tons are sequestered in oil palms leaving a net emission from land use change of 153 ton carbon or 560 ton CO_2/ha. It must be mentioned that these values have uncertainties around 50% (Germer and Sauerborn, 2008).

So what are the impacts related to the production of palm oil from a plantation planted on former secondary forest? According to MPOB (2010), 0.26 ha are required to produce 1 ton palm oil per year. Thus, if a plantation is in operation for one generation of oil palms (25 years), 0.01 ha is needed to produce 1 ton palm oil, for two generations, 0.005 ha are needed for three generations, 0.0033 and for four generations, 0.0026 ha are needed. This corresponds to 5.6, 2.8, 1.8 and 1.4 ton CO_2/ton palm oil produced for plantations in operation for 1, 2, 3 and 4 generations respectively. In comparison, Choo et al., 2011, present GHG emission from the production of biodiesel from palm oil (excluding land use change) of 0.8 ton CO_2/ton biodiesel with methane capture and 1.2 ton CO_2/ton without methane capture provided that 39% (by weight) of the processed FBB is allocated to palm kernels (for palm kernel oil and palm kernel cake) and shells (for fuel in external industrial boilers). Whether this allocation is appropriate is not discussed in this study. Using the same allocation for the land use, 3.4, 1.7, 1.1 and 0.9 ton CO_2 are emitted from land use change alone per ton palm oil/biodiesel produced for 1, 2, 3 and 4 generations respectively.

However, three questions arise in relation to estimation of the average land use change impacts for palm oil derived biodiesel: Which emission quantity should be used in an environmental assessment? Do we consider the land use change impacts of plantations established several years ago? And how much of the Malaysian oil palm land is planted on former forest?

In the life cycle assessment methodology presented in ILCD (2010), the land use change emissions must be allocated to the first plantation cycle since longer projections are too uncertain. Thus, for a new plantation converted from secondary forest, the full 3.4 ton CO_2/ton palm oil must be included in an environmental assessment. For a plantation of second generation or older, no land use change impacts are incurred. Thus, the land use impacts of all the plantations established on forest in the past 25 years should be included in the assessment.

This study has derived from FAO (2010) that 1.3 million ha of the 4.9 million ha of oil palm plantations in Malaysia in 2010 were established on former secondary forest since 1986 (25 years) amounting to 26% of the total oil palm plantation area. Assuming that establishing all other oil palm plantations in the 25 year period was carbon neutral, 26% of the 3.4 ton CO_2 from land use change per ton palm oil, must be added to the production emissions to get the full carbon emissions. The results are presented in Table 1. In comparison, the processing and combustion of fossil diesel release 84 g CO_2/MJ.

TABLE 1 – CO_2-eq EMISSIONS FROM MALAYSIAN BIODIESEL PRODUCTION

	Land use change emissions		Production [ton/ton Biodiesel]	Total [ton/ton Biodiesel]	Total [g/MJ biodiesel]
	CPO from FSF* [ton/ton CPO]	Avg. CPO [ton/ton CPO]			
With CH_4 capture	3.4	0.9	0.8	1.7	46
Without CH_4 capture			1.2	2.1	57

*) Former Secondary Forest

The results in Table 1 depict the current emissions. The authors of this study have conducted a still unpublished study indicating that reductions in the CO_2 emissions can almost cancel out the production emissions (not incl. land use change) through improved recycling schemes.

Indirect land use change occurs when e.g. oil palm plantations are replacing an agricultural crop or another plantation. Unless there is less demand in the market for these products, they will need to be produced elsewhere. The direct land use change from yearly agricultural crop to oil palm plantation will increase the carbon stock through sequestration in the palms and increase in soil carbon.

However, if the replaced crop (or a similar crop) needs to be produced elsewhere to meet the market demand, then there is a chance that it could lead to increased carbon emissions. Thus, this assessment has chosen to maintain the conversion from yearly crop to oil palm plantation as carbon neutral. Likewise, replacing a rubber plantation with oil palms may lead to significant GHG emissions if the rubber needs to be manufactured synthetically instead (Reinhardt et al., 2007).

Some amendments to the soil carbon emissions may be made following the soil carbon sampling and analysis, but the conclusions are not expected to be affected.

CONCLUSION

Based on critical literature reviews an assessment was made on the carbon balance of land conversion from secondary tropical forest to oil palm plantation in Malaysia and the results were compared to the emissions from production of palm oil derived biodiesel. The results show a net emission of 560 kg CO_2/ha of land converted, which results in a land use change emission of 3.4 ton CO_2/ton biodiesel from first generation plantations on former secondary forest. With 26% of the current oil palm area in Malaysia being first generation plantations planted on secondary forest, a national average ton of palm oil derived biodiesel has a land use change emission of 0.9 ton CO_2 on top of the 0.8 or 1.2 ton CO_2/ton for the production stage depending on whether methane is captured from the POME digestion.

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Appendix 6 – Conferences & Presentations

Conferences

IPLC2009 – International Palm Oil Life Cycle Assessment Conference, Kuala Lumpur, Malaysia, October 2009, arranged by MPOC (Malaysian Palm Oil Council)

- Main purpose: Networking and determination of state-of-the-art palm oil research

IPOSC2010 – International Palm Oil Sustainability Conference, Kota Kinabalu, Malaysia, May 2010, arranged by MPOC (Malaysian Palm Oil Council)

- Main purpose: Networking and determination of state-of-the-art palm oil research

ISFFP2010 – International Symposium on Forestry and Forest Products, Kuala Lumpur, Malaysia, October 2010, arranged by FRIM (Forest Research Institute of Malaysia)

- Main purpose: Networking and determination of state-of-the-art Malaysian forest and oil palm plantation research

ICESE2011 – International Conference on Environment Science and Engineering, Bali, Indonesia, April 2011, arranged by APCBEES (Asia-Pacific Chemical, Biological & Environmental Engineering Society)

- Oral presentation of conference paper: 'Exploring opportunities for sustainability in the Malaysian palm oil industry' (Padfield et al., 2011)

PIPOC2011 – Malaysian Palm Oil Board International Palm Oil Congress, Kuala Lumpur, Malaysia, November 2011, arranged by MPOB (Malaysian Palm Oil Board)

- Poster presentation of conference paper: 'Oil palm plantations and biodiesel – Land use change impacts on the carbon balance' (Hansen et al., 2011)

Other project presentations (guest lectures)

DTU course: *Global product chains and sustainable development*, March 2010
DTU/UTM[3] course: *Sustainable production: Practicing life cycle assessment*, June 2010
DTU/UTM course: *Sustainable production and consumption*, June 2011
UTM course: course title unknown, November 2011
NU(M)[4] course: *Topics in environmental management science seminars*, December 2011
DTU course: *Advanced life cycle assessment and evaluation of environmental impacts*, June 2012
DTU course: *Sustainable production and consumption*, August 2012
DTU course: *Sustainable Production and consumption*, September 2012

Peer reviewer

- International Journal of Life Cycle Assessment — 4 papers
- Waste Management and Research — 1 paper
- Integrated Environmental Assessment and Management — 1 paper
- Energy & Fuels — 1 paper

[3] University of Technology Malaysia
[4] Nottingham University (Malaysia)