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Chapter 6

Methodological issues in comparative life cycle assessment

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Abstract

Palm oil systems generate substantial amounts of biomass residues which are, according to best agricultural practices, preferably returned back to plantation in order to maintain soil fertility. However, there are often variations in this practice. Differences in economic status and possible treatment options for biomass residues determine the preferences to perform life cycle assessment (LCA), leading to a divergence in results. Difficulties when comparing LCA results based on literature are not unusual. The objectives of this paper are to provide guidelines for methodological choices that enable a systematic comparison of diverse scenarios for the treatment and valuation of empty fruit bunches (EFBs) and to explore effects of the scenarios on the environmental performances of a palm oil system.

Eleven scenarios were selected to address the possible EFB valuation and expanded boundaries with reference to the main palm oil system (EFBs applied as mulch, converted to compost or ethanol, treated in an incinerator, and sold as coproducts). The life cycle inventories were modeled based upon an Ecoinvent database. Solutions to multifunctional problems were suggested, including the application of system expansion, substitution, and partitioning, depending upon the nature of the scenarios.

Comparison among LCA results based on the same multifunctional units (crude palm oil + palm kernel oil + palm kernel cake) can be accomplished only in cases where additional coproducts were utilized internally. Based on the global warming impact, the mulch option was preferred. The effect of the avoided process of producing synthetic fertilizers and the assumption that all parts of mulch are available as soil nutrient dominantly determined the final result. These need further verification. This study also demonstrates that the status of EFB as waste or goods is influential on the final results if the EFB is employed externally but has no effect if it is utilized internally.

The proposed guidelines provide methodological choices in terms of system boundary, functional unit, and solutions to multifunctional problems. The methods can be used to systematically compare LCA results of different treatment options and valuation of EFB. The preferred alternative for managing this biomass residue could improve environmental performances and orient toward best practices, such as those suggested by the Roundtable on Sustainable Palm Oil (RSPO). Further studies incorporating a site-specific case of palm oil systems would better illustrate the usefulness of the proposed guidelines.

Keywords
Allocation methods . Bioethanol . Biomass residues . Compost . Global warming . Mulch . Multifunctionality . System boundary.

6.1 Introduction

6.1.1 Palm oil and sustainability

Elaeis guineensisis a tropical forest palm that is native to West and Central Africa. It produces three to eight times more oil for a specified area than any other tropical or temperate oil crops (Sheil et al., 2009). Palm oil is an extremely productive business on a large scale and is commercially profitable due to the increasing global demand for edible oils and biofuels (Sheil et al., 2009). Indonesia has become the world's largest palm oil producer, with approximately 21 million metric ton produced in 2009. Indonesia and Malaysia collectively produced around 87 % of the global palm oil (Stichnothe and Schuchardt, 2011). However, the sustainability of the oil palm cultivation and production of palm oil have come under increasing scrutiny, particularly concerning the impacts on global warming as a consequence of massive land use changes (Koh and Ghazoul, 2010). To address these issues, the Roundtable on Sustainable Palm Oil (RSPO) was established in 2003 (legally registered in 2004) in order to promote the use of sustainable palm oil through a voluntary certification scheme and to identify methods that would lead to environmental improvement (Laurance et al., 2010). Among the promoted good practices, a potential instrument to improve sustainability in the life cycle of palm oil systems is proper management of biomass residues (Hansen et al., 2012).

6.1.2 Potential of solid biomass residues and treatment options

Oil palm biomass comprises fronds, leaves, trunks, root, fruit bunches, and inflorescences, of which approximately only about 10 % yields palm oil and palm kernel oil (Lee and Ofori-Boateng, 2013). Fronds and trunks are generated in plantation areas from periodic harvesting of fresh fruit bunches (FFBs) and periodic replanting of old palm trees, respectively. The cumulative amount of fronds for the 23 years of the productive period of a palm tree is about 1.8 t on a dry weight basis, and the total biomass that is cut down during replanting is about 0.71 t of trunk and fronds per palm (Yusoff, 2006). The exact amount will vary significantly depending upon planting material and field management. In 2011 alone, Indonesia and Malaysia generated nearly 182 million metric ton of dry solid palm biomass which is projected to increase to almost 230 million metric ton by 2020 (MPOB, 2012). Palm oil mills also generate substantial amounts of biomass residues. For example, 1 t of FFB on wet basis results in 0.220 t of empty fruit bunch (EFB), 0.135 t of mesocarp fiber, and 0.055 t of palm kernel shell (Yusoff, 2006).

Press fiber and shell are commonly exploited as solid fuels for steam boilers in order to generate electricity and to meet the internal energy demand for the operation of the palm oil mill, which are often located in remote areas far from national grids (Stichnothe and Schuchardt, 2011). From the perspective of best agricultural practices, fresh EFBs are preferably returned to plantation as mulch to maintain soil fertility (Salétes et al., 2004). This closed loop nutrient cycle can reduce the need for external fertilizers, which subsequently results in an efficient palm oil system. However, the extensive distance between oil mills and plantations may develop into a limiting factor for the feasibility of land application. Indeed, fresh EFBs, which are wet, bulky, and voluminous, are undesirable for handling and transportation. Consequently, there are variations in practice. Some of the EFBs may be further processed into bioenergy, converted to compost, directly sold as coproducts, or incinerated with or without energy recovery. These various treatment options are more likely to occur in oil mills with limited or no plantation areas, which typically process FFBs from other plantations.

The interest in converting biomass residues into other valuable products is also increasing (Stichnothe and Schuchardt, 2010; Hansen et al., 2012; Chiew and Shimada, 2013; Tuck et al., 2012). Some of these developments are directed toward bioenergy development (Lim and Lee, 2011; Wiloso et al., 2012; Chiew and Shimada, 2013). In Malaysia, for instance, the Small Renewable Energy Power Program (SREP) was launched in 2001 to encourage utilization of agriculture residues for generating electricity that would be connected to the national grid. This policy has attracted investments for developing combined heat and power plants (CHPs) exploiting palm oil biomass residues, including EFB. Some CHPs were installed at the palm oil mills, and others were independent power plants connected to the grid. Thus far, there are three CHPs operating from 1 to 14 MW as reported under the SREP program (Chiew and Shimada, 2013). In Indonesia, the government has also recently issued new regulations concerning the price of electricity for bioenergy-based power plants (Kusdiana, 2013). Within the last 10 years, ten on-grid power plants based on palm oil residues were constructed, with a contracted capacity of 2 to 10 MW. However, not all of these plants are continuously in operation. The primary issues are the increasing price and the lack of continuous supply of biomass feedstock (Kusdiana, 2013).

Considering the significant amounts and the diversity of palm biomass residues, potential use and manners of valuation are numerous. Certain options may offer better economic and environmental benefits than others. However, most of the palm oil producers have not yet received a specific directive for selecting which options are most environmentally appropriate. As a consequence, some of these companies are continuing to practice old disposal methods, such as dump and burn (Chiew and Shimada, 2013), thus wasting economic opportunities and adding carbon emissions to the atmosphere.

6.1.3 Comparison of previous LCA studies on EFB

Recent life cycle assessment (LCA) studies on palm oil systems involving further treatment of EFB are illustrated in Table 6.1. In addition to the primary products (palm oil or biodiesel), the system also produced coproducts such as compost, bioethanol, biochar, biooil, and/or syngas. The tabulated LCA studies were limited to those investigating the impact on global warming, representing the most studied impact category. For that purpose, quantitative data were extracted from the papers as depicted in the last row of Table 6.1. The LCA results show that the global warming impacts ranged broadly from positive values (greenhouse gas (GHG) emissions) to negative values (GHG savings). From the point of the LCA procedure, these results are not practically comparable since the scores were not based on the same functional units. This is the primary difficulty when utilizing literature data to compare LCA results. The use of different functional units is not unusual since each study is developed for a specific goal and scope, depending on the objective of the study.

Comparing and interpreting results among independent LCA studies are not a straightforward task. The ISO 14044 requires comparison between product systems to be made on the basis of the same functional unit, which provides a reference to relate the inputs and the outputs (ISO 2006). With this reference, comparison among different product systems could be made on a common basis. In contrast, comparison based on different functional units would be of no values. To properly compare different EFB treatments, therefore, a dedicated LCA study must be conducted specifically for the purpose of that comparison.

6.1.4 Valuation of biomass residues

The common criteria in the valuation of biomass residues are that coproducts provide relatively similar proceeds as the main product, while by-products have lesser value than coproducts, and waste has a negative value, i.e., treatment costs that are not offset by further valuation (Singh et al.2010). However, in the LCA community, by-products are not typically differentiated from coproducts. Rather, all economic outputs other than the main product are considered coproducts with different values. These coproducts are encompassed within a generic term that comprises all potential outputs from a process. When adopting this view, the system boundary of a palm oil system must include all generated biomass residues throughout the process chains. Therefore, in addition to trunks, fronds, and inflorescences from the plantation, the life cycle inventory (LCI) must also incorporate POME, shell, fiber, and EFB from the oil mills.

Table 6.1. Comparison of LCA results on global warming involving different treatments for EFB.

LCA Parameters	Stichnothe & Schuchardt (2010)	Lim & Lee (2011)	Hansen *et al* (2012)
Product systems	Palm oil	Biodiesel	Biodiesel
Expanded product systems	Palm oil + compost	Biodiesel + bioethanol	Biodiesel + pyrolysis products (biochar, biooil, syngas)
Goals	To evaluate environmental impacts of treating EFB (and POME[*]) in a palm oil system	To maximize the output from a limited amount of land by integrating bioethanol processes in a biodiesel system	To compare GHG balances of different treatments of EFB in a bioediesel system
Functional units	1 metric ton of FFB	Use of 1 ha of land in 100 years	1 metric ton of biodiesel
GHG emissions (+) GHG savings (–)	+5.1 up to +7.4 kg CO_2-eq/ metric ton FFB (explanation of Figure 2[b])	+100 up to +900 t CO_2-eq/ ha land (estimated from Figure 4[a])	–440 kg CO_2-eq/ metric ton biodiesel (Table 6.3[b])

POME = palm oil mill effluent.

[a] Scenario 1 = 200+800+200+0+0–1100 = 100; Scenario 2 = 200+800+200+0+1100–1400 = 900; Scenario 3 = 200+950+200+0+350–1200 = 500 (for detail see Figure 4 of Lim & Lee (2011)).

[b] Stichnothe and Schudhardt (2010) assumed that biogas was used to replace the fuel for starting a boiler (internal use), while Hansen *et al* (2012) assumed biogas was used for electricity production to supply the national grid (external use).

Economic flows in LCA travel between two unit processes; therefore, each economic flow must be the output of one process or the input of another process (Heijungs and Frischknecht, 1998). The economic value of flows can be employed as a criterion to determine the status of biomass residues. Guinée et al. (2009) defined products as possessing a positive economic value, whereas waste featured a negative economic value. More specifically, products in the LCA terminology include goods, energy, or services (Guinée et al., 2009). In the current paper, we considered EFB as either waste or goods, depending on the specific conditions of the scenarios.

The process following a waste flow can be either a treatment unit to reduce the pollution strength of the waste or a conversion unit to create a certain product. The latter process provides both a waste treatment function and a function intending to produce a certain product (Bellon-Maurel et al., 2013). In the context of defining a system boundary, a waste stream is conventionally assumed to be free of environmental burden. The impact is directed entirely at the products and coproducts preceding the waste stream. This signifies that actors in the upstream chain must compensate for the treatment or elimination of the waste stream.

There are numerous cases where it is uncertain whether the price of an agricultural residue is positive or negative. Due to technological developments, fluctuations in markets, and governmental policy, waste may rapidly become goods or vice versa. Depletion of natural resources has encouraged the recycling of waste into useful products. These developments may profoundly affect the valuation of biomass residues in a palm oil system. For the moment, the EFB may not yet have an actual market value; however, in the future, it may become valuable. In this context, there has been increasing interest in utilizing EFB as a potential feedstock for bioenergy (Lim and Lee, 2011; Wiloso et al., 2012; Chiew and Shimada, 2013) and other biorefinery products such as biochar, biooil, and syngas (Hansen et al., 2012), but LCA studies addressing biomass residues within different valuation schemes are, thus far, lacking. This paper intends to fill the gap.

6.1.5 Multifunctionality and burden allocation

A multifunctional process is a unit process yielding more than one functional flow. One way to solve a multifunctional problem is by partitioning methods which artificially split the multifunctional process into a number of independently operating monofunctional processes (Heijungs and Guinée, 2007). With this approach, the emissions will decrease; however, the functional unit is not modified. There are different types of multifunctional processes depending on specific situations, i.e., coproduction, recycling, and combined waste processing (Guinée et al., 2004). Coproduction features more than one functional outflow and no functional inflow. Recycling comprises one or more functional outflows and one or more functional inflows. It reduces potentially harmful emissions from waste while simultaneously creating a useful product. Combined waste processing comprises no functional outflow but more than one functional inflow. The illustrated application of the above concept on handling biomass residues in an agricultural system is shown in Figure 6.1 (based on Wiloso and Heijungs, 2013). If the biomass residues are valued as goods or waste (cases a and c), the environmental burden is partitioned between product1 and product2 or waste1 and waste2, respectively. If the biomass residues valued as waste are converted to products (case b), the environmental burden is to be partitioned between the upstream (waste input) and downstream (product output) links. In cases b and c, some and all burdens, respectively, will be attributed to the upstream product system. However, for simplicity, these upstream links are not shown in Figure 6.1. The partitioning factors can be based on different principles: physical properties or economic values of the functional flows. The physical properties can be based on the relative mass, carbon content, or energy content, whereas economic values are based on the relative market value of the functional flows.

The ISO standard (ISO 2006) prefers to avoid the above allocation methods when addressing multifunctional problems. The priority is to divide processes into subprocesses or expand the boundary of the product system. System expansion includes a coproduct as an additional function to a product system. The resulting expanded system, therefore, consists of more than one functional flow. It modifies the original functional unit into a new functional unit with two or more products with no change in emissions. The ISO standard mentions system expansion and partitioning but does not mention substitution, also referred to as subtraction or avoided burdens (Heijungs, 2014). However, almost all guidelines mention substitution.

The term system expansion is often mixed up with the substitution method. Both approaches address multifunctional problems but manifest quite differently. Substitution adds an avoided process to the system that exactly cancels out the coproduct. The production of a coproduct by the system under study circumvents another production process in another system. This avoided production process results in avoided emissions that should be subtracted from the studied product system (Wardenaar et al., 2012).

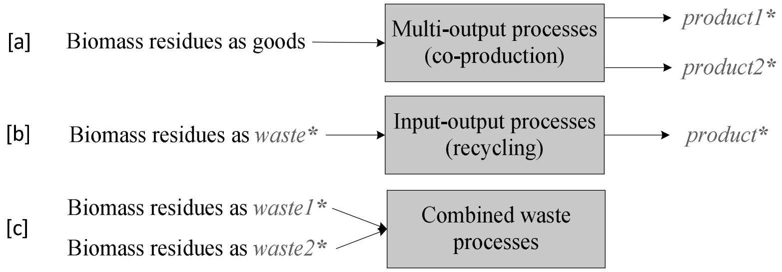

Figure 6.1. Status of biomass residues and possible multifunctional processes. The last case (combined waste processes) does not yield products, but emissions. (*in italic = functional flow). For simplicity, the upstream links producing biomass residues are not shown.

6.1.6 Objective of the paper

There is an increasing interest in utilizing EFB in palm oil systems as feedstock for useful products. The pace of LCA research in the area of coproduct valuation is also accelerating. However, these developments are not without issues. The ISO 14044 leaves too much room in terms of methodological choices to perform an LCA (Heijungs and Guinée, 2007). In addition, the overall complexity is potentially increased by different valuation of biomass residues as goods or waste. Diversity in treatment options for biomass residues, which is particularly prevalent in the case of palm oil system, may also cause variations in the preferences to perform LCA, leading to divergence in results. Meanwhile, in order to select suitable options, valid and consistent methodology is required. The above discussion leads to an important research question of how to properly assess and compare the effect of different treatment options and valuation of EFB on the performance of a palm oil system. The objectives of this paper are to provide guidelines for methodological choices that enable a systematic comparison of diverse scenarios for the treatment and valuation of EFB and to explore effects of the scenarios on the environmental performances of a palm oil system. Methodological choices in terms of system boundary, functional units, and solutions to multifunctional problems are suggested, and their implementations on assessing various scenarios are illustrated.

6.2 Methods

The LCI models were developed to represent a palm oil system integrated with various options in handling EFB. Eleven scenarios were selected to cover possible EFB valuation (as goods or waste) and expanded boundaries with reference to the main palm oil system (application as mulch, conversion to compost or ethanol, treatment in an incinerator, and EFBs directly sold as coproducts). Illustration on these scenarios can be seen in Fig. 2a and 2b. Ecoinvent assumes that, in the palm oil system, the trunks, fiber, and shell are internally (closed loop) recycled (Jungbluth et al., 2007). More specifically, the biomass residues in the plantation (trunks) were recycled with no significant additional inputs or net emissions. Fronds cut down for harvesting the FFB were not mentioned in the report; however, we assumed that besides trunks, fronds were also internally recycled. Meanwhile, fiber, shell, and EFB were cogenerated to produce heat and electricity to be used internally in the oil mills. Our current study assumed the same as above (Ecoinvent) but excluded the EFB from the cogeneration process and treated it further in various ways.

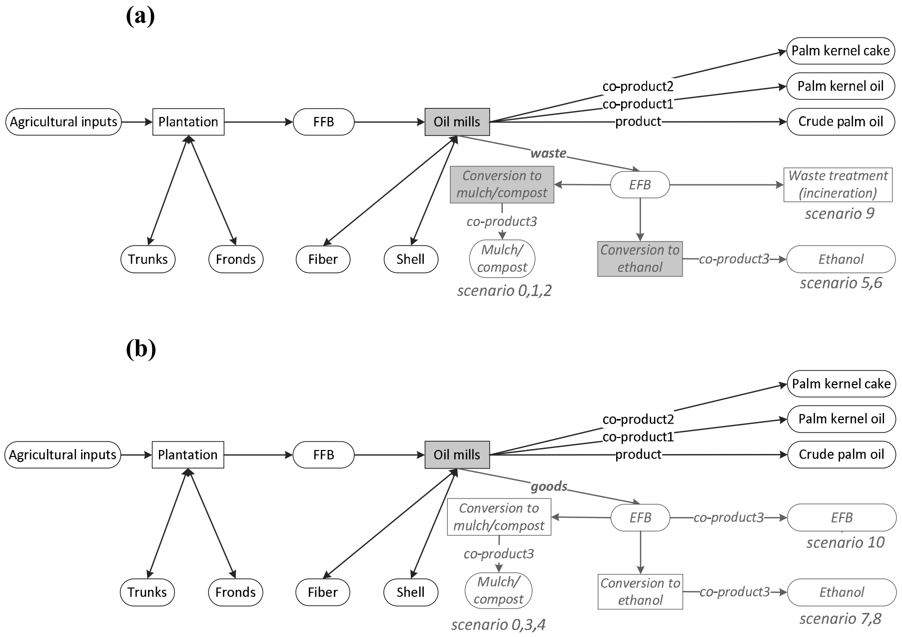

Figure 6.2. (a) System boundary of possible treatment options for EFB when valued as *waste*: applied as mulch or converted to compost (Scenarios 0, 1, and 2), converted to ethanol (Scenarios 5 and 6), and treated in an incinerator (Scenario 9). EFB sub-systems are in *italic*. (⬭ = goods or waste; ☐ = unit process; ▨ = multifunctional process; ↔ = biomass is used internally). (b) System boundary of possible treatment options for EFB when valued as *goods*: applied as mulch or converted to compost (Scenarios 0, 3, and 4), converted to ethanol (Scenarios 7 and 8), sold as a co-product (Scenario 10). EFB sub-systems are in *italic*. (⬭ = goods or waste; ☐ = unit process; ▨ = multifunctional process; ↔ = biomass is used internally).

The application of EFB as mulch or conversion of EFB into compost and ethanol was seen as a way to manage biomass residues leading to environmental improvement.

Incineration was used to represent treatment of EFB in a waste processing unit. EFB can also be regarded as a direct coproduct when it has market values. Processing of these additional coproducts was assumed to take place within the oil mill area so that no transportation was required for the EFB feedstock. The mulch, compost, and ethanol can be employed internally or externally. Internal uses indicate that the mulch or compost is applied to the plantation field as a substitution for inorganic fertilizer or the ethanol is used as biofuel to substitute gasoline for the oil mill operation. External uses mean that these coproducts will become a component of another product system that is external to the palm oil system.

Table 6.2 summarizes the guidelines for the methodological choices to assess environmental impact for the 11 scenarios reflecting different decision situations. The approaches to solve multifunctional problems are a combination of system expansion, substitution, and partitioning depending upon the nature of the scenario. For example, scenarios 0–8 employ a combination of system expansion and substitution or system expansion and partitioning approaches. These scenarios are considered expanded systems since they included additional coproducts (mulch, compost, or ethanol). Scenario 10 uses only one method to solve multifunctional problems, i.e., partitioning. Substitution refers to the use of the resulting coproducts within the main palm oil system (scenarios 0, 1, 3, 5, and 7) which consequently avoided the use of other products of similar functions. In this regard, inorganic fertilizer and gasoline were selected to substitute the mulch or compost and the ethanol, respectively. Currently, diesel oil is dominantly used in a palm oil system. The possible change from the current practice (diesel oil) to the future scenario (ethanol) could be evaluated in terms of their environmental performances.

Table 6.2. Guidelines for methodological choices for comparison of different treatment options and valuation for EFB.

Scenario	System boundary of different treatment options with reference to the main palm oil system	EFB valuation	Approaches in dealing with multifunctional issues		
			Expanding the product system with additional coproducts related to EFB	Partitioning of multifunctional processes	Substituting with avoided processes
0–M	Direct application of fresh EFB as mulch, internal or external uses[a]	Waste Goods	Mulch	Production of mulch	Production of inorganic fertilizer
1–WCI	Conversion of EFB to compost, internal use	Waste	Compost	·	Production of inorganic fertilizer
2–WCE	Conversion of EFB to compost, external use	Waste	Compost	Production of compost	·
3–GCI	Conversion of EFB to compost, internal use	Goods	Compost	·	Production of inorganic fertilizer

Sce-nario	System boundary of different treatment options with reference to the main palm oil system	EFB valuation	Approaches in dealing with multifunctional issues		
			Expanding the product system with additional coproducts related to EFB	Partitioning of multifunc-tional processes	Substituting with avoided processes
4–GCE	Conversion of EFB to compost, external use	Goods	Compost	·	·
5–WEI	Conversion of EFB to ethanol, internal use	Waste	Ethanol	·	Production of gasoline
6–WEE	Conversion of EFB to ethanol, external use	Waste	Ethanol	Production of ethanol	·
7–GEI	Conversion of EFB to ethanol, internal use	Goods	Ethanol	·	Production of gasoline
8–GEE	Conversion of EFB to ethanol, external use	Goods	Ethanol	·	·
9–WI	Treatment of EFB in an incinerator, internal treatment	Waste	·	·	·
10–GcoP	Coproduction (EFB is direct coproducts), external use	Goods	·	Production of CPO, PKO, PKC, and EFB	·

CPO = Crude Palm Oil, *PKO* = Palm Kernel Oil, *PKC* = Palm Kernel Cake.

[a]The effect of the preparation of EFB as mulch on field sites (apart from transportation from oil mills to plantation fields) was so small that it did not change the base line value (see detail in Table 6.3). Therefore, it does not make any different either EFB was valued as waste or goods, or either used internally or externally. For convenient, therefore, all of these variations are combined as one scenario.

Comparison among scenarios was performed based on the multi-functional unit, CPO+PKO+PKC. It was employed as a baseline without including EFB in the inventory. The reason for selecting these three products rather than a mono-functional unit (CPO) is to better represent the environmental burden of the overall system. Further processes on EFB (Scenarios 0-8 and 10 in Figure 6.2) result in additional co-products, i.e. mulch, compost, ethanol, or EFB. When these co-products are introduced in the inventory, the expanded product systems become CPO+PKO+PKC+mulch, CPO+PKO+PKC+compost, CPO+PKO+PKC+ethanol, or CPO+PKO+PKC+EFB, respectively. Meanwhile, the incineration option (Scenario 9) is a simple waste treatment case with no additional co-product.

In addition to producing mulch, compost and ethanol, Scenarios 0, 2, and 6 were also recycling cases since the input EFB was valued as waste. In this case, the environmental burden would need to be partitioned between the upstream and downstream flows. This partitioning reflects burden attribution between the function to reduce the pollution strength of the waste (treatment) and the function to create new products (production). Scenario 10 is a co-production case with EFB as a direct co-product exhibiting certain market values. In this regard, EFB as a co-product is sold to external parties whereby there is no control over their final uses. It could be used, for example, for compost, fibers, or energy.

The models were developed with the LCA software CMLCA v5.2 (2012) and based on inventories of an Ecoinvent database v2.2 (2010). An impact indicator on global warming was selected as the primary criterion to compare the LCA results. The impact assessment referred to the CML 2001 method for climate change (GWP 100 year average, global). The following section describes the inventories of the main palm oil system and additional EFB processes in more detail. All processes were described by indicating the ID-number, region, and year of the Ecoinvent database. Also, assumptions that were used in every process are indicated so that confirmation for the final LCA results could be made. Some modification from the default inventories was made, particularly for EFB availability (initially co-generated to produce energy) and ethanol processes (initially including feedstock transportation). In addition to Sections 6.2.1-6.2.6, a more complete description of the product systems is located in the supplementary material, Table SM1.

6.2.1 Palm oil

The LCI model consisted of the production of FFB at a farm (ID#199: Malaysia, 2002–2006) and palm oil in oil mills (ID#150MO: Malaysia, 1995–2006). The first inventory assumed that land provision included conversion of tropical rain forest to agricultural area. Plantation operation included seedling preparation; field emissions; and transportation of FFB, pesticides, and fertilizers.

Most palm oil mills produce palm kernels, which are then transported to specialized kernel oil extraction facilities. For simplicity, in this study, we assumed that the palm oil mills processed all potential coproducts, i.e., CPO, PKO, and PKC. Therefore, the total burden could be distributed properly among these coproducts. If the kernels are to be sent to other mills, we need to introduce transportation factor, which may add layers of uncertainty.

The second inventory included a 100-km transport of FFB from farm to oil mill gates. The oil production was based on mechanical processes including extraction of oil by screw press and removal of impurities in a settling tank with a centrifuge and evaporator. Every kilogram of processed FFB resulted in 0.2156 kg CPO, 0.0266 kg PKO, and 0.0317 PKC. Economic values of these products were CPO=Ringgit Malaysia (RM) 1.490/kg, PKO=RM 2.565/kg, and PKC=RM 0.175/kg, in which RM denotes Malaysian currency. Based on these data, economic partitioning coefficients were determined as CPO=81.3 %, PKO=17.3 %, and PKC=1.4 %. Environmental performances of the palm oil system were based on a multifunctional unit of 1,000 kg CPO+123 kg PKO+147 kg PKC or 1,270 kg CPO + PKO + PKC in short. In addition, the system also coproduced 1,051 kg fresh EFB at 40 % dry matter. All of the above data are based on Ecoinvent report No. 17 (Jungbluth et al. 2007). A modification was made to the default inventory by excluding the contribution of EFB in energy production, a cogeneration process (ID#79MO).

6.2.2 Mulch

The LCI model consisted of the application of mulch (ID#171). Production of inorganic fertilizers such as ammonium nitrate as N (ID#40<006484-52-2>), single superphosphate as P_2O_5 (ID#54), and potassium chloride as K_2O (ID#50<007447-40-7>) was also considered to account for the effect of mulch substitution with inorganic fertilizers

(Nemecek and Kägi 2007). Transportation of mulch from oil mills to plantation fields included lorry transport (ID#1941) and tractor transport (ID#188). Inorganic fertilizers were provided by utilizing additional rail transport (ID#1983). The transportation distances were based on 100 km between oil mills and farm gates (lorry), 25 km to reach plantation fields (tractor) for mulch, and an additional 600 km of rail transport for substituted fertilizers (Jungbluth et al. 2007).

In the inventory, 1,051 kg fresh EFB was applied directly as mulch. Land application as mulch would require approximately 30 t EFB per hectare (Haron, 2013). Therefore, the economic outputs of the expanded system were 1,270 kg CPO + PKO + PKC + 0.035 ha of plantation area. The fertilizing values of EFB mulch were adopted from Haron (2013), i.e., 0.8 % N, 0.22 % P_2O_5, and 2.9 % K_2O fertilizer on a dry basis. Similar values were also provided by Caliman et al. (2013). Based on the above unit processes, the mulch was equivalent to 9.61 kg ammonium nitrate, 4.40 kg superphosphate, and 20.32 kg potassium chloride. The production of the above amount of inorganic fertilizers emitted 103.9 kg CO_2-eq. The fertilizing value of the mulch is credited if it is internally employed as fertilizer (scenario 0).

6.2.3 Compost

The LCI model consisted of the production of compost (ID#58). The technology was based on open windrow composting as described in Ecoinvent report No. 15 (Nemecek and Kägi, 2007). Unit processes for the production and transportation of inorganic fertilizers were identical to those of the mulch. Chiew and Shimada (2013) suggested that 2,600 kg of fresh EFB resulted in 1,000-kg compost with fertilizing values of 2.2 % N, 1.28 % P, and 2.79 % K on a dry basis. Based on that, in the inventory, 1,051 kg fresh EFB was converted to 404.2-kg compost of 50 % dry matter. As a result, the economic outputs of the expanded system were 1,270 kg CPO + PKO + PKC + 404.2-kg compost. Based on the above unit processes, the compost was equivalent to 12.70 kg ammonium nitrate, 28.21 kg superphosphate, and 11.32 kg potassium chloride. The production of the above amount of inorganic fertilizers emitted 188.3 kg CO_2-eq. The fertilizing value of the compost is credited if it is internally employed as fertilizer (scenarios 1 and 3).

6.2.4 Ethanol

The LCI models consisted of the production of 95 % ethanol (ID#161MO) and further dehydration to 99.7 % ethanol (ID#11795). The first inventory included the production of ethanol and electricity from hardwood chips. Process stages included pretreatment to isolate cellulose from wood matrix, simultaneous saccharification and cofermentation, and distillation to recover ethanol. Economic partitioning coefficients of the resulted ethanol and electricity were 99.7 and 0.3 %, respectively. A further description can be found in Jungbluth et al. (2007). A modification was made to the default inventory by excluding the transportation of wood chips from forest to distillery (ID#161MO). Further, wood chip feedstock was replaced by fresh EFB based on equivalent dry weight. Production of gasoline (ID#1570) was considered to account for the effect of ethanol substitution.

In the inventory, 0.55448-kg dry mass of EFB, equivalent to 0.00232-m^3 hardwood chips, was converted to 0.144-kg 99.7 % ethanol. All inputs and emissions for the same dry mass of EFB were assumed equal to those for dry mass of hardwood chips. As a result, the economic outputs of the expanded system were 1,270 kg CPO + PKO + PKC + 109.3 kg ethanol. The energy content of ethanol and gasoline is 31 and 46 MJ/kg, respectively (Chiew and Shimada, 2013) Therefore, 109.3 kg ethanol is equivalent to 73.66 kg gasoline. The production of this amount of gasoline emitted 50.1 kg CO_2-eq. The energy content of the bioethanol is credited if it is internally utilized as biofuel (scenarios 5 and 7). The comparison between ethanol and gasoline was done at the production gates of ethanol and gasoline. This is quite a reasonable approximation since the difference in emissions from the combustion of these fuels is negligible compared to the difference in the upstream processes (fuel production). If such use phase will be calculated, the combustion of biogenic carbon (ethanol) should be considered as well because carbon capture during plant growth was included in the inventory (Electronic Supplementary Material, Table SM1).

6.2.5 Incineration

The LCI model consisted of the controlled burning of wood in a municipal solid waste incinerator (D#2130). A controlled incineration was chosen since open burning is prohibited in a palm oil system. The incinerator produced electricity and heat; however, no burden allocation was assigned to these coproducts. The generated solid residues were landfilled. A further description can be found in Ecoinvent report No. 13 (Doka, 2003). Prior to being fed into an incinerator, drying is required to bring the water content of the EFB from 60 to 20 %. The unit process employed for this purpose was grass drying (ID#160). Overall, based on 1,051-kg EFB input, two processes were involved, i.e., evaporation of 525.5 kg water and incineration of 525.5 kg EFB of 20 % water content.

6.2.6 EFBs as direct coproducts

The free on board (FOB) prices of EFB at the oil mills ranged between Indonesian Rupiah (IDR) 20/kg EFB and IDR 50/kg EFB, but it was often available at no cost (anonymous field survey in Northern Sumatera, July 2011). The FOB price of palm oil at oil mills was IDR 9,000/kg CPO (GAPKI, 2013). These data were used to determine the partial environmental burden attributed to EFB as a direct coproduct. For another currency, the following conversion rates can be used: US$1=IDR 9,070 in December 2011 and US$1=IDR 12,250 in December 2013 (www.freecurrencyrates.com).

6.3 Results and discussion

The global warming performance at the cradle-to-gate boundary (the plantation and oil mill phases) was 2,068 kg CO_2-eq. and at the gate-to-gate boundary (the oil mill phase) was 144.7 kg CO_2-eq. These results were based on the Ecoinvent assumption that EFBs together with shell and fiber were burned in a cogeneration process. In the current paper, we modified this assumption that EFB was available for other purposes while the energy produced by fiber and shell was sufficient for the entire mill operation. In fact, this is often the case in practice. Therefore, we excluded the EFB contribution to the cogeneration process, which was ascertained to be 21.1 kg CO_2-eq. Subtracting this from the default values, the global warming performances of the above systems change to 2,047 kg CO_2-eq. and 123.6 kg CO_2-eq., respectively. Detailed calculation presented in this section is included in the Electronic Supplementary Material, Tables SM2 and SM3.

Contribution of the upstream operations to the farm gate amounted to 94 % of the total emissions (2,047 kg CO_2-eq.). Transport of FFB from the farm gate to the oil mill and the oil mill operations, hence, only accounted for the remaining 6 % or 123.6 kg CO_2-eq./1,270 kg CPO + PKO + PKC. The contribution of the plantation phase was so dominant that the effects of different treatments on EFB in the final LCA results could hardly be observed at the cradle-to-gate boundary. We further examined changes due to different treatments to EFB only within the oil mill boundary. Therefore, the process of producing FFB in the plantation was cut off. This was meant to zoom in the quantitative figures to be able to see the effect of different treatments. In the case of mulch and compost, coproducts which are internally recycled, the physical substitution with mineral fertilizers would of course be taken place in the plantation phase. This substitution should satisfy two general requirements: (1) the options deliver the same function and (2) the function has the same unit. In the fields, mulch and compost function as nutrient provider to soil. Therefore, these organics and their substituted synthetic fertilizers can be compared to each other on the basis of their fertilizing values. Additionally, the substitution of synthetic fertilizers with mulch or compost requires that all the emissions up to the point of substitution (for example, the compost process and field emissions) are assigned to the main product system. Furthermore, in order to have meaningful comparisons, all quantitative results presented in Table 6.3 were calculated based on the same, gate-to-gate, system boundary. This is quite a common practice in comparative LCA.

The implementation of the proposed guidelines on methodological choices to compare 11 possible scenarios is presented in Table 6.3. It illustrates a step-by-step calculation of the final results. More detailed calculation is included in the Electronic Supplementary Material, Tables SM4 to SM7. The global warming impacts were adjusted considering multifunctional problems in terms of expanding the product system with additional coproducts, substitution with equivalent products, or burden partitioning.

Table 6.3. Global warming performances of a palm oil system reckoning with different treatment options and valuation for EFB (kg CO_2-eq/1270 kg CPO+PKO+PKC).

Scenario	System boundary of different treatment options with reference to the main palm oil system	Initial value	Adjustment on LCA scores considering multifunctional issues			Final value	
		CPO+ PKO+ PKC[a]	Expanding the product system with additional coproducts	Partitioning of multifunctional processes	Substituting with avoided processes[b]	CPO+ PKO + PKC	Mulch, compost, ethanol, EFB for external uses
0−M	Wastes or Goods, Mulch, Internal or External[c]	123.6	+0.7	negligible	−103.9	20.4	negligible
1−WCI	Wastes, Compost, Internal	123.6	+146.4	·	−188.3	81.7	·
2a−WCE	Wastes, Compost, External (treatment:production=2:1)	123.6	·	+97.6[d]	·	221.2	48.8[d]
2b−WCE	Wastes, Compost, External (treatment:production=1:2)	123.6	·	+48.8[d]	·	172.4	97.6[d]
3−GCI	Goods, Compost, Internal	123.6	+146.4	·	−188.3	81.7	·
4−GCE	Goods, Compost, External	123.6	·	·	·	123.6	146.4
5−	Wastes, Ethanol,	123.6	+42.2[e]	·	−50.1	115.7	·

Scenario	System boundary of different treatment options with reference to the main palm oil system	Initial value	Adjustment on LCA scores considering multifunctional issues			Final value	
		CPO+ PKO+ PKC[a]	Expanding the product system with additional coproducts	Partitioning of multi-functional processes	Substituting with avoided processes[b]	CPO+ PKO + PKC	Mulch, compost, ethanol, EFB for external uses
WEI	Internal						
6a–WEE	Wastes, Ethanol, External (treatment:production=2:1)	123.6	·	+28.1[d]	·	151.7	14.1[d]
6b–WEE	Wastes, Ethanol, External (treatment:production=1:2)	123.6	·	+14.1[d]	·	137.7	28.1[d]
7–GEI	Goods, Ethanol, Internal	123.6	+42.2[e]	·	−50.1	115.7	·
8–GEE	Goods, Ethanol, External	123.6	·	·	·	123.6	42.2[e]
9 WI–[f]	Wastes, Incinerator	123.6	·	·	·	366.8	·
10a–GcoP	Goods, co-Production (EFB price = 0.0022*CPO)	123.6	·	−0.3	·	123.3	0.3
10b–GcoP	Goods, co-Production (EFB price = 0.0056*CPO)	123.6	·	−0.8	·	122.8	0.8

Some figures do not add up due to round off. All data presented in this table can be traced back to Tables SM1-SM7 of the Electronic Supplementary Material (Online Resource).

[a] Corrected values, i.e. 144.7 (default) – 21.1 (EFB contribution in co-generation process) = 123.6 kg CO_2-eq.

[b] Substitution with NPK fertilizer (9.61 kg ammonium nitrate + 4.40 kg superphosphate + 20.32 kg potassium chloride = 1051 kg or 0.035 ha of EFB mulch), (12.70 kg ammonium nitrate + 28.21 kg superphosphate + 11.32 kg potassium chloride = 404.2 kg of EFB compost), or with fossil fuel (73.66 kg gasoline = 109.3 kg 99.7% ethanol).

[c] The effect of the application of EFB as mulch was so small (0.7 kg CO_2-eq) that it practically became negligible when partitioned.

[d] Partitioning ratio of 2:1 indicates that Scenarios 2a and 6a allocated twice heavier burden for reducing the pollution strength of EFB than for producing compost or ethanol. In contrast, Scenarios 2b and 6b (1:2) allocated twice heavier burden for producing compost or ethanol than reducing the pollution strength of EFB.

[e] Corrected values, i.e. 57.1 (default) – 14.9 (transportation of wood chips from forest to distillery) = 42.2 kg CO_2-eq.

[f] Consisted of two processes: drying (237.1 kg CO_2-eq) and incineration (6.2 kg CO_2-eq).

Based on the last two columns in Table 6.3, the global warming impacts of the 11 scenarios are visualized in Figure 6.3. The white bars represent the impact of the additional coproducts (mulch, compost, ethanol, or EFB) when employed externally, while the black bars represent the final impacts of the primary palm oil products (CPO + PKO + PKC). These results are point value data with no uncertainty estimates. LCA results are compared based on these point values since additional assumptions and data, other than those from Ecoinvent, were not completed with uncertainty estimates. However, these data are sufficient to illustrate how comparison between different scenarios was performed.

The final results are presented based on how products of the EFB processes are exploited with reference to the palm oil system: internal uses (scenarios 0, 1, 3, 5, 7, and 9) or external uses (scenarios 2, 4, 6, 8, and 10). Comparison based on the same multifunctional units CPO + PKO + PKC is possible only for the internal use cases. These are the cases where the mulch, compost, and ethanol were used internally to substitute inorganic fertilizers and gasoline, respectively. It is assumed that the inorganic fertilizer processes were the avoided processes, producing coproducts with functioning equivalent to that of mulch or compost. Similarly, the gasoline processes were the avoided processes, producing coproducts with functioning equivalent to that of ethanol. Therefore, the functional units of these scenarios after the inclusion of coproducts and substitution with equivalent products are the following:

- Scenario 0: (CPO+PKO+PKC) + (mulch) - (fertilizer) ≈ (CPO+PKO+PKC)’
- Scenarios 1 and 3: (CPO+PKO+PKC) + (compost) - (fertilizer) ≈ (CPO+PKO+PKC)’’
- Scenarios 5 and 7: (CPO+PKO+PKC) + (ethanol) - (gasoline) ≈ (CPO+PKO+PKC)’’’
- Scenario 9: (CPO+PKO+PKC) ≈ (CPO+PKO+PKC)’’’’.

These multifunctional flows have different emission values that can be utilized as a basis for comparison since they have the same functional unit (CPO + PKO + PKC) and the same unit (kg CO_2-eq.). Referring to the baseline value of 123.6 kg CO_2-eq./1,270 kg CPO + PKO + PKC, the mulch option (20.4 kg CO_2-eq.) was the best choice as compared to compost (81.7 kg CO_2-eq.), ethanol (115.7 kg CO_2-eq.), or incineration (366.8 kg CO_2 -eq.) options.

Incorporation of transportation of processed EFB (125 km) and the avoided substituted fertilizers (725 km) increased the impact by 33.2 kg CO_2-eq. for the mulch and 10.6 kg CO_2-eq. for the compost options. These transportation-related burdens are presented in Figure 6.3 as dashed boxes placed on top of the black boxes. The effect of the avoided process of producing substituted fertilizers (103.9 kg CO_2-eq. and 188.3 kg CO_2-eq. for mulch and compost, respectively) was more dominant than transportation. A sensitivity analysis for different processes of substituted fertilizers and different transport distances appears to be necessary in these types of closed loop applications. Such analysis, however, was not included in the current study.

The conclusion on mulch as the best option needs further verification since we assumed that all parts of the EFB were available as soil nutrient. In fact, due to the nature of EFB which is wet and bulky, some parts would undergo anaerobic degradation which emits methane, a strong GHG. Naturally, aerobic oxidation would also take place. In mulch application with one EFB layer, an anaerobic process may be negligible, but in thicker piles, the methane emission could be significant. These aerobic and anaerobic emissions would obviously reduce the amount of nutrients entering the soil matrix and thus reduce the amount of the substituted synthetic fertilizers. In general, the impacts of mulch and compost on soil fertility and field emissions involve complex processes which are not well characterized. Additionally, the processes depend on a number of site-specific conditions. All of these factors potentially increase uncertainty of the final results.

In practice, there are other more influential factors determining the decisions. For example, a company that we visited in Sumatera informed us that, when applying EFB on commercial plantation fields, the total distance is usually within 10 km. This criterion to limit transport distances for EFB field application was primarily based on economic consideration rather than environmental assessment. However, this situation could serve as a basis for the company to define which portion of EFB may be available for ethanol conversion.

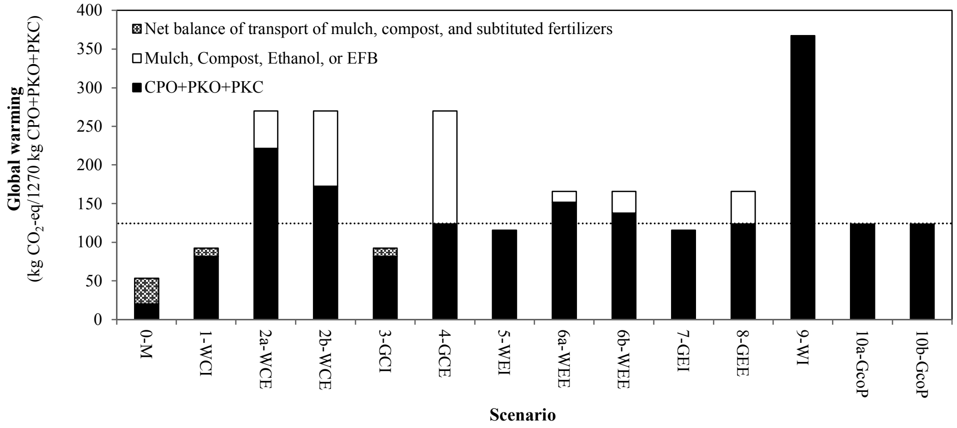

Figure 6.3. Global warming performances of different scenarios. Dashed line is the reference case (EFB treatments were not included in the inventory) with an impact score of 123.6 kg CO_2-eq/1270 kg CPO+PKO+PKC. Emissions from the transportation of the mulch (0–M) and the compost (1–WCI or 3–GCI) are 33.2 and 10.6 kg CO_2-eq/1270 kg CPO+PKO+PKC, respectively. All others are based on data in Table 6.3.

The process of producing compost (146.4 kg CO_2-eq.) had a much greater impact than producing ethanol (42.2 kg CO_2-eq.). The explanation is related to the choice of using an open windrow process which emitted GHG from composting piles directly to the atmosphere. However, this highly burdened process of producing compost was compensated by the avoided process of producing substituted fertilizers. As a result, the overall performance of the compost was better than the ethanol options. The incineration scenario was the worst case because fresh EFB contained excessive amount (60 %) of moisture which is required to be first evaporated to only 20 %. This prior drying step was discovered to be the major contributor (237.1 kg CO_2-eq.) to the incineration option. In practice, EFB is normally not dried beforehand. Prior drying was modeled only for the purpose of estimating the emissions of incinerating such wet EFB. Theoretically, this approach would give less emission than direct incineration (without drying). In this closed loop system (scenarios 0, 1, 3, 5, and 7 for mulch, compost, and ethanol), the status of EFB, as waste or goods, had no effect on the final results.

Besides functional units, technological choices and assumptions related to the inventory could as well strongly influence the final results. Functional units are parts of methodological choices, while technological choices and other assumptions are rather arbitrary, depending on the scope of the study. Difference in final results is possible if the same comparison studies used different methodological choices, technological choices, or assumptions. For example, the conclusion on mulch as the best option in this paper is different from Hansen et al. (2012) who suggested pyrolysis products as a better option. Since all aspects in our study have been transparently presented, we believe that the conclusion is valid within the context of LCA methodology. The relative importance of functional unit, technological choices, and assumptions to the final results could be explored further by performing sensitivity analysis. However, such analysis is outside the scope of the current study.

Comparison of LCA results cannot be made for scenarios 2, 4, 6, 8, and 10. The expanded functional units of these scenarios are CPO + PKO + PKC + additional coproducts (compost, ethanol, or EFB). These coproducts are employed externally, and any knowledge regarding their specific utilization by other parties is unknown. Therefore, substitution mechanism, as in the case of internal uses, could not be performed. Instead, these coproducts with their embedded emissions entered other product systems that are external to palm oil systems. Selling the EFB as coproducts to an external ethanol plant or converting the EFB internally, for example, would exhibit the same impact provided that the same technology is used.

In scenarios 2 and 6, the status of EFB as waste strongly influences the final LCA results. This is because the environmental burden was divided between the upstream and downstream links. Partitioning also applied to the coproduction cases (scenario 10), but the effect of EFB as coproducts was so minimal that it cannot be ascertained in Fig. 3. This is because the values of EFB were much less than the prices of the main palm oil products (CPO, PKO, and PKC). If in the future the price of EFB increases, the effect of this coproduct to the palm oil system will increase accordingly.

The above comparative analysis was by no means complete. For example, the inventory did not include transportation of ethanol from a distillery to gas station and its emissions on use. Also, the plantation phase might use imported fertilizers thereby increasing transport distances. The mulch and compost substituted synthetic fertilizers based on equivalent fertilizing values, which is quite a simplistic approach. It might not accurately consider carbon- and nitrogen-based GHG emissions on field, the difference in nitrogen emissions between organic and mineral fertilizers, the role of organic fertilizers on soil structure, biodiversity, and long-term soil fertility. However, the fertilizer equivalent may be the only easily implementable approach available at the present time. In the context of time and location, the palm oil inventory represented Malaysian averages for 2002–2006, while the EFB processes were primarily European cases. Further studies utilizing a more site-specific data would reduce some uncertainty and better illustrate the applicability of the proposed guidelines. However, we think that the presented analysis is sufficient to illustrate how comparison among different scenarios was performed.

6.4 Conclusions

Comparison between LCA results based on the same multifunctional units can be conducted only in the cases where additional coproducts were employed internally. In this closed loop system, the status of EFB as waste or goods has no effect on the final results. Based on the global warming impact, the mulch option was preferred as compared to the compost, ethanol, or incineration options. This preference, however, needs further verification since we assumed that all parts of the EFB were available as soil nutrient; in fact, some parts would undergo aerobic and anaerobic degradation, emitting GHGs to the atmosphere. The effect of the avoided process of producing synthetic fertilizers also dominated the final result. If used externally, the coproducts with known burden characteristics will become a component of another product system that is external to the palm oil system. In this regard, the status of EFB as waste strongly influences the final LCA results due to burden partitioning between the function to reduce the pollution strength of waste and the function to create products. Comparison among external use scenarios requires further analysis incorporating additional information on specific uses of the coproducts by external parties.

The proposed guidelines provide methodological choices in terms of system boundary, functional unit, and solutions to multifunctional problems. The methods can be used to systematically compare LCA results of different treatment options and valuation of EFB. The preferred alternative for managing this biomass residue could improve environmental performances and orient toward best practices, such as those suggested by RSPO. Further studies incorporating a sitespecific case of palm oil systems would better illustrate the usefulness of the proposed guidelines.

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6.6 References

Bellon-Maurel V, Aissani L, Bessou C, Lardon L, Loiseau E, Risch E, Roux P, Junqua G. 2013. What scientific issues in life cycle assessment applied to waste and biomass valorization? Editorial. Waste Biomass Valor 4:377–383.

Caliman JP, Suhardi, Pujianto. 2013. Impact of by-products recycling on soil quality. In: Webb MJ, Nelson PN, Bessou C, Caliman JP (eds) Proceedings of workshop: sustainable management of soil in oil palm plantings, Medan, 7–8 November 2013.

Chiew YL, Shimada S. 2013. Current state and environmental impact assessment for utilizing oil palm empty fruit bunches for fuel, fiber and fertilizer—a case study of Malaysia. Biomass Bioenergy 51: 109–124.

Doka G. 2003. Life cycle inventories of waste treatment services. Ecoinvent report No. 13. Swiss Center for Life Cycle Inventories, St. Gallen.

GAPKI (Indonesian Palm Oil Association). 2013. http://www.gapki.or. id/Page/CPOPrice?Index=7&selectedPage=0. Accessed 13 October 2013.

Guinée JB, Heijungs R, Huppes G. 2004. Economic allocation: examples and derived decision tree. Int J Life Cycle Assess 9(1):23–33.

Guinée JB, Heijungs R, van der Voet E. 2009. A greenhouse gas indicator for bio-energy: some theoretical issues with practical implications. Int J Life Cycle Assess 14(4):328–339.

Hansen SB, Olsen SI, Ujang Z. 2012. Greenhouse gas reductions through enhanced use of residues in the life cycle of Malaysian palm oil derived biodiesel. Bioresour Technol 104:358–366.

Haron K. 2013. Sustainable nutrient management in oil palm ecosystem. In: Webb MJ, Nelson PN, Bessou C, Caliman JP (eds) Proceedings of workshop: sustainable management of soil in oil palm plantings, Medan, 7–8 November 2013.

Heijungs R. 2014. Ten easy lessons for good communication of LCA. Int J Life Cycle Assess 19(3):473–476.

Heijungs R, Frischknecht R. 1998. A special view on the nature of the allocation problem. Int J Life Cycle Assess 3(5):321–332.

Heijungs R, Guinée JB. 2007. Allocation and"what-if"scenarios in life cycle assessment of waste management systems. Waste Manag 27(8):997–1005.

ISO. 2006. Environmental management—life cycle assessment—requirements and guidelines (ISO 14044). International Organization for Standardization, Geneva.

Jungbluth N, Chudacoff M, Dauriat A, Dinkel F, Doka G, Faist Emmenegger M, Gnansounou E, Kljun N, Schleiss K, Spielmann M, Stettler C, Sutter J. 2007. Life cycle inventories of bioenergy. Ecoinvent report No. 17. Swiss Center for Life Cycle Inventories, Duebendorf.

Koh LP, Ghazoul J. 2010. Spatially explicit scenario analysis for reconciling agricultural expansion, forest protection, and carbon conservation in Indonesia. PNAS 107(24):11140–11144

Kusdiana D. 2013. Existing and new bioenergy policies needed and implementation target. Paper presented at EBTKE Conference and Exhibition 2013, Ministry of Energy and Mineral Resources of The Republic of Indonesia, Jakarta, 21–22 August 2013.

Laurance WF, Koh LP, Butler R, Sodhi NS, Bradshaw CJA, Neidel JD, Consunji H, Vega JM. 2010. Improving the performance of the roundtable on sustainable palm oil for nature conservation. Conserv Biol 24(2):377–381.

Lee KT, Ofori-Boateng C. 2013. Oil palm biomass as feedstock for biofuel production. In: Sustainability of biofuel production from oil palm biomass, Springer, Singapore, pp 77–106.

Lim S, Lee KT. 2011. Parallel production of biodiesel and bioethanol in palm-oil-based biorefineries: life cycle assessment on the energy and greenhouse gases emissions. Biofuels Bioprod Bioref 5:132–150.

Nemecek T, Kägi T. 2007. Life cycle inventories of agricultural production systems. Ecoinvent report No. 15. Swiss Center for Life Cycle Inventories, Duebendorf.

MPOB (Malaysian Palm Oil Board). 2012. Economics and industrial development division.www.mpob.gov.my. Accessed 3 February 2012.

Salétes S, Caliman JP, Raham D. 2004. Study of mineral nutrient losses from oil palm empty fruit bunches during temporary storage. J Oil Palm Res 16:11–21.

Sheil D, Casson A, Meijaard E, van Noordwijk M, Gaskell J, Groves JS, Wertz K, Kanninen M. 2009. The impacts and opportunities of oil palm in Southeast Asia. CIFOR, Bogor

Singh LA, Pant D, Korres NE, Nizami AS, Prasad S, Murphy JD. 2010. Key issues in life cycle assessment of ethanol production from lignocellulosic biomass: challenges and perspectives. Bioresour Technol 101:5003–5012.

Stichnothe H, Schuchardt F. 2010. Comparison of different treatment options for palm oil production waste on a life cycle basis. Int J Life Cycle Assess 15:907–915.

Stichnothe H, Schuchardt F. 2011. Life cycle assessment of two palm oil production systems. Biomass Bioenergy 35:3976–3984.

Tuck CO, Pérez E, Horváth IT, Sheldon RA, Poliakoff M. 2012. Valorization of biomass: deriving more value from waste. Science 337:695–699.

Wardenaar T, van Ruijven T, Beltran AM, Vad K, Guinée J, Heijungs R. 2012. Differences between LCA for analysis and LCA for policy: a case study on the consequences of allocation choices in bio-energy policies. Int J Life Cycle Assess 17(8):1059–1067.

Wiloso EI, Heijungs R. 2013. Key issues in conducting life cycle assessment of bio-based renewable energy sources. In: Singh A, Pant D, Olsen SI (eds) Life cycle assessment of renewable energy sources. Springer, London, pp 13–36.

Wiloso EI, Heijungs R, de Snoo GR. 2012. LCA of second generation bioethanol: a review and some issues to be resolved for good LCA practice. Renew Sustain Energy Rev 16(7):5295–5308.

Yusoff S. 2006. Renewable energy from palm oil—innovation on effective utilization of waste. J Clean Prod 14:87–93.

Electronic Supplementary Material

Methodological issues in comparative life cycle assessment: treatment options for empty fruit bunches in a palm oil system

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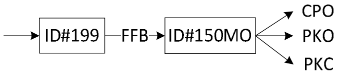
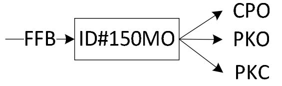
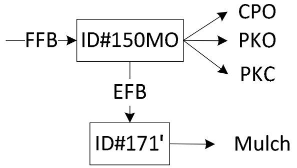
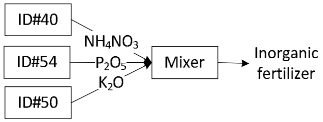
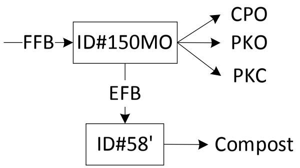
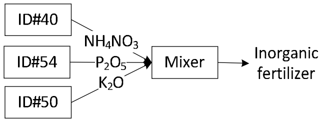
This electronic supplementary material (Online Resource) contains more information on system definition, assumptions, and detail calculation of the results presented in the manuscript.

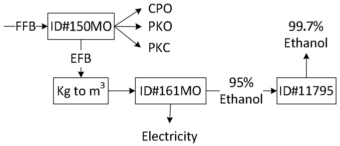
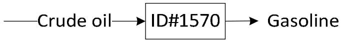
Table SM1. System definition*).

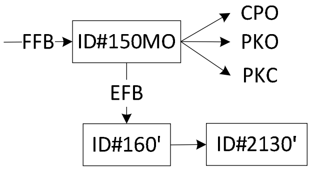
System component	Foreground processes (default UPR of Ecoinvent v2.2, 2010)			This study	
	Main processes	Substituted processes	Allocation	Data from literature, assumptions, and calculation	Fragments of process flow diagram
Palm oil	- Palm fruit bunches, at farm (ID#199: Malaysia, 2002-2006). Economic outflow = 1 kg fresh fruit bunches. (Trunk was internally recycled; CO_2 capture was modelled as an environmental inflow). - Palm fruit bunches, in oil mill (ID#150MO:	-	ID#150MO: Economic partitioning coefficients: CPO = 81.3%, PKO = 17.3%, PKC = 1.4%. (Economic values in 2006: CPO = RM 1.490/kg,	- Fresh fruit bunches of 1 kg resulted in 0.1488 kg fibers of 60% DM, 0.0696 kg shell of 90% DM, and 0.2266 kg EFB of 40% DM (Jungbluth *et al*, 2007). - At the production of 1000 kg CPO, the resulted fibers, shell, and EFB are 690 kg, 323 kg, and 1051 kg on wet basis, respectively; or 414 kg, 290.7 kg, and 420.4 kg on dry basis, respectively. - The impact of the default palm oil	- Cradle-to-gate boundary (plantation and oil mills)  - Gate-to-gate boundary (oil mills only)

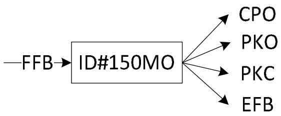
System component	Foreground processes (default UPR of Ecoinvent v2.2, 2010)			This study	
	Main processes	Substituted processes	Allocation	Data from literature, assumptions, and calculation	Fragments of process flow diagram
	Malaysia, 1995-2006). Economic outflows = 0.2156 kg CPO, 0.0266 kg PKO, and 0.0317 kg PKC. (Fiber, shell, and EFB were internally recycled; Treatment of POME was modelled as an economic inflow).		PKO = RM 2.565/kg, and PKC = RM 0.175/kg).	systems was corrected by excluding the contribution of EFB in energy production, a co-generation process as much as 21.1 kg CO_2-eq. • See Tables SM2 and SM3 for further detail.	
Mulch	• Mulching (ID#171: Switzerland, 1991-2002). (Services only, no material input for compost).	• Ammonium nitrate, as N, at regional storehouse (ID#40<006 484-52-2>: Europe, 1999). Economic outflow = 1 kg ammonium nitrate. • Single superphosphate, as P_2O_5,		• Land application as mulch would require approximately 30 metric ton fresh EFB per hectare (Haron, 2013). Therefore, 1051 kg EFB resulted in 0.035 ha mulch. The economic outputs of the expanded system were 1270 kg CPO+PKO+PKC and 1051 kg or 0.035 ha EFB mulch. • The fertilizing values of EFB mulch were adopted from Haron (2013), i.e. 0.8% N, 0.22% P_2O_5, and 2.9% K_2O fertilizer on dry basis.	ID#171' is a modified process with fresh EFB as an inflow and EFB mulch as an outflow.  Substituted processes (1051 kg EFB mulch to replace 34.32 kg inorganic fertilizers)

System component	Foreground processes (default UPR of Ecoinvent v2.2, 2010)			This study	
	Main processes	Substituted processes	Allocation	Data from literature, assumptions, and calculation	Fragments of process flow diagram
		at regional storehouse (ID# 54: Europe, 1999). Economic outflow = 1 kg superphosphate. • Potassium chloride, as K_2O, at regional storehouse (ID#50<007447-40-7>: Europe, 2000). Economic outflow = 1 kg potassium chloride.		• Based on the above unit processes, the mulch was equivalent to 9.61 kg ammonium nitrate, 4.40 kg superphosphate, and 20.32 kg potassium chloride. The production of the above amount of inorganic fertilizers emitted 103.9 kg CO_2-eq. Therefore, internal utilization of 1051 kg or 0.035 ha EFB mulch will avoid global warming impact as much as 103.9 kg CO_2-eq. • See Tables SM6a and SM7 for further detail.	

Sys-tem compo nent	Foreground processes (default UPR of Ecoinvent v2.2, 2010)			This study	
	Main processes	**Substituted processes**	**Allocation**	**Data from literature, assumptions, and calculation**	**Fragments of process flow diagram**
Com-post	• Compost, at plant (ID#58: Switzerland, 1999). Economic outflow = 1 kg compost. (Services only, no material input).	• (ID#40<006 484-52-2>: Europe, 1999). • (ID# 54: Europe, 1999). • (ID#50<007 447-40-7>: Europe, 2000). The same as above	-	• Chiew and Shimada (2013) suggested that 2600 kg of fresh EFB resulted in 1000 kg compost with fertilizing values of 2.2% N, 1.28% P, 2.79% K on dry basis. • In the inventory, 1051 kg EFB of 40% dry matter was converted to 404.2 kg compost of 50% dry matter. As a result, the economic outputs of the expanded system were 1270 kg CPO+PKO+PKC+ 404.2 kg compost. • Based on the above unit processes, the compost was equivalent to 12.70 kg ammonium nitrate, 28.21 kg superphosphate, and 11.33 kg potassium chloride. • The production of the above amount of inorganic fertilizers emitted 188.3 kg CO_2-eq. Therefore, internal utilization of 404.2 kg EFB compost will avoid global warming impact as much as 188.3 kg CO_2-eq. • See Tables SM6b and SM7 for further detail.	ID#58' is a modified process with fresh EFB as an inflow and EFB compost as an outflow.  Substituted processes (404.2 kg EFB compost to replace 52.24 kg inorganic fertilizers): 
Etha-nol	• Wood, in distillery (ID#161MO:	• Petrol, unleaded, at	ID#161MO: Economic	• Bulk density of hardwood chips (u=80% or 44.4% water content)	Hardwood chips as default feedstock for ethanol production

Sys-tem compo nent	Foreground processes (default UPR of Ecoinvent v2.2, 2010)			This study	
	Main processes	**Substituted processes**	**Allocation**	**Data from literature, assumptions, and calculation**	**Fragments of process flow diagram**
	Switzerland, 1999-2006). Economic outflows = 0.144 kg 95% ethanol, electricity = 0.00649 kWh. (Input material was 0.00232 m^3 hardwood chips u=80% or 55.6% DM). - Ethanol, 99.7% in H_2O, from wood, at distillation (ID#11795: Sweden, 2000-2008). Economic outflow = 1 kg 99.7% ethanol. (Input material was 1 kg 95% ethanol).	refinery (ID#1570: Switzerland, 1980-2000). Economic outflow = 1 kg petrol. (Petrol = gasoline)	partitioning coefficients: 95% ethanol = 99.7%; electricity = 0.3%.	was 556 kg DM/ton or 2.325 m^3 chips (Jungbluth et al, 2007). - Solid content of 0.00232 m^3 hardwood chips was equal to 0.55448 kg dry EFB. This amount of solid was converted to 0.144 kg of 95% ethanol, and further to 0.144 kg of 99.7% ethanol. Or, 420.4 kg dry EFB resulted in 109.3 kg of 99.7% ethanol. - As a result, the economic outputs of the expanded system were 1270 kg CPO+PKO+PKC+ 109.3 kg of 99.7% ethanol - Assumed that inputs, ethanol product, and emissions resulted from 1 kg dry EFB were equal to those from 1 kg dry softwood chips. - The impact of the default ethanol process (57.1 kg CO_2-eq) was corrected by subtracting the impact of transporting feedstock as much as 14.9 kg CO_2-eq. - Energy content of ethanol and gasoline were 31 MJ/kg and 46 MJ/kg, respectively (Chiew and Shimada, 2013). Energy content	were replaced by EFB.  Substituted processes (109.3 kg 99.7% ethanol from EFB to replace 73.66 kg gasoline): 

Sys-tem compo nent	Foreground processes (default UPR of Ecoinvent v2.2, 2010)			This study	
	Main processes	Substituted processes	Allocation	Data from literature, assumptions, and calculation	Fragments of process flow diagram
				of 109.3 kg of 99.7% ethanol was the same as that of 73.66 kg gasoline. • The production of the above amount of gasoline emitted 50.1 kg CO_2-eq. Therefore, internal utilization of 109.3 kg 99.7% ethanol will avoid global warming impact as much as 50.1 kg CO_2-eq. • See Table SM4 for further detail.	
Incinerator	• Grass drying (ID#160: Switzerland, 1985-2002). Economic outflow = 1 kg water evaporated. (Services only, no grass input). • Disposal, wood untreated, 20% water, to municipal incineration (D#2130: Switzerland, 1994-2000). Economic outflow = disposal of 1 kg wood waste.	-	<u>ID#2130</u>: No allocation applied for electricity and heat. All burdens were charged to the waste input.	• Solid content of 0.2266 kg EFB of 40% DM was equal to 0.1133 kg wood of 80% DM, i.e. 0.09064 kg. • Assumed that inputs and emissions resulted from 1 kg dry EFB were equal to those of 1 kg dry wood. • The EFB process consisted of ID#160’ (evaporation of 525.5 kg water) and ID#2130’ (incineration of 525.5 kg wood of 80% DM). • See Table SM5 for further detail.	 ID#160’ is a modified process with EFB of 40% DM as an inflow and EFB of 80% DM as an outflow. ID#2130’ is a modified process with EFB of 80% DM as an inflow.

System component	Foreground processes (default UPR of Ecoinvent v2.2, 2010)			This study	
	Main processes	Substituted processes	Allocation	Data from literature, assumptions, and calculation	Fragments of process flow diagram
	(Services only, no wood input).				
EFB as co-products	• Palm fruit bunches, in oil mill (ID#150MO: Malaysia, 1995-2006). Economic outflow = 0.2156 kg CPO, 0.0266 kg PKO, 0.0317 kg PKC, and 0.2266 kg EFB at 40% DM.	-	ID#150MO: The same as above.	Market values of CPO and EFB as co-products: • FOB price of CPO at oil mills was IDR 9000/kg (GAPKI website, 2013). • FOB prices of EFB at oil mills were IDR 20/kg and IDR 50/kg. Often, it was free (Anonymous, field survey in Northern Sumatera, July 2011).	

Notes:

1) Ecoinvent processes were based on single-output and multi-output UPR (unit process raw) with infra-structure databases.
2) Multi-output processes (ID#MO150 and ID#MO161) were added to the single-output process database, and the corresponding single-output processes were removed.
3) ID#MO150 (palm oil) and ID#MO161 (ethanol 95%) are ID numbers of the multi-output UPR database, while the rest are ID numbers of the single-output UPR database.
4) ID#171' (mulch), ID#58' (compost), ID#160' (drying), and ID#2130' (incineration) are modified version of the Ecoinvent processes in terms of input-output flows for the purpose of easy to understand presentation of the process diagram.
5) IDR = Indonesian Rupiah; RM = Malaysian Ringgit; DM = dry matter; POME = palm oil mill effluent.

Table SM2. Contribution analysis on the global warming performances of a palm oil system[a].

Processes	System boundary	
	Cradle to gate[b]	Gate to gate[c]
Provision of land	43%	0
Plantation operation	36%	0
Lorry operation	4%	54%
Oil mill operation	< 0.5%	7%

[a] EFB together with fibers and shell were burned in a co-generation unit, and the resulted electricity and heat were used internally.

[b] Production of FFB (plantation) and CPO+PKO+PKC (oil mills). For the production of 1000 kg CPO, 123 kg PKO, and 147 kg PKC, the global warming performances were 1681.9 kg CO_2-eq, 357.9 kg CO_2-eq, and 29.0 kg CO_2-eq, respectively. (2067.8 kg CO_2-eq/1270 kg CPO+PKO+PKC). These figures do not add up due to round off.

[c] Production of CPO+PKO+PKC only (plantation stage was cut off). For the production of 1000 kg CPO, 123 kg PKO, and 147 kg PKC, the global warming performances were 117.7 kg CO_2-eq, 25.0 kg CO_2-eq, and 2.0 kg CO_2-eq, respectively. (144.7 kg CO_2-eq/1270 kg CPO+PKO+PKC). These figures do not add up due to round off.

Table SM 3. Co-generation[a] of fiber, shell, and EFB to produce heat and electricity.

Raw materials (at 1000 kg produced CPO)	Wet weight (kg)	Dry weight (%)	Dry weight (kg)	Dry weight Ratio (%)	Global warming impact[b] (kg CO_2-eq)
Fibers	690	60	414.0	36.8	20.8
Shell	323	90	290.5	25.8	14.6
EFB	1051	40	420.4	37.4	21.1
Total				100	56.4

[a] Unit process = wood chips, burned in cogen 6400kWth, allocation energy (ID#79MO: Switzerland, 2000-2001). In this inventory, partitioning coefficients based on energy content for electricity and heat were 9.7% and 90.3%, respectively. These figures do not add up due to round off.

[b] Bulk density of wood chips = 188.6 kg dry matter/m^3 (wood chips, mixed, from industry, u=40%; ID# 2353: Europe, 2002); Emissions were assumed proportional to dry matter. The corrected global warming impact of the default palm oil system by excluding the contribution of EFB. Cradle-to-gate boundary = 2067.8 – 21.1 = 2046.7 kg CO_2-eq; Gate-to-gate boundary = 144.7 – 21.1 = 123.6 kg CO_2-eq.

Table SM4. Transportation of hardwood chips from forest to distillery.

Transported materials	Weight (kg)	Transport[a] (km)		Global warming impact (kg CO_2-eq)
		Tractor and trailer	Lorry	
Hardwood chips	1051	5	65	14.9

[a] Transport, tractor and trailer (ID#188: Switzerland, 1991-2002); Transport, lorry 20-28 metric ton, fleet average (ID#1942: Switzerland, 2005). The corrected global warming impact of the default ethanol process (excluding the contribution of feedstock transportation) = 57.1 – 14.9 = 42.2 kg CO_2-eq.

Table SM5 Incineration of EFB

Unit processes	EFB input	Evaporated water	Global warming impact
Grass drying	1051 kg at 60% water	525.5 kg	237.1 kg CO_2-eq
Incineration	525.5 kg at 20% water	-	6.2 kg CO_2-eq

Table SM6. Substituted inorganic fertilizers

(a) for mulch

Fertilizer substitutes for mulch	Active compoundsbased on Ecoinvent LCIs[a] (%)			Weight (kg)[b]	
	N	P_2O_5	K_2O	Substituted mulch (dry matter)	Inorganic fertilizers
Ammonium nitrate	35			420.4	9.61
Superphosphate		21		420.4	4.40
Potassium chloride			60	420.4	20.32

Total weight, kg	34.32
Impact of producing fertilizers, kg CO_2-eq	103.9

[a] The fertilizing value of EFB mulch was equivalent to 0.8% N, 0.22% P_2O_5, and 2.9% K_2O fertilizer (Haron, 2013); 0.79% N, 0.23% P_2O_5, and 2.80% K_2O fertilizer based on dry basis (Caliman et al, 2013).

[b] Based on molecular weight, N in NH_4NO_3 is 35%, P in P_2O_5 is 43.66%, and K in K_2O is 82.98%. 420.4 kg dry mulch = 1051 kg fresh EFB x 40% dry matter.

(b) for compost

Fertilizer substitutes for compost	Active compounds based on Ecoinvent LCIs (%)			Weight (kg)	
	N	P_2O_5	K_2O	Substituted compost[c] (dry matter)	Inorganic fertilizers
Ammonium nitrate	35			202.1	12.70
Superphosphate		21		202.1	28.21
Potassium chloride			60	202.1	11.33

Total weight, kg	52.24
Impact of producing fertilizers, kg CO_2-eq	188.3

[c] Fresh EFB contained 40% DM (Jungbluth et al, 2007); Compost product had 50% DM (Nemecek and Kägi, 2007); Chiew and Shimada (2013): 2600 kg EFB was converted to 1000 kg EFB compost; EFB compost has fertilizing values equivalent to 2.2% N, 1.28% P, and 2.79% K on dry basis.

Table SM7. Transportation of compost, mulch, and the substituted inorganic fertilizers[a].

Transported materials	Weight (kg)	Transport (km)			Global warming impact (kg CO_2-eq)
		Tractor and trailer	Lorry	Rail	
Compost	404.2	25	100	0	13.6
Mulch	1051	25	100	0	35.2
Inorganic fertilizers (compost substitute)	34.3	25	100	600	2.0
Inorganic fertilizers (mulch substitute)	52.2	25	100	600	3.0

[a] Transport, tractor and trailer (ID#188: Switzerland, 1991-2002); Transport, lorry 3.5-16 metric ton, fleet average (ID#1941: Europe, 2005); Transport, freight, rail (ID#1983: Europe, 2000). Fresh EFB contained 40% DM (Jungbluth et al, 2007); Compost product contained 50% DM (Nemecek and Kägi, 2007).

Additional transportation factors for the compost option = 13.6 – 3.0 = 10.6 kg CO_2-eq.

Additional transportation factors for the mulch option = 35.2 – 2.0 = 33.2 kg CO_2-eq.