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Energy balances and greenhouse gas emissions of palm oil biodiesel in Indonesia

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Abstract

This study presents a cradle-to-gate assessment of the energy balances and greenhouse gas (GHG) emissions of Indonesian palm oil biodiesel production, including the stages of land-use change (LUC), agricultural phase, transportation, milling, biodiesel processing, and comparing the results from different farming systems, including company plantations and smallholder plantations (either out growers or independent growers) in different locations in Kalimantan and Sumatra of Indonesia. The findings demonstrate that there are considerable differences between the farming systems and the locations in net energy yields (43.6–49.2 GJ t^{-1} biodiesel yr^{-1}) as well as GHG emissions (1969.6–5626.4 kg CO_{2eq} t^{-1} biodiesel yr^{-1}). The output to input ratios are positive in all cases. The largest GHG emissions result from LUC effects, followed by the transesterification, fertilizer production, agricultural production processes, milling, and transportation. Ecosystem carbon payback times range from 11 to 42 years.

Keywords: ecosystem carbon payback time, energy balances, farming systems, greenhouse gas emissions, land-use change, net energy yield, palm oil biodiesel

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Introduction

Background

Owing to increasing energy prices and depleting natural deposits of fossil fuel precursors, many countries have been looking for alternative energy sources. The use of biodiesel, which is often produced by the transesterification of vegetable oils with methanol or ethanol, is considered a feasible alternative, presenting additional advantages such as possible reductions of carbon dioxide emissions, carbon monoxide, hydrocarbon, and sulfur oxide emissions compared with conventional fossil fuels (Crabbe *et al*., 2001; Kallivroussis *et al*., 2002; Ansori *et al*., 2005; Mootabadi *et al*., 2008). A primary raw material for producing biodiesel is the oil obtained from the fruits of the oil palm tree (*Elaeis guineensis*). Palm oil production is an important source of income and a major contributor to economic growth for many countries in South-East Asia, Central and West Africa, and Central America (Kalam & Masjuki, 2002). Palm oil is widely used as cooking oil, as an ingredient for margarine and many processed foods, as well as a feedstock component for biodiesel production (Supranto, 2003; IOPRI, 2006).

Most countries in the Asian region are net importers of petroleum fuels. Increasing energy demand and spiraling oil prices are putting financial strain on some countries and are also causing environmental degradation (Srivastava, 2000). Energy security has gained greater significance than ever; food production, improved living conditions, and environmental quality are interrelated (Brown & Jacobson, 2005). In this context, the use of biodiesel as an indigenous and renewable energy source can play a vital role in reducing dependence on petroleum imports and can also catalyze the rural economic development (Yi-Hsu *et al*., 2003).

In Indonesia, oil palm production plays a significant role in the country's economy and society. Today, an estimated 1.5 million small farmers grow oil palms in Indonesia and many more are connected with spin-offs (Ansori *et al*., 2005). Oil palm production in Indonesia is practiced in diverse farming systems and within different socioeconomical contexts. Thus, Indonesia is a

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particularly interesting case for studying biodiesel production from palm oil.

Regional differences between palm oil production in Kalimantan and Sumatra

Oil palm trees (*E. guineensis*) were brought by the Dutch to Bogor (West Java, Indonesia) as ornamental plants and then spread throughout Sumatra in the early 20th century (IOPRI, 2006). In the 1960s, major oil palm plantations were established in Sumatra by the government of Indonesia within the frame of transmigration programs. Thirty years later, that is, from 1987 onward, oil palm plantations were introduced in Kalimantan, imitating the plantation schemes implemented in the transmigration programs in Sumatra (Bangun, 2006). Despite the similar organization of oil palm production in Sumatra and Kalimantan, regional disparities persist due to different ecological environments, (e.g., mineral land and peat land composition in palm oil plantation areas), socioeconomic settings (e.g., know-how of palm oil processing), infrastructure (e.g., better sustained roads and bridges in Sumatra), and timeframes (e.g., due to longer operating experience – Sumatra's palm oil industry was developed 30 years earlier than in Kalimantan).

Business structure of Indonesian oil palm plantations

At present, 51% of the oil palm plantations in Indonesia are owned by large private companies, whereas 37% belong to smallholders and 12% to state-owned companies (Hasibuan, 2006). Recently, the area of smallholder plantations in Indonesia has been rising rapidly, from 0.6 M ha in 1990 to 2.2 M ha in 2005 (IOPRI, 2006). The smallholder plantations can be categorized into two types. These are dependent smallholder (or out grower) plantations and independent smallholder plantations. Dependent smallholders usually own a small piece of land within a large plantation that is managed by a company. They cultivate their own palm trees, but they depend on the company for many aspects, such as fertilizer and pesticides supplies, as well as selling their palm fruits to the mill. It is not viable for single smallholder plantations to build their own mills, so they deliver their fruits to the company's mill for further processing (Brown & Jacobson, 2005; IOPRI, 2006). Dependent smallholders are generally forced to apply the same technologies and practices as those used by large-scale plantations. Therefore, dependent smallholders are normally not free to take their own decisions regarding the cultivation of their plots. Consequently, input application such as fertilizer, herbicides, and pesticides will most likely be as intensive as in the company's plantation. In contrast, independent smallholders are free to manage their plantations according to their own beliefs. However, their lack of know-how and management skills is very often a severe drawback. In addition, independent smallholders are hampered by a lack of capital for purchasing inputs and buying good quality seedlings. Consequently, the yields of independent smallholders tend to be lower compared with those of estates or dependent smallholders, 12 t ha^{-1} yr^{-1} fresh fruit bunches (FFB) and 19 t ha^{-1} yr^{-1} FFB, respectively (IOPRI, 2006). In general, smallholders face difficulties in acquiring land because they have little collateral to warrant conversion of land for agricultural uses.

Life cycle assessment of palm oil production

Life cycle assessment (LCA; ISO 14044:2006) is an internationally known methodology for the evaluation of the environmental performance of a product, process, or pathway along its partial or whole life cycle, considering the impacts generated from 'cradle to grave'. Biofuel life cycles are often assessed from 'cradle to gate'. Several authors (Jusoff & Hansen, 2007; Yee *et al*., 2009; Schmidt, 2010) have noted that the LCA of palm oil industries often led to diverging results due to different approaches and methodologies, especially in the case of biofuels. An assessment focusing on the mere energy balance of biodiesel production from palm oil in Thailand was carried out to provide reliable information for promotion decisions (Pleanjai & Gheewal, 2009). The energy balance of palm oil biodiesel produced in Colombia and Brazil was determined on the basis of different scenarios (Angarita *et al*., 2009). From these studies, it is not possible to verify the greenhouse gas (GHG) emissions or the reduction in fertilizer application due to the use of by-products (e.g., empty fruit bunches EFB), as no information is given on the input assumed in the calculations regarding the agricultural phase. An LCA on the energy balances and GHG emissions of biodiesel from palm oil in Brazil considers the use of coproducts for power production, production of organic fertilizers and allocation procedures (De Souza *et al*., 2010). In their study, they found that fuel consumption is responsible for 18% of the GHG emission in palm biodiesel LCA. The cradle-to-grave methodology was also used to compare two biodiesel systems involving gross and net energy production per hectare per year and the GHG emission reduction (Thamsiriroj & Murphy, 2009). Their results show that the net emissions released from palm oil systems are lower than from the rape system (39.2 kg CO_2 GJ^{-1} compared with 62.2 kg CO_2 GJ^{-1}). Comparing LCAs of different energy crops and regions, it is concluded that energy crops should be cultivated on marginal land to meet the increasing demand for agricultural goods and contribute to environmental improvement (Schmidt, 2010). The LCA including the energy balance and GHG emissions of biodiesel from palm oil in Malaysia was carried out to evaluate the potential benefits of palm biodiesel (Pananapaan *et al*., 2009). Yee *et al*. (2009) found that the utilization of palm biodiesel would generate an energy yield ratio of 3.53 (output energy/input energy), indicating a net positive energy generated and ensuring its sustainability.

Two major issues need to be addressed when assessing the efficacy of biofuels, namely the net reduction in fossil carbon emissions and the effect of alternative land-use strategies on carbon stores in the biosphere (Righelato & Spracklen, 2007). To mitigate global climate change, biofuels need to be produced with little reduction of organic carbon stocks in the soils and vegetation of natural and managed ecosystems (Fargione *et al*., 2008). Degraded and abandoned agricultural lands could be used to grow native perennials for biofuel production. This would spare the destruction of native ecosystems and reduce GHG emissions from land-use change (LUC), the latter being significant (Edwards *et al*., 2008). LUC can result in a decrease of the organic carbon stored in the soil. Although land conversion only happens once, its effect can be large and long-lasting. The soil reaches a new (lower) carbon content at a decaying-exponential rate, characterized by an approximately 20-year time-constant and an annual CO_2 emission of the order of 3.7 t ha^{-1} (Commission of the European Communities, 2009) with the uncertainty range being more than 50%. LUC is concluded to be the most decisive factor in overall GHG emissions (Wicke *et al*., 2008a). Palm oil energy chains based on land that was previously natural rainforest or peat land have such large emissions that they cannot meet GHG emission reduction targets of 50–70% as demanded by the Cramer Commission in the Netherlands (Cramer, 2006).

The studies presented do not consider different farming systems and regions. However, empirical evidence suggests that major differences exist between farming systems and regions in one country. The knowledge of these differences and the factors leading to different results can contribute to a more environmentally sound development of palm oil production from existing and new plantations in Indonesia and also elsewhere in the world.

Objective

The objective of this study is to estimate the energy and GHG emission balance of palm-oil-based biodiesel production in Indonesia, including the stages of LUC, plantation work, transportation, milling, and processing including all prechain processes and to assess how regional and structural differences affect these energy and GHG balances.

Methodology

System boundaries, period of analysis, and functional unit

In this investigation, LCA methodology is implemented to study the production of palm oil-based biodiesel in Indonesia under different production conditions in terms of energy efficiencies and GHG emissions. The balances were generated using an LCA software Umberto® (ifu/ifeu, 2005).

The balances present a cradle-to-gate assessment including LUC, prechain processes (e.g., production of fertilizers, diesel fuel, and machines), agricultural production processes, transportation, crude palm oil (CPO) extraction, and refining, as well as transesterification into biodiesel. Several coproducts of palm oil can be utilized as food or for oleo-chemical and energy purposes. Glycerol can be utilized as a cosmetic material. Kernel oil can be used as frying oil and oleo-chemical industries. Currently, these products are used for energy purposes. Figure 1 shows a system overview of stages considered for biodiesel production from palm oil covering the establishment of plantations, processing of FFB to CPO, and subsequent processing to palm oil biodiesel. The data analysis includes the material and energy input and output of each stage.

The period of analysis is 1 year. The emission impulses from LUC and establishment of the plantations were converted to annual emissions for a plantation standing time.

The material and energy inputs are measured as energy used per ton of biodiesel, that is, the functional unit is 1 t of biodiesel. Values are also given per hectare and year.

Data base

Primary information and detailed data were collected at several locations in the islands of Sumatra and Kalimantan in 2009 using personal interviews with representatives of the processing industries, plantation companies, and smallholders growing oil palm trees (Table 1). All relevant field data such as type and quantities of seedlings, fertilizers, herbicides, pesticides, water and machinery, yields of FFB and CPO, transport distances, and other information were collected by face-to-face interviews.

Description of the biodiesel production process

Agricultural production stage. The plantation or agricultural stage comprises land preparation, raising and planting of seedlings, application of fertilizers, herbicides and pesticides, harvesting, and transport.

Land preparation: Secondary forests are removed using excavators and bulldozers to establish new plantations in Kalimantan and Sumatra. In the peat land areas, palm oil companies use excavators capable of cutting the trees, digging out the roots, and removing the residual biomass. In this way, the soil is cleaned for planting the palm trees.

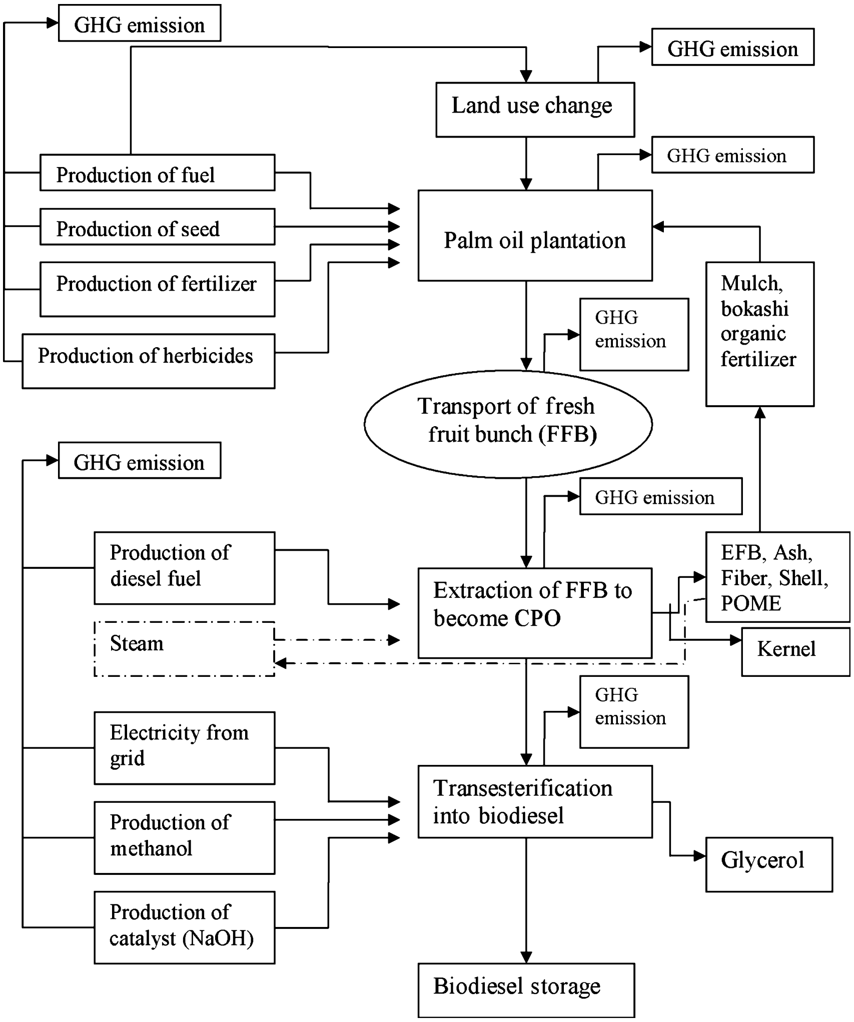

Fig. 1 System overview of stages considered for biodiesel production from palm oil (dashed boxes and line indicate internal processes).

Table 1 Plantations for data acquisition

No.	Plantation	Type of company	Province	Total size of plantation* (ha)
1	PT BW plantations Tbk	Company	Central Kalimantan	12 500
2	PT. MPE plantation	Company	West Kalimantan	11 500
3	PT. Asam Jawa	Company	North Sumatra	13 500
4	PT. Rohul Jaya	Company	Rokan Hilir in Riau	14 500
5	Grower farmer	Dependent	Central Kalimantan	10 000
6	Sanggau Cooperatives	Independent	West Kalimantan	12 000
7	Rohul Jaya Cooperatives	Dependent	Riau	7500
8	Grower	Independent	North Sumatra	6500

*Including unproductive and replanted areas.

Seedlings: The quality of the seedlings determines the success of the oil palm production. Many small farmers obtain cheap seeds of low quality and without yield warranty from other farmers in their neighborhood. The result is low productivity of the trees that cannot be increased even by intensive use of fertilizers. In contrast, big companies use certified seedlings from Indonesian Oil Palm Research Institute (IOPRI), private seedling companies in Indonesia, or certified imports from

Malaysia (Pahan, 2008), and other parts of the world as well. Young palm trees need to be irrigated by pumped water during the seedling establishment phase up to the age of 18 months, before they are moved to the plantation area.

Planting: When the land is ready for planting, the seedlings are moved to the new area. Trucks are used to cover distances of between five and seven kilometers from the seedling nurseries to the plantations. In most cases, the seedlings are planted manually.

Fertilizers: Several types of fertilizers are applied in oil palm plantations in Kalimantan and Sumatra. N, P, K, and Mg are applied in compound form twice a year. Fertilizers used in oil palm plantations in Kalimantan are produced on the island of Java and transported to Kalimantan by sea. From the port, they are taken by trucks to the plantation. Fertilizers used in plantations in Sumatra are produced on the island itself and transported by truck.

Agrochemicals: The use of agrochemicals in oil palm cultivation, in particular, for palm tree protection, is low. Herbicides are used in mature plantations to maintain harvesting circles around the palm trees and keep interrow access paths clean. Other ground weeds are controlled mechanically or by spot spraying. A typical program comprises the application of 0.56 kg ha^{-1} Paraquat, often with the addition of 2.8 L ha^{-1} diesel oil, three times a year. Rodenticides are widely used in some areas. An effective program for rat control applies a wax-bound bait mixed with maize and Warfarin. Insecticide use is generally kept to a minimum. Fungicides are virtually never used in mature plantations.

Harvesting: Most of the oil palm fruits in Indonesia are harvested manually.

Transportation: Owing to unstable or slippery road conditions during the rainy season, medium-size trucks are used to transport the FFB to shelter areas and to the oil mills. Especially in Kalimantan, vessels are also employed to cross-wide rivers. Most estates maintain two or three tractors for general work, as well as for application of chemicals or transportation of palm oil mill effluent (POME) as organic fertilizer. Other transport operations considered include transportation of fertilizer by sea, inland transportation of fertilizer, transportation of the seedlings to the nursery, transportation of the young palm trees to the plantation, transportation of the FFB to the mill, and transportation of the FFB to the mill by ferry.

Palm oil processing. Milling is an integral part of the process to convert FFB into separated CPO, palm kernel oil, and by-products or waste. Power is required at several stages for various purposes. It may be used to produce steam for sterilization and processing, to drive the extraction and separation equipment, and to provide processing water (1.2 t of water per ton FFB). Electricity is needed for ancillary farm and domestic purposes.

The palm oil mill processes 40 t FFB per hour, which is equivalent to a mill processing about 120 000–150 000 t FFB per year.

For oil extraction, there are two main sources of energy input: production waste for generating steam for mill machinery and kernel crushing and diesel fuel for engine start-up. For the calculations regarding the CPO production stage, we considered for input FFB, water, steam produced from production waste, diesel fuel for on-site electricity generation, and for output fiber, shells, decanter cake, EFB, ash, POME, emissions to air, CPO, and kernel oil.

In the investigated plantations in Sumatra, the POME is conveyed from the mill through ten consecutive ponds equipped with nets to filter out the solids and with impellers for aeration. The first two of them are covered to avoid methane emissions to the air. After this cleaning process, the water is released to the river that is entering the plantation and is later on used for palm tree irrigation purposes. This activity belongs to a Clean Development Mechanism (CDM) project of the milling company. In the Kalimantan mills, the ponds are still under construction for CDM projects that will be built comparably to the Sumatra mill. Thus, the emissions will also be similar between both regions and therefore methane emissions from POME were not included in the calculations.

Transesterification. For the transesterification of palm oil, the two components methanol and sodium hydroxide are required, as well as electricity for shaking the oil and the components to produce biodiesel. The reactor considered in our calculations for producing biodiesel from palm oil is a 20 000 L batch-type reactor operating at a maximum of three batches per day with a reactor time of 8 h per batch (Pleanjai *et al.*, 2004). The operating temperature is 50–60 °C. The biodiesel production rate is around 16 t per batch. Transesterification of the oil produces a mixture of methyl esters (biodiesel) and glycerol. The biodiesel is separated from the glycerol by gravity, then the remaining mixture is washed with water and acetic acid until the washing water is neutral. The methyl ester is then dried by heating. The biodiesel yield is around 87% of the CPO processed. The percentage of yield for biodiesel production can be calculated based on a stoichiometric material balance. Glycerol is a by-product that can be used to produce soap or other materials. For the transesterification stage, we included the inputs of CPO, water, grid electricity, methanol, and sodium hydroxide, and the outputs methyl ester, glycerol in our calculation.

Energy balance

Energy balance refers to the quantification and systematic representation of the physical transformation and a flow of energy sequestered in the consumption and production process of goods and involve both direct and indirect energy input (Angarita *et al.*, 2009; De Souza *et al.*, 2010). Analysis of the energy balance of biomass production should provide in-depth understanding of the environmental compatibility, and its preservation can be used for energy efficiency policy. The energy balance of a biodiesel production system can focus on the relation between the energy produced (energy output per ton biodiesel) and the energy consumed (energy input per ton biodiesel) for each unit of the production process, thus presenting an important index for the economic and environmental feasibility of biodiesel production (Hallmann, 2000; Angarita *et al.*, 2009; Pleanjai & Gheewal, 2009; Janaun & Ellis, 2010). In

Table 2 Yields and application in the plantations investigated

	Geographic region					
	Kalimantan			Sumatra		
		Smallholder			Smallholder	
Owner structure	Company plantation	Dependent	Independent	Company plantation	Dependent	Independent
Palm lifetime (year)	27	27	21	27	27	21
FFB producing lifetime (yr^{-1})	20	20	16	20	20	18
Share of Peat land (%)	37	10	0	33	0	0
Palm density (ha^{-1})						
On mineral land	138	138	138	142	138	138
On peat land	145	145	142	148	145	145
FFB production (t ha^{-1} yr^{-1})						
On mineral land	20.5	20	14	23.5	20	12
On peat land	22.5	21	14.5	22	21	12.5
Biodiesel yield (t ha^{-1} yr^{-1})	4.29	4.09	2.94	4.64	4.04	2.48
Fertilizer (kg ha^{-1} yr^{-1})						
N	53	53	39	18.5	113	37
P	114	114	91	55	114	94
K	110	110	90	39	110	77
Mg	92	98	86	36	92	90
Distance plantation to mill (km)	27	37	48	24	35	45

FFB, fresh fruit bunches.

our study, we consider the energy balance for the different production stages from land-use preparation, prechain processes, transportation, agricultural stages, milling, through to biodiesel production (Table 2).

Total energy input is the overall energy from all activities during preprocesses, transportations, agricultural phase (palm oil plantation), palm oil extraction, and biodiesel processing. Total energy output is the overall energy from products that are produced: biodiesel, glycerol, kernel shell, bokhasi, EFB for electricity, and electricity surplus. It is given as GJ t^{-1} biodiesel yr^{-1}. The net energy yield is the total energy output deducted by total energy input (given in GJ ha^{-1} yr^{-1} as well as in GJ t^{-1} biodiesel yr^{-1}). The output/input ratio is the quotient of total output energy divided by total input energy.

Greenhouse gas emissions

Our study determines the GHG emissions from CPO-based biodiesel production, based on a life cycle inventory, and accounts for all GHG emissions that arise between initial land conversions and final use of the palm-oil-based energy. Considered GHG es are carbon dioxide [$\mathrm{CO_2}$, global warming potential (GWP): 1], methane ($\mathrm{CH_4}$, GWP: 21), and nitrous oxide ($\mathrm{N_2O}$, GWP: 310), which are summed up to carbon dioxide equivalents ($\mathrm{CO_2}$-eq).

Land-use change. To account for GHG emissions resulting from converting forests into oil palm plantations, the following equation from guidelines (IPCC, 2006; Wicke *et al.*, 2008a) is applied:

$$\mathrm{LUC}_{\mathrm{emissions}} = 3.7 \times \left[\frac{\mathrm{LUCC}}{T_{\mathrm{LUC}}Y} - \frac{\mathrm{C}_{\mathrm{uptake}}}{(T_{\mathrm{plant}}Y)}\right], \tag{1}$$

where $\mathrm{LUC}_{\mathrm{emissions}}$ is the net emissions from LUC (kg $\mathrm{CO_2}$-eq. MJ^{-1}), 3.7 is the molecular weight ratio of $\mathrm{CO_2}$ to C (dimensionless), LUCC is the loss of carbon from LUC (kg C ha^{-1}), $\mathrm{C}_{\mathrm{uptake}}$ is the carbon uptake by oil palm during the plantation lifetime (kg C ha^{-1}), T_{LUC} is the allocation time period of LUC emissions (year), T_{plant} is the plantation lifetime (year), and Y is the net energy yield (GJ ha^{-1} yr^{-1}). $\mathrm{T}_{\mathrm{LUC}}$ is assumed here to be equal to plantation lifetime.

The total amount of GHG emissions for a reused peat land area can be determined by adding $\mathrm{CO_2}$ and $\mathrm{N_2O}$ emission from peat decomposition after drainage when the peat land is first drained and afterward replanted with oil palm (IPCC, 2006). Data input to LUC emission calculation is based on the IPCC default values for different reference land-use systems (IPCC, 2006). The dead organic matter carbon stock and soil carbon (Table 3) are adopted from Wicke *et al.* (2008a).

Fertilizer. Greenhouse gas emissions from organic as well as from mineral fertilization are calculated for six different alternatives (large companies and smallholders in Kalimantan and Sumatra). Both types of fertilizers emit GHGs during production, as well as during and after their application to the field. The GHG emissions from N, P, Mg production are accounted for by multiplying the amount of the specific fertilizer with the emission factor for the production of the fertilizer (Tables 2 and 4). Due to unknown detailed

Table 3 Input data for land-use change (adopted from Wicke *et al.*, 2008a)

Parameter	Unit	Value	Reference
Above-ground biomass before land conversion			
1. Natural over forest	t DM ha^{-1}	350	IPCC (2006)
2. Logged-over forest*	t DM ha^{-1}	175	Lasco (2002)
Above-ground biomass at oil palm plantation after 25 years	t DM ha^{-1}	118	Syahrinudin (2005)
Carbon fraction			
1. Natural rainforest	kg C t^{-1} DM	490	IPCC (2006)
2. Palm tree	kg C t^{-1} DM	400	Syahrinudin (2005)
C stock of litter and dead wood			
1. Before conversion	t C ha^{-1}	2.1	IPCC (2006)
2. Oil Palm plantation	t C ha^{-1}	5.9	Syahrinudin (2005)
Soil organic C			
1. Reference (low activity clay soils)	t C ha^{-1}	60	IPCC (2006)
2. Oil palm plantation†	t C ha^{-1}	40	Syahrinudin (2005)
Emission factor			
1. C from drained peat land	t C ha^{-1} yr^{-1}	10.7‡	IPCC (2006)
2. N_2O drained peat land	kg N_2O ha^{-1} yr^{-1}	8	IPCC (2006)

*Reducing above-ground biomass due to logging can range from 22% to 67%. We assume 50% of original biomass.

†It is assumed that 50% of the soil carbon found in the first 100 cm is stored in the upper 30 cm (Syahrinudin, 2005).

‡In the IPCC guidelines, CO_2 emission from peat oxidation depends on the original land type, as different land types have different drainage depth requirements. In this study, the average of the two emissions (10.7 t C $ha^{-1}yr^{-1}$) is assumed.

DM, dry matter.

characteristics of direct GHG emissions from fertilizer application under subtropical conditions, only a rough estimate was included in the analysis, considering a 1% loss of the applied N as N_2O. The authors are aware of this uncertainty as the amount of losses to the atmosphere might be great: fertilizers are applied partly manually and stay above-ground in heaps.

Transportation. The GHG emissions from transportation of inputs to the plantation as well as transportation of FFB to the mill are totaled and apportioned for the unit of GHG emissions per hectare (i.e., CO_2-eq ha^{-1} yr^{-1}). Transportation of CPO from the mill to the transesterification site across the distance of 500 m is done via pipe and, thus, GHG emissions are negligible.

Milling. Greenhouse gas emissions during the mill processing result from diesel fuel use only, as GHG emissions from POME were not considered. The emissions are allocated according to their output mass with 86% to the CPO and 14% to kernel.

Transesterification. The GHG emissions from the prechains of methanol and sodium hydroxide as well as electricity generation are included. No data for direct emissions from the production site were available.

Ecosystem carbon payback time. The environmental performance of biofuels with respect to LUC effects and overall carbon balance can be assessed and compared using the methodology of ecosystem carbon payback time (ECPT) developed by Gibbs *et al.* (2008). ECPT measures the years required to compensate for the carbon loss induced from LUC processes of the featured ecosystem by avoided carbon emission (carbon savings) due to biofuel:

$$\mathrm{ECPT} = \frac{\mathrm{Carbon}_{\mathrm{landsource}} - \mathrm{Carbon}_{\mathrm{biofuelcrop}}}{\mathrm{Biofuel}_{\mathrm{carbonsavings}}}, \tag{2}$$

where $\mathrm{Carbon}_{\mathrm{landsource}}$ is the carbon stock of the converted land source (t C ha^{-1}), $\mathrm{Carbon}_{\mathrm{biofuelcrop}}$ is the carbon stock of the biofuel crop land (t C ha^{-1}), and $\mathrm{Biofuel}_{\mathrm{carbonsavings}}$ is the annual carbon saving from using biofuels in place of fossil fuels (t C ha^{-1} yr^{-1}).

Emission reduction over fossil fuel. The Commission the European Union states that GHG emission savings from biofuels are to be calculated using the following equation (Commission of the European Communities, 2009):

$$\mathrm{SAVING} = \frac{E_\mathrm{F} - E_\mathrm{B}}{E_\mathrm{F}}, \tag{3}$$

where E_B is total emission from the biofuel and E_F is the total emission from fossil comparator.

Results and discussion

Energy balances

Energy input. The total energy input throughout the production of palm oil biodiesel varies from 49.53 to 85.42 GJ ha^{-1} yr^{-1} (Table 5). The largest demand for energy results from the process of transesterification,

Table 4 Energy content and GHG emission factors of materials and energy sources

Factor	Energy content	GHG emissions
Nitrogen	48.90 MJ kg^{-1} (Patyk *et al.*, 2003)	6056.3 g CO_2-eq kg^{-1} (Patyk & Reinhardt, 1997)
Phosphorus (P_2O_5)	17.43 MJ kg^{-1} (Patyk et al., 2003)	1017 g CO_2-eq kg^{-1} (Patyk & Reinhardt, 1997)
Potassium (K_2O)	10.38 MJ kg^{-1} (Patyk et al., 2003)	583.2 g CO_2-eq kg^{-1} (Patyk & Reinhardt, 1997)
Biodiesel	39 600 MJ t^{-1} (Neto *et al.*, 2004)	–
Sodium hydroxide	26 230 MJ t^{-1} (Ahmed *et al.*, 1994)	ifu/ifeu (2005 – Umberto module library)
Glycerol	18.05 MJ t^{-1} (Bartok, 2004)	–
Fiber and shell	19.89 GJ t^{-1} (Chow *et al.*, 2003)	–
Diesel	41.33 MJ kg^{-1} (Fritsche *et al.*, 2001)	87.5 g CO_2-eq kg^{-1} (Fritsche *et al.*, 2001)
Steam	2604 MJ L^{-1} (EPA, 2002)	–
Methanol	13.23 MJ L^{-1} (Bartok, 2004)	1981.4 g CO_2-eq kg^{-1} (Federal Environmental Agency, 2000)
Electricity		134.2 g CO_2-eq MJ^{-1} (Hallmann, 2000)

followed by oil extraction, prechain processes, agricultural production processes, and transportation. On a hectare base, energy input is largest in private companies with 81.82 to 84.66 GJ ha^{-1} yr^{-1}, followed by dependent smallholders with 76.48 to 78.36 GJ ha^{-1} yr^{-1}, and lowest for the independent smallholders with 49.53 to 57.49 GJ ha^{-1} yr^{-1} in Sumatra and Kalimantan.

The energy input of the private plantation in Kalimantan is 81.82 GJ ha^{-1} yr^{-1} and slightly lower than the 84.66 GJ ha^{-1} yr^{-1} for the private company plantation in Sumatra. This is because the higher FFB yields of 23.5 t ha^{-1} in Sumatra require more energy input in the plantation areas than in Kalimantan with FFB yields of 21.5 t ha^{-1} yr^{-1}. Energy inputs for agricultural production, oil extraction, and biodiesel production are higher in Sumatra than in Kalimantan (Table 5).

Energy inputs in smallholder plantations, both dependent and independent, range between 49.53 and 78.36 GJ ha^{-1} yr^{-1}. The energy input of smallholder plantations is lowest in Sumatra (49.97 GJ ha^{-1} yr^{-1}) and highest in Kalimantan (78.36 GJ ha^{-1} yr^{-1}). One reason for this is the higher energy consumption for transportation (including shipping) of fertilizer, other inputs and products in Kalimantan compared with Sumatra.

An activity with a high demand for energy is forest and land clearing, which is done once in a plantation life. Several vehicles, such as bulldozers and excavators, are used to perform forest and land clearing. The energy input for land clearing in Kalimantan and Sumatra is similar, ranging from 0.02 to 0.04 GJ ha^{-1} yr^{-1}.

The energy input required for prechain processes, such as the provision of polybags, fertilizer, and fuel for transportation, is dissimilar among the farming systems, mainly because of different production intensities. For example, the specific fertilizer application intensities contribute to the disparities in energy inputs between the farming systems. Besides, the energy required for providing and delivering fertilizer to the point of use is subject to a number of other variables, including the transportation distance.

Milling of FFB is an integral part of the process of converting FFB into separated CPO, palm kernels, and by-product or waste. The machines and energy provided for milling FFB include steam for sterilization and processing, power for driving the extraction and separation equipment, power to provide processing water, and electricity for ancillary farm and domestic needs.

According to other studies, the primary energy required to produce CPO and the subsequent process significantly contribute to the total energy input (Pleanjai & Gheewal, 2009; Yee *et al.*, 2009; Kamahara *et al.*, 2010). This is confirmed by our results, showing that 39% of the energy demand comes from the oil extraction process. The diverse numbers in Table 5 reflect the different yields obtained in the farming systems.

The energy input required for traction and transportation was found to be the main item in the agricultural phase (Yee *et al.*, 2009). This includes the transportation of fertilizers, pesticides, seedlings, etc. as well as the transportation of FFB from the oil palm plantation to the palm oil mills and subsequently the removal of EFB from the palm oil mills to the plantation area using tractors. In Malaysia, the energy requirement for palm oil transportation activities totals 2.4 GJ ha^{-1} yr^{-1} (Yusoff & Hansen, 2007) with the highest contribution being made in the agricultural phase. In our study, we found a range of energy input for transportation between 1.49 and 2.63 GJ ha^{-1} yr^{-1}.

Several authors state that the highest energy input in palm oil biodiesel production comprises methanol feedstock, energy during the biodiesel production process, and fertilizer production (Yee *et al.*, 2009; Kamahara *et al.*, 2010). It is emphasized that the total energy utilized in the transesterification of palm oil into biodiesel is 1.80 GJ t^{-1} CPO yr^{-1} on a yearly basis, and the

Table 5 Energy input, energy output, net energy yields and output/input ratios of palm oil biodiesel production (GJ ha^{-1} yr^{-1})

Activity	Kalimantan			Sumatra		
	Company plantation	Smallholder		Company plantation	Smallholder	
		Dependent	Independent		Dependent	Independent
Energy input						
Land-use change*	0.03	0.03	0.04	0.03	0.03	0.02
Prechain						
Polybag production	0.47	0.46	0.46	0.48	0.46	0.46
N fertilizer	2.90	2.81	2.04	1.15	2.81	2.04
P fertilizer	2.01	1.94	1.89	0.99	1.94	1.89
K_2O fertilizer	1.17	1.14	0.81	0.46	1.14	0.81
MgO	0.66	0.66	0.61	0.49	0.57	0.69
Insecticide	0.34	0.34	0.34	0.34	0.34	0.34
Rat baiting	0.16	0.16	0.16	0.16	0.16	0.16
Diesel fuel production for plantation	0.44	0.44	0.34	1.5	0.8	0.72
Fuel for transport	0.27	0.24	0.18	0.20	0.23	0.23
Fuel for sea-transport of fertilizer	0.008	0.007	0.006	–	–	–
Subtotal	8.43	8.20	6.84	5.77	8.45	7.34
Transportation						
Fertilizer by sea	0.05	0.05	0.04	–	–	–
Fertilizer inland	0.13	0.13	0.11	0.06	0.06	0.06
Seedlings to nursery	0.26	0.11	0.11	0.20	0.04	0.04
Young palms to plantation	0.11	0.26	0.26	0.11	0.11	0.11
FFB to mill by truck	1.33	1.27	0.92	0.72	0.56	0.67
FFB to mill by ferry	0.07	0.07	0.05	–	–	–
Subtotal	1.95	1.89	1.49	1.10	0.76	0.87
Agricultural phase						
Irrigation for nursery	0.11	0.11	0.11	0.11	0.11	0.09
Road construction	0.61	0.61	0.61	0.61	0.61	0.51
General Works	0.24	0.24	0.12	0.24	0.24	0.11
Organic fertilizer application	–	–	–	0.07	0.07	–
Personnel transport within plantation	0.76	0.76	0.76	0.76	0.76	0.63
Harvesting	Manual	Manual	Manual	Manual	Manual	Manual
Harvesting transport within in plantation	0.91	0.91	0.18	1.37	0.63	0.15
Subtotal	2.63	2.63	1.78	3.16	2.42	1.49
Industrial phase						
Oil extraction						
Steam for power plant, mill machinery, kernel crushing	32.00	30.52	21.99	34.66	30.15	18.51
Power for engine start-up	0.72	0.69	0.5	0.78	0.67	0.42
Subtotal	32.72	31.21	22.49	35.44	30.82	18.93
Transesterification						
Methanol	28.03	26.74	19.33	30.42	26.42	16.23
Sodium hydroxide	0.46	0.44	0.32	0.51	0.44	0.27
Electricity	7.57	7.22	5.21	8.23	7.14	4.38
Subtotal	36.06	34.4	24.86	39.16	34	20.88
Total energy input (GJ ha^{-1} yr^{-1})	81.82	78.36	57.49	84.66	76.48	49.53
Total energy input (GJ t^{-1} yr^{-1} biodiesel)	19.07	19.16	19.55	18.24	18.93	19.97

Table 5 (continued)

	Kalimantan			Sumatra		
		Smallholder			Smallholder	
Activity	Company plantation	Dependent	Independent	Company plantation	Dependent	Independent
Energy output						
Bio-diesel	169.69	161.85	116.61	183.79	159.87	98.13
Glycerol	24.42	23.28	16.77	26.44	22.99	15.89
Kernel shell	16.88	16.12	11.61	18.29	15.92	9.77
Bokhasi†	–	–	–	1.11	0.96	0.61
EFB for electricity	29.45	28.08	20.23	31.89	27.84	17.02
Electricity surplus	28.68	27.36	19.7	31.07	27.03	16.58
Total energy output (GJ ha^{-1} yr^{-1})	269.12	256.69	184.92	292.59	254.61	158.00
Total energy output (GJ t^{-1} yr^{-1} biodiesel)	62.73	62.76	62.90	63.06	63.03	63.71
Net energy yield (GJ ha^{-1} yr^{-1})	187.30	178.33	127.43	207.93	178.13	108.47
Net energy yield (GJ t^{-1} yr^{-1} biodiesel)	43.66	43.61	49.21	44.81	44.09	43.74
Ratio output/input	3.29	3.27	3.22	3.46	3.29	3.19

*The energy input from land-use change is converted to annual emissions for a plantation standing time of 27 years (company plantations and dependent smallholders) and 21 years (independent smallholders).

†Bokashi is a microbially fermented organic fertilizer made from various agricultural and industrial organic wastes such as palm oil mill effluent and empty palm oil fruit bunches (EFB).

FFB, fresh fruit bunches.

primary energy that is required to produce raw material and subsequently utilized in the process must be accounted for as part of the total energy input (Yee *et al.*, 2009). It has to be added that on a mass basis (GJ biodiesel t^{-1} yr^{-1}) there are hardly any differences between regions and farm types (Table 5).

Energy output. Process outputs from palm oil milling are CPO, palm kernels, fibers, shells, EFB, and POME. The additional outputs of a mill are considered to be valuable coproducts because they are readily used as fuel in electricity and steam production for the mill (Santosa, 2008).

The total energy output ranges from 158 to 292.59 GJ ha^{-1} yr^{-1} (Table 5). Work of De Souza *et al.* (2010) demonstrates that the energy output equals 158 GJ ha^{-1} yr^{-1}, which comprises 147 GJ ha^{-1} yr^{-1} relating to biodiesel and 11 GJ ha^{-1} yr^{-1} of surplus energy. Surplus electricity is the result obtained when the electricity needed by the milling process is deducted from the overall electricity produced by the coproducts such as fiber and shells (Table 5).

On a hectare basis, the highest energy output per hectare is achieved by large private industries. The large private plantation in Sumatra produces a higher energy output of 292.59 GJ ha^{-1} yr^{-1} than the plantation in Kalimantan with 269.12 GJ ha^{-1} yr^{-1}. This is mainly because in the Sumatra plantation, FFB yields are higher than in Kalimantan. Furthermore, the palm oil industry in Sumatra also produces bokashi as organic fertilizer from wastewater, which is not the case for the palm oil industry in Kalimantan.

The energy output from dependent smallholders in both Kalimantan and Sumatra is higher than that from independent smallholders. The main reason for this is the yield difference, with yields of dependent smallholders being nearly as high as the yields achieved in company plantations.

Net energy yield. The net energy yields range from 108.47 to 207.93 GJ ha^{-1} yr^{-1} (Table 5). On a hectare base, the highest net energy yields are achieved in the company plantations in Kalimantan and Sumatra, followed by dependent smallholders and finally independent smallholders at both locations. This is because the large plantations achieve higher CPO yields than smallholders. The net energy yields on a mass basis vary only slightly between 43.61 and 49.21 GJ t^{-1} yr^{-1}. Several researchers record net energy yields between 29.46 and 40.62 GJ t^{-1} yr^{-1} (Yusoff & Hansen, 2007; Angarita *et al.*, 2009; Pleanjai & Gheewal, 2009).

The output/input ratio. The ratio of energy output to input in our study ranges from 3.19 to 3.46, being highest in company plantations, followed by the dependent and independent smallholder plantations in Kalimantan and Sumatra. By comparison, a ratio of energy output to input of 5.4 is reported for Brazil (De Souza *et al.*, 2010), whereas other authors obtain ratios ranging from 3.40 to 4.69 (Yusoff & Hansen, 2007; Angarita *et al.*, 2009; Pleanjai & Gheewal, 2009). The highest ratio figure documented is 7.78 (Yee *et al.*, 2009). Independent smallholder farmers commonly have a considerably smaller input of fertilizers and pesticides than large plantations and supported dependent smallholders. This is due to the relatively high costs that such inputs would inflict on the small scale producers (Hasnah & Coelli, 2004). Hence, positive and negative impacts result: less reliance on fertilizers and pesticides has a positive effect on the environment and reduces ground water pollution. On the other hand, traditional growing techniques improve the yield from year to year. Without or with only small amounts of fertilizer and pesticide input, the yield stays comparably low and production potentials remain untapped.

GHG emissions

Total GHG emissions in the farming systems studied range from 7957 to 24 137 kg CO_2-eq ha^{-1} yr^{-1} (Table 6). The GHG emissions are highest in the case of large companies, medium for dependent smallholders, and lowest for independent smallholders, in both Kalimantan and Sumatra. The highest contribution to the GHG emissions results from LUC, followed by biodiesel production, prechain processes, agricultural production, transportation, and palm oil processing.

Emissions from LUC are responsible for more than 80% of total GHG emissions. The emissions caused in the large company plantations are higher in Kalimantan with 24 137 kg CO_2-eq ha^{-1} yr^{-1} than in Sumatra with 21 952 kg CO_2-eq ha^{-1} yr^{-1}. The main reason for this is that peat land conversion affects 37% of total plantation area in Kalimantan compared with 33% in Sumatra. On both islands, the peat land percentage of total plantation area in the farms investigated is clearly higher than previously estimated from existing and planned oil palm concessions, at 25% in Sumatra and 29% in Kalimantan (Hooijer *et al.*, 2006). The most decisive factor for GHG emissions is whether the plantation is established on land that was previously natural rainforest or peat land (Reijnders & Huijbregts, 2006; Wicke *et al.*, 2008b; Schmidt & Christensen, 2009). There are claims that the carbon stored in the oil palm plantation will be higher than that emitted due to land conversion (Reijnders & Huijbregts, 2006). However, our results indicate that the amount of GHGs released from converting land into oil palm plantations varies greatly between the different locations and farming systems. Furthermore, GHG emissions from prechain processes in company plantations are twice as high in Kalimantan with 784 kg CO_2-eq ha^{-1} yr^{-1} as in Sumatra with 391 kg CO_2-eq ha^{-1} yr^{-1}. Also, the transportation activities cause double emissions of 155 kg CO_2-eq ha^{-1} yr^{-1} in Kalimantan compared with 87 kg CO_2-eq ha^{-1} yr^{-1} in Sumatra. Among the prechain processes, nitrogen is associated with the highest contribution (59%) to overall GHG emissions in company plantations in Kalimantan compared with the contribution from nitrogen applied in Sumatra's company plantations (46%). Company plantations in Sumatra use organic fertilizer obtained from POME, whereas plantations in Kalimantan depend mostly on inorganic fertilizer, and only few use EFB as organic fertilizer.

Previous studies confirmed that the emissions from N_2O and urea fertilizer application contribute significantly to transportation emissions (IPCC, 2006; Wicke *et al.*, 2008a). However, our findings show that the most significant contribution is attributed to the transportation of FFB to the mill, accounting for 62–72% of the total transportation GHG emissions. This is attributable to the long and in some cases very difficult transportation routes from palm oil fields to the mill.

In the agricultural production phase, the highest share of GHG emissions (58%) in smallholder plantations in Sumatra and Kalimantan comes from direct emissions of N_2O from mineral fertilizer application. In the company plantations in Sumatra, GHG emissions from nitrogen fertilizer applications account for 31% of total GHG emissions and are smaller than in company plantations in Kalimantan with 58%. The reason is the use of POME as organic fertilizer in company plantations in Sumatra. How much GHG are emitted due to POME use still has to be investigated. In other studies, emissions associated with the agricultural phase account for 47–74% of the total GHG emissions (Yusoff & Hansen, 2007; Pleanjai & Gheewal, 2009; Yee *et al.*, 2009; De Souza *et al.*, 2010). This results from the fact that nitrogen fertilizer contributes significantly to the emission of GHG. Our findings show that the use of organic fertilizer produced from POME might reduce the amount of GHG emissions by nearly 50% compared with the use of inorganic fertilizer, but missing data concerning emissions from POME will lower this reduction.

The final step of biodiesel production is responsible for the second largest share of GHG emissions, mainly due to the consumption of methanol and grid electricity. The GHG emission shares for methanol production vary from 56% to 59% of the total GHG emission for the production of biodiesel. The rest is caused by the utilization of electricity and sodium hydroxide, with respective shares of 38% and 6%. Other authors state that in the

Table 6 GWP-100 (global warming potential) emission results (kg CO_2–eq ha^{-1} yr^{-1})

	Kalimantan			Sumatra		
		Smallholder			Smallholder	
Activity	Company plantation	Dependent	Independent	Company plantation	Dependent	Independent
Land-use change*	21 254.57	9609.34	11 122.57	19 529.35	5296.30	6809.52
Prechain						
Polybag production	14.38	14.11	14.11	14.61	14.01	14.01
N fertilizer	459.84	444.93	322.64	182.67	444.64	322.35
P fertilizer	144.31	139.46	136.22	71.27	139.41	136.18
K_2O fertilizer	78.66	76.22	54.31	28.88	76.19	54.29
Insecticides	17.98	17.98	17.98	17.98	17.98	17.98
Rat baiting	4.45	4.45	4.45	4.45	4.45	4.45
Diesel fuel production	64.18	62.83	45.78	71.41	42.89	39.39
Fuel for sea-transport of fertilizer	0.53	0.51	0.42	–	–	–
Subtotal	784.33	760.49	595.91	391.27	739.58	588.65
Transportation						
Fertilizer by sea	3.73	3.61	2.97	–	–	–
Fertilizer inland	10.65	10.31	8.48	4.52	10.30	8.48
Seedlings to nursery	20.86	20.47	20.47	16.21	2.82	2.82
Young palms to plantation	8.81	8.64	8.64	8.95	8.58	8.58
FFB to mill by truck	105.64	100.76	72.59	57.21	44.79	53.45
FFB to mill by ferry	5.66	5.40	3.89	–	–	–
Subtotal	155.35	149.19	117.04	86.89	66.49	73.33
Agricultural phase						
Baby palm nursery	1.19	1.168	1.168	1.21	1.16	1.159
Irrigation for nursery	8.19	8.19	8.19	8.19	8.19	8.19
Road construction	46.81	46.81	46.81	46.81	46.81	46.81
General works	18.72	18.72	18.72	18.72	18.72	18.72
Organic fertilizer application	–	–	–	5.3	5.3	–
N_2O mineral fertilizer	293.08	283.58	308.45	116.42	283.4	205.45
N_2O organic fertilizer	–	–	–	17.45	–	–
Personnel transport within plantation	58.51	58.51	58.51	58.51	58.51	58.51
Harvest transport within in plantation	70.21	70.21	14.04	105.32	70.21	14.04
Subtotal	496.71	487.19	455.89	377.93	492.30	352.88
Industrial phase						
Oil extraction						
Diesel for engine start-up	55.74	53.16	38.3	60.37	52.51	32.23
Subtotal	55.74	53.16	38.30	60.37	52.51	32.23
Transesterification						
Methanol	812.69	775.15	558.44	880.22	765.63	469.95
Sodium hydroxide	47.08	44.91	32.35	50.99	44.35	27.22
Electricity	530.90	506.38	364.81	575.02	500.16	306.99
Subtotal	1390.67	1326.44	955.6	1506.23	1310.14	804.16
Total incl. LUC	24 137.37	12 385.81	13 285.31	21 952.04	7957.32	8660.77
Total excl. LUC	2882.80	2776.47	2162.74	2422.67	2661.02	1851.25
Emissions incl. LUC (kg CO_2 t^{-1} yr^{-1} biodiesel)	5626.43	3028.31	4518.81	4731.04	1969.63	3492.25
Emissions excl. LUC (kg CO_2 t^{-1} yr^{-1} biodiesel)	671.98	678.84	735.62	522.13	658.67	746.47

Table 6 (continued)

Activity	Kalimantan			Sumatra		
	Company plantation	Smallholder		Company plantation	Smallholder	
		Dependent	Independent		Dependent	Independent
Emissions incl. LUC ($g\ CO_2$-eq $MJ^{-1}\ yr^{-1}$)	150	81	121	126	53	93
Emissions excl. LUC ($g\ CO_2$-eq $MJ^{-1}\ yr^{-1}$)	18	4	6	3	4	7

Remarks:

Energy content of biodiesel by volume (lower calorific value) = 33 MJ L^{-1} (Commission of the European Communities, 2009, Annex III).

Density biodiesel = 0.88 kg L^{-1}.

*The emission impulse from land-use change (LUC) is converted to annual emissions for a plantation standing time of 27 years (company plantations and dependent smallholders) and 21 years (independent smallholders).

FFB, fresh fruit bunches.

transesterification stage, the major CO_2 emissions come from the electricity generation and emissions from steam boilers (Yee *et al.*, 2009).

Savings of GHG emissions. Excluding LUC, emission reductions attributable to the use of biodiesel over fossil fuels vary from 79% to 97%, with the largest reductions being achieved by company plantations in Sumatra followed by dependent and independent smallholder plantations in Kalimantan and Sumatra (Table 7). Company plantations in Sumatra achieve higher savings of 84% than company plantations in Kalimantan with 80% per hectare. This is due to much higher yields of FFB in Sumatra compared with Kalimantan. The dependent smallholder plantations attain slightly higher savings than the independent smallholder plantations in both Kalimantan and Sumatra, with a difference of 2–3%.

The palm oil system GHG emission saving was calculated to be around 55% in Thailand (Thamsiriroj & Murphy, 2009). The European Commission estimates GHG emission savings of various biofuels between 51% and 71%. The default value for GHG emission savings for palm oil biodiesel is 56% if processed at oil mills with methane capture (Commission of the European Communities, 2009).

If LUC emissions are included, the savings are much lower, if any can be generated at all: dependent smallholders can only realize lower emission savings (9% in Kalimantan, 41% in Sumatra) than the ones demanded from the EU, the other production systems are generating no savings at all (Table 7) during the first plantation standing time.

Ecosystem carbon payback time. The carbon payback time for the cases analyzed varies from 11 to 42 years, with the carbon dept of C released from displaced forests equal to 39 to 157 t C $ha^{-1}\ yr^{-1}$ (Table 7). The ECPT of large company plantations is longer than that of smallholders, in both Kalimantan and Sumatra. The deficit is compensated after 42 years in large company plantations of Kalimantan. The compensation period of 36 years is shorter in the case of company plantations in Sumatra, with the forest displacement equal to 144 t C $ha^{-1}\ yr^{-1}$. This is because 37% of the total plantation area of the company in Kalimantan is peat land compared with 33% in the case of the company plantation in Sumatra. The long carbon payback periods for peat land and natural rainforest indicate that palm oil from these land types cannot be considered sustainable (Wicke *et al.*, 2008a). In contrast, they stated that possible GHG emission savings from plantations on logged-over forests may result in an ECPT of 8 years (if coproduct glycerol is allocated). We calculated a comparable ECPT of 11 years for dependent smallholder plantations in Sumatra. Other studies found ECPT around 86 years for plantations replacing tropical forests (Fargione *et al.*, 2008). Wicke *et al.* (2008b) found that to achieve GHG mitigation using palm oil biodiesel, it is essential to avoid peat land deforestation and drainage. Yield improvements and using the large areas of degraded land existing in Indonesia would make it possible to minimize additional land requirement for oil palm plantations. ECPT for degraded land was estimated at 10 years for degraded grassland (Danielsen *et al.*, 2008), 30 years for degraded forest, and <10 years for grassland and cropped lands (Gibbs *et al.*, 2008). The calculations of the ECPT suggest that in the dependent smallholder systems in Kalimantan (20 years), in Sumatra (11 years) as well as in the independent smallholder system in Sumatra (18 years) within the respective plantation standing times of 27 and 21 years, GHG emission

Table 7 Emission reduction over fossil fuel excl. and incl. land-use change (LUC) emissions (given in kg CO_2e-eq ha^{-1} yr^{-1} and kg CO_2-eq L^{-1} biodiesel), and ecosystem carbon payback time

	Kalimantan			Sumatra		
		Smallholder		Company plantation	Smallholder	
Parameter	Company plantation	Dependent	Independent		Dependent	Independent
Emission reduction per hectare excl. LUC (kg CO_2-eq ha^{-1})						
E_F	14 260	13 590	9770	15 420	13 420	8240
E_B	2882	2776	2163	2423	2661	1851
Saving	11 378	10 814	7607	12 997	10 759	6389
Saving (%)	80	80	78	84	80	78
Emission reduction per liter biodiesel excl. LUC (kg CO_2-eq L^{-1})						
E_F	2.77	2.77	2.77	2.77	2.77	2.77
E_B	0.59	0.13	0.19	0.09	0.13	0.23
Saving	2.18	2.64	2.58	2.68	2.64	2.54
Saving (%)	79	95	93	97	95	92
Emission reduction per hectare incl. LUC (kg CO_2-eq ha^{-1})						
E_F	14 260	13 590	9770	15 420	13 420	8240
E_B	24 137	12 386	13 285	21 952	7957	8661
Saving	No savings	1204	No savings	No savings	5463	No savings
Saving (%)	No savings	9	No savings	No savings	41	No savings
Emission reduction per liter biodiesel incl. LUC (kg CO_2-eq L^{-1})						
E_F	2.77	2.77	2.77	2.77	2.77	2.77
E_B	4.95	2.66	3.98	4.16	1.73	3.07
Saving	No savings	0.11	No savings	No savings	1.04	No savings
Saving (%)	No savings	4	No savings	No savings	37	No savings
Ecosystem carbon payback time (ECPT)						
Sum of LUC ($tCha^{-1}$)	156.51	70.76	63.70	143.81	39.00	39.00
Saving* ($tCha^{-1}yr^{-1}$)	3.73	3.55	2.55	4.03	3.51	2.15
ECPT (year)	42	20	25	36	11	18

Remarks:

E_F = total emission from fossil fuel comparator (fossil diesel).

E_B = total emission from biodiesel.

Saving = $(E_F - E_B)/E_F$.

*Avoided direct emissions from fossil fuel use (calculated from biofuel yields ha^{-1} that substitute fossil diesel with E_F = 0.87 t C t^{-1} fossil diesel; Gibbs *et al.*, 2008).

Density biodiesel = 0.88 kg L^{-1}.

reductions could be achieved. After that time, the E_B for the dependent plantations would amount to 4 g CO_2-eq MJ^{-1} biodiesel and for the independent smallholders in Sumatra to 7 g CO_2-eq MJ^{-1} (Table 6).

The EU reference value is 68 g CO_2-eq MJ^{-1} (Commission of the European Communities, 2009), so that during the first standing time only, the dependent smallholders in Sumatra (53 g CO_2-eq MJ^{-1}) would meet the European conditions.

Conclusions

The results of this study indicate that biodiesel production from palm oil and the related energy balance and GHG emissions vary between different locations in Kalimantan and Sumatra as well as between different farming systems (company plantations, dependent smallholder plantations, and independent smallholder plantations). The output to input ratios are positive in all cases. The overall energy input is higher in plantations in Sumatra compared with plantations in Kalimantan. Production of biodiesel based on palm oil requires its largest energy input during the industrial phase. The largest GHG emissions are produced by LUC especially if planted on peatland, followed by the industrial phase, fertilizer production, agricultural production activities, milling, and transportation. LUC by converting peat land and forests to oil palm plantations results in long ECPT. For the dependent plantations, ECPT indicates the possibility of net GHG savings within the first plantation standing time. Due to their low share of peat land and their efficient management, only palm oil biodiesel from dependent smallholder plantations in Sumatra could meet the European target of emission savings if LUC emissions are considered.

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