Supply Chain Analysis, Delivered Cost, and Life Cycle Assessment of Oil Palm Empty Fruit Bunch Biomass for Green Chemical Production in Malaysia

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Financial, environmental, and supply chain analyses of empty fruit bunch (EFB) biomass are needed for the development of a sustainable green chemicals industry in Malaysia. Herein, holistic analysis of the supply system and EFB life cycle cradle-to-gate are analyzed in an effort to make recommendations for the commercial-scale collection and delivery of EFB from crude palm oil (CPO) extraction facilities to biorefineries in Malaysia. Supply chain modeling tracked inputs and outputs for financial analysis. The openLCA software was used for life cycle assessment (LCA). Allocation scenarios were used to explore the impact of accounting methodologies on the competitiveness of EFB compared to other feedstocks. Sensitivity analysis on the effect of transportation distance, emission flows, and allocation methods on resulting environmental impacts were conducted. The No Burden, Economic, and Mass allocation scenarios resulted in -1629, -1619, and -1474 kg CO_2-eq. BD tonne^{-1} EFB global warming impacts (GW), respectively. Delivered cost for EFB was calculated to be approximately 45 US$ BD tonne^{-1}. Environmental burdens were sensitive to allocation scenario, covered area, and land use change. Delivered cost was sensitive to transport distance, covered area, and yield. It was shown that there is sufficient Malaysia EFB available for between 9 and 28 biorefineries, depending upon the scale of production.

Keywords: EFB; Biomass; Green chemicals; LCA; Delivered cost; Supply chain analysis

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Abbreviations List

AC	acidification
BDMT	bone dry metric tonne
CA	carcinogenics
CAPEX	capital expenditure
CHP	combined heat and power
CPO	crude palm oil
EC	ecotoxicity
EFB	empty fruit bunches
EU	eutrophication
FFB	fresh fruit bunches
GHG	greenhouse gases
GIS	geospatial information science
GMT	green metric tonne

GW	global warming impact
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
LUC	land use change
NC	non-carcinogenics
OZ	ozone depletion
PO	photochemical oxidation
POME	palm oil mill effluent
RE	respiratory effects

INTRODUCTION

Evidence of the impact of anthropogenic emissions on the warming of the global climate (Wallace *et al.* 2012; Santer *et al.* 2013; Stern and Kaufmann 2014) and continued depletion of conventional fossil-based feedstocks for advanced chemicals synthesis (Shafiee and Topal 2009; Sorrell *et al.* 2010; Sorrell *et al.* 2012; Höök and Tang 2013) have promoted research and development of alternative platforms and feedstocks for fuel, energy, and chemical production. Alternatives to fossil-based feedstocks are predominated by cellulosic biomass-based feedstocks and starches. Independent corporate research and government incentivization in developed countries has led to substantive research, resulting in actionable findings and the identification of high-potential feedstocks. In less developed countries, such as Malaysia, the extent of research and development has been less, and therefore the commercialization of bioenergy, biofuels, and biomaterials industries has been slower. This is despite a plentitude of high yield, fast growth biomass types in such countries.

Due to the high selling price and lack of market security for biomass, research to reduce production costs and ensure adequate availability of renewable feedstocks must be completed before commercialization. In the United States, biomass supply systems are relatively well established and the financial, supply chain, and environmental life cycle impacts have been initially mapped. Such analysis can be applied in a similar manner to Malaysia (Chiew *et al.* 2011; Choo *et al.* 2011; Chiew and Shimada 2013; Daystar *et al.* 2014). Currently, there is minimal infrastructure in place to use biomass for renewable energy or renewable chemical production in Malaysia due to currency volatility and financial risk in the biomass supply chain and uncertainty in the downstream market for biomass and biomass-based products (Zhou and Thomson 2009; Richard 2010; Lamers *et al.* 2011; Junginger *et al.* 2011; Chakraborty *et al.* 2012; Jupesta 2012).

Oil palm empty fruit bunch (EFB) is an example of a biomass type that is readily available in Malaysia and which has an appropriate composition for the bio-sugar platform, wherein thermochemical pretreatment processes and biochemical conversion processes are utilized to produce fermentable sugars. Oil palm plantations in Malaysia produce fresh fruit bunches (FFB), which are hand harvested and transported to crude palm oil (CPO) extraction facilities. There are currently more than 400 CPO extraction facilities throughout Malaysia, and these collect FFB from oil palm plantations, employing over 600,000 laborers, covering more than 5,000,000 hectares, and constituting more than 60% of all GDP from commodity exports (Rasid *et al.* 2013; MPOB 2014).

FFB grows to maturity every 15 to 20 days and is hand harvested and loaded into a 10 tonne truck within the plantation. From there the FFB is delivered directly to the CPO extraction facility, where it is sterilized using steam to reduce the rate of decomposition due to microbial activity. After sterilization the FFB is crushed to extract the dirty CPO. Subsequently the kernels are further crushed to produce palm kernel oil, which is sometimes further refined separately from the CPO, but oftentimes is combined with the CPO before further refining. The oil and water are separated from the palm kernels, fiber, and EFB, which are dried before being used primarily (~60%) for combined heat and power (CHP). The lignocellulosic biomass which remains and is not used for CHP is approximately 40% of produced EFB, or 9.2% of the FFB harvested, on a dry basis (Halimah *et al.* 2010; Choo *et al.* 2011; MPOB 2014). Some palm oil producers consider excess EFB devoid of value and send it to be landfilled, while others land apply EFB at the plantation as compost and a minority of more advanced CPO mills pelletize or briquette the EFB for export or sale.

Other factors that can affect the feasibility of commercialization are feedstock cost and availability, feedstock composition and convertibility, and the resultant product quality and market conditions. This study does not deal with the conversion process specifically, and market conditions are more appropriately studied as part of a techno-economic conversion study. However, a basic understanding of the potential usability of delivered biomass is necessary in order to parameterize the feasibility of commercialization. Recent advancements in the pretreatment (Yanus *et al.* 2010; Jung *et al.* 2011; Shamsudin *et al.* 2012; Tan *et al.* 2013) and conversion of EFB biomass to polysaccharides and monomeric saccharides (Alam *et al.* 2009; Varman *et al.* 2010; Hamzah *et al.* 2011; Lim and Andrésen 2011; Piarpuzán *et al.* 2011; Sulaiman and Abdullah 2011; Wang *et al.* 2012) suggest that the commercial-scale bio-sugar production platform is potentially feasible in Malaysia.

The EFB composition (Table 1) is suitable for various purposes and end-uses, including conventional energy and carbohydrate recovery technologies (CHP, anaerobic digestion and biogas combustion, and land application at oil palm plantations) as well as advanced technologies (biochemical conversion, thermochemical conversion, and pelletization).

Table 1. Composition of EFB from 10 Recent Literature Sources and the Mean and Standard Deviation of the Values

	a	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**i**	**j**	**Mean ± SD**
Glucan (%)	52.3	41.9	53.6	41.1	39.3	43.8	54.2	38.9	48.0	56.0	46.9 ± 6.7
Total hemicellulose (%)	27.6	26.2	21.8	23.1	36.5	35.0	30.4	19.9	30.5	31.6	28.3 ± 5.6
Arabinan (%)		4.8									
Xylan (%)	27.6	18.7	17.0	23.1			30.4	16.0	30.5	31.6	
Mannan (%)			2.3					3.9			
Galactan (%)		2.7	2.5								
Extractives (%)	2.2					4.8					3.5 ± 1.8
Ash (%)					1.8		0.7	5.8		0.5	2.2 ± 2.5
Lignin (%)	17.9	31.8	24.6	35.7	22.3	16.4	14.8	35.4	21.5	11.7	23.2 ± 8.6

Sources: a = Tan *et al.* 2012; b = Jung *et al.* 2013; c = Nieves *et al.* 2011; d = Milatti *et al.* 2011; e = Piarpuzan *et al.* 2010; f = Hamzah *et al.* 2008; g = Rahman *et al.* 2007; h = Jung *et al.* 2011; i = Zhang *et al.* 2011; j = Rahman *et al.* 2006.

Composition data were balanced to 100% dry mass closure through normalization of composition values by moisture content and subsequently by adjusting the amount of hemicelluloses, which are often least accurately measured, especially as compared to ash, extractives and lignin (Omar *et al.* 2011; Fogassy *et al.* 2013).

This residual EFB biomass can be used for a several applications, based upon embodied energy content (or heating value) as well as cellulose and hemicellulose polysaccharide content coupled with the state-of-technology estimations of enzymatic hydrolysis of such material. Rather than disposing waste EFB biomass, it is possible to use this biomass for bioenergy or bio-based chemical production via various conversion pathways. Once a reliable supply chain is established and an established market develops, this could be a very profitable industry in Malaysia. Recent literature supports these claims and suggest possible conversion pathways and end products for the utilization of waste EFB in Malaysia. For a more complete background, please refer to the following sources: (Alam *et al.* 2009; Gutierrez *et al.* 2009; Abdullah *et al.* 2010; Lau *et al.* 2010; Tan *et al.* 2010; Abnisa *et al.* 2011; Bazmi *et al.* 2011; Sulaiman and Abdullah 2011; Sulaiman *et al.* 2011; Baharuddin *et al.* 2012; Shamsudin *et al.* 2012; Harsono *et al.* 2013; Lange and Pellegrini 2013; Ogi *et al.* 2013; Sirajudin *et al.* 2013; Tan *et al.* 2013).

Chiew *et al.* (2011) estimated the available EFB from palm oil extraction facilities in Malaysia and have proposed the use of EFB for CHP. Chiew *et al.* (2011) have also used geospatial information system (GIS) data to propose the location of a CHP plant based upon current palm oil extraction facilities and the estimated availability of EFB. Values for CPO extraction facility size, EFB production rates, as well as physical and chemical characteristics of this available biomass were utilized for the research presented herein. Choo *et al.* (2011) conducted greenhouse gas (GHG) analysis for the palm oil extraction facility and data related to the energy content of, major unit processes related to, and environmental impacts due to the production of palm oil were incorporated into this current work. Chiew and Shimada (2013) utilized life cycle assessment (LCA) for quantifying the environmental and human health impacts associated with the palm oil and EFB production system and further compared seven different reuse or recycling technologies, which were used for the alternative cases here, such as: composting of the EFB at the palm oil plantations and combustion for CHP at the palm oil mill. Data related to national average palm oil plantation size, productivity, FFB and EFB yield, and other various inputs and outputs to the biomass production life cycle stages were used from this previous work (Chiew and Shimada 2013). The estimated quantity of EFB produced as a by-product of the palm oil industry in Malaysia in 2013 is shown in Fig. 1.

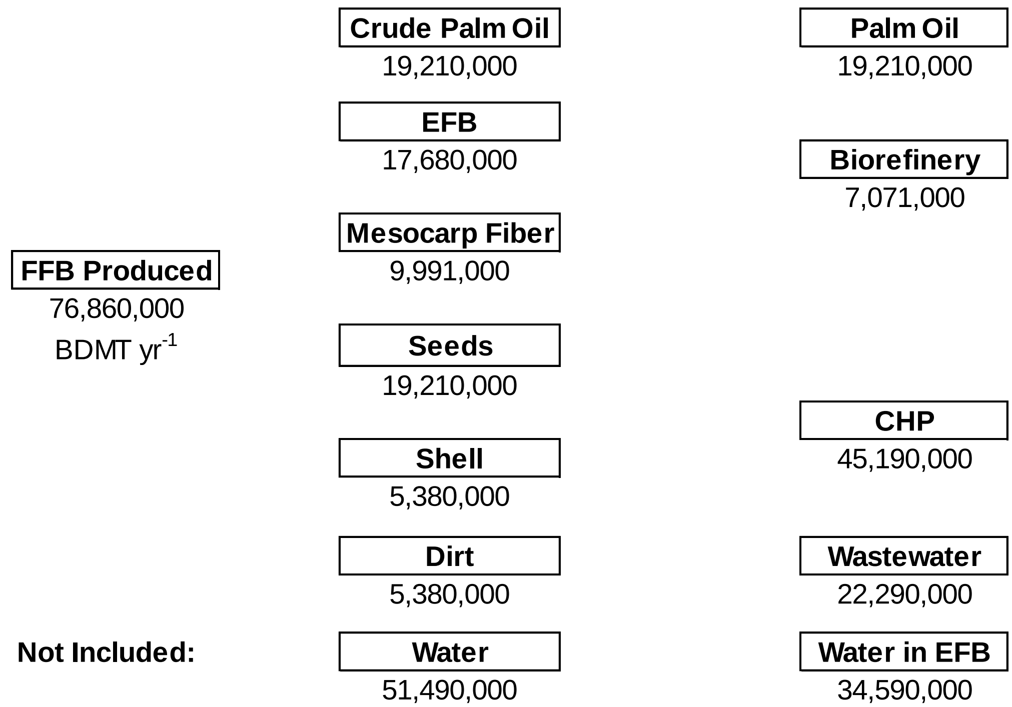

Fig. 1. Estimated annual available quantity of EFB, in metric tonnes per year for a bio-sugar platform in Malaysia (MPOB 2014)

Using a mass balance for an average palm oil mill, the quantity of available EFB after diversion for CHP is approximately 7,071,044 tonnes per year, or 14 biorefineries for bio-sugar production at the 500,000 bone dry metric tonnes (BDMT) yr^{-1} scale. There were approximately 416 existing CPO mills in Malaysia as of 2009 (Razak 2010; Chin *et al.* 2013) and current estimates are between 400 and 500 (UNDP 2011; Abdullah and Sulaiman 2013; Gahab 2013; Rasid *et al.* 2013; Hansen and Nygaard 2014; MPOB 2014).

The goal of this study was to identify the environmental life cycle burdens associated with the supply of EFB biomass to a biorefinery, to calculate the delivered cost, and to identify the current national availability of EFB biomass in Malaysia and resulting potential for bio-based monomeric sugar production. The scope of the LCA includes primary flow data, energy usage, and transportation impacts across the full cradle-to-gate life cycle. Thus, a supply chain model was developed to calculate the inputs and outputs to the EFB production life cycle. A life cycle inventory (LCI) was then used to conduct an attributional LCA and, based upon the valuation of various cost drivers, the delivered cost was calculated as delivered at three production scales to a biorefinery. Allocation methodologies and sensitivity analyses were conducted to identify and account for uncertainty in the analysis. This study provides pertinent, objective, and actionable logistical, financial, and environmental data for commercial-scale biomass collection and delivery to biorefineries in Malaysia.

METHODS

Goal and Scope

The goal of this research is to identify the technical feasibility as well as environmental and human health impacts of EFB biomass production and supply for a bio-sugar platform (biorefinery) requiring 500,000 OD metric tonnes of biomass in Malaysia. Additional production scales analyzed include 250,000 OD metric tonnes yr^{-1} and 750,000 OD metric tonnes yr^{-1}. The biorefinery is assumed to be centrally located among the palm oil extraction facilities by which it is being fed. The procedure is consistent with other studies on biomass supply chains already published (Gonzalez 2011; Gonzalez *et al.* 2011a,b, 2012; Daystar *et al.* 2014).

This research includes identifying logistical and technical barriers associated with the biomass supply chain, the land-use change and environmental impact of the biomass life cycle, the availability of the biomass, and the conducting of a LCA and sensitivity analysis for the biomass. This research combines project-scale financial analysis and projection, a biomass availability survey, supply chain logistics analysis, and LCA of the environmental impacts of the biomasses that industry will find relevant and valuable in establishing a consistent use for EFB.

The scope of this study includes the establishment and growth of a palm oil plantation, harvesting and transport of FFB to a palm oil mill, and processing and delivery of EFB to a biorefinery. Figure 1 shows the system boundary and major inputs and outputs to the system. In all scenarios the EFB delivery processes from CPO facility to biorefinery are fully attributed to the EFB product. In all scenarios, the palm oil extraction process and the drying are not considered within the boundary of the EFB product process since the main goal of these processes is to produce the oil.

According to the International Organization for Standardization standards related to LCA (ISO 14044), it is preferable to first use system expansion for dealing with co-products or by-products, and if system expansion is not possible, only then can allocation methods such as mass allocation or economic allocation be used. For the systems analyzed during this study, system expansion was not ideal because the co-produced EFB is not produced in any other manner and therefore there is not a comparable life cycle system against which to compare for the system expansion method. Thus, several scenarios for allocation of the environmental and human health burdens for the FFB production to the EFB co-product were evaluated, as follows:

1. No Burden Scenario – allocates 0% of the burdens from the production of FFB to EFB co-product, considering EFB a waste stream of the palm oil extraction process.

2. Mass Allocated Burden Scenario – allocates the burden from FFB production to EFB co-product based upon the mass of EFB (available to biorefinery) to EFB plus CPO, which is 26.9%. See Eq. 1:

$$Mass\ Allocation = \frac{EFB\ to\ biorefinery * 100\ \%}{EFB\ to\ biorefinery + CPO} \tag{1}$$

3. Economically Allocated Burden Scenario – allocates the burdens from FFB production to EFB (available to biorefinery) based upon the economic value of EFB

produced to the economic value of EFB plus CPO produced, which is 1.67%. See Eq. 2:

$$Economic\ Allocation\ = \frac{(\$\ EFB*EFB\ to\ biorefinery)*100\%}{(\$\ EFB*EFB\ to\ biorefinery)+(\$\ CPO*CPO)} \qquad (2)$$

4. Full Burden Scenario – considers all life cycle stages for the production of FFB and allocates 100% of all burdens to EFB. This is a scenario that explains what the maximum effect of capturing EFB could be, with the extremely conservative assumption that there is no other co-product of interest. It is not currently valid but is used as a comparison to other allocations scenarios.

It is important to note that the carbon sequestered in plant growth that ends up in EFB going to a biorefinery is not allocated but is assigned fully to the EFB to the biorefinery, consistent with our previous treatments for residual biomasses (Daystar *et al.* 2014).

The *functional unit* for this study is 1 BDMT of EFB at 45% moisture content delivered to a biorefinery. Additional functional units for analysis include: 1 metric tonne of carbohydrates delivered as 1.25 BDMT of EFB at 45% moisture content delivered to a biorefinery and 1 hectare of oil palm plantation managed for FFB production over one year. The system boundary for this study includes the seedling operations, oil palm plantation establishment and maintenance, FFB harvest and transport, EFB loading, and transport to the biorefinery (Figure 2).

The CPO extraction process, combustion of EFB, fiber and shells for CHP, and palm oil mill effluent (POME) treatment are not included in the system boundary because these processes are solely attributable to the CPO co-product.

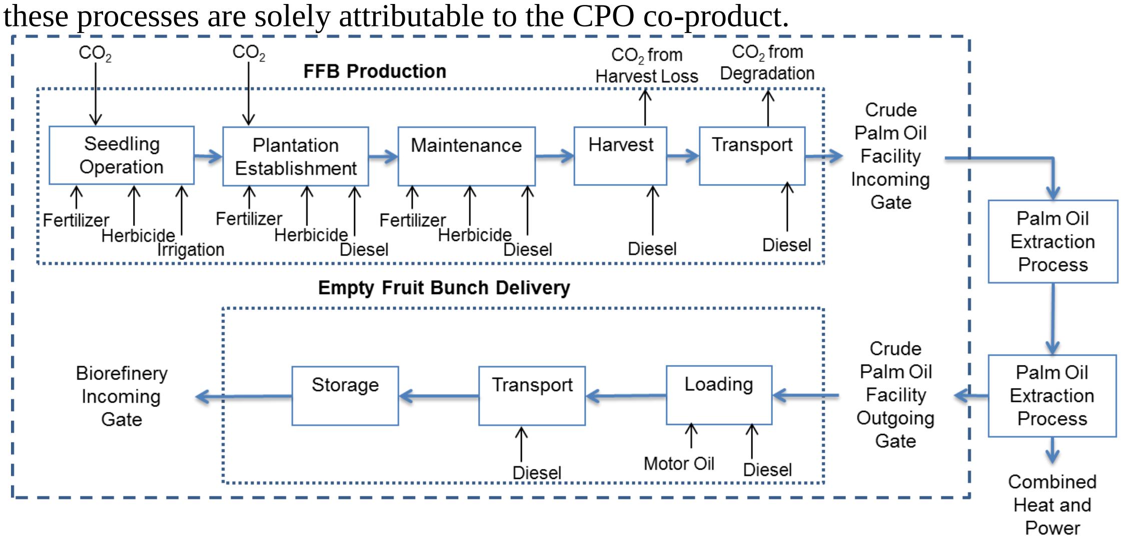

Fig. 2. Life cycle stages and major inputs and outputs for the palm oil FFB and EFB production and delivery systems

Supply Chain Analysis

Supply chain models to track input and output flows were created using Excel® (Microsoft Inc., Redmond, CA) spreadsheets to track the flow of carbon, carbohydrates, mass and energy, fertilizers, herbicides, pesticides, fuel, irrigation water, land use for plantations, and waste streams through the biomass production system. Data surrounding the agricultural practices used for oil palm tree plantation management were collected from the literature (de Vries *et al.* 2010; Halimah *et al.* 2010) and were used to model the life cycle activities for plantation establishment, plantation maintenance, FFB harvest, FFB transportation, EFB storage, loading and transport of the primary biomass to the biorefinery.

A detailed supply system model was created in order to use process data to develop an LCI of primary emissions and upstream/downstream emissions. Baseline values for biomass delivery (in bone-dry metric tonnes [BDMT]) were established for each supply model, including 250,000 BDMT yr^{-1}, 500,000 BDMT yr^{-1}, and 750,000 BDMT yr^{-1}. Through literature review (Ismail *et al.* 2003; Pleanjai *et al.* 2007), yield, moisture content, chemical composition, ultimate and proximate composition, and other biomass characteristics were input to the model to back-calculate the green metric tonne (GMT) harvest rate, necessary land use, and maximum transportation distance as a function of covered area and rotation length.

Covered area is defined here as the percentage of total collection area covered by biomass plantation growth, and rotation length is the number of years between plantation establishment and harvest. Also from the literature, chemical usage and waste data including fertilizers, herbicides, pesticides, fungicides, transportation fuel, lime, irrigation water, and degradation during storage were calculated per hectare and per tonne of FFB harvested and transported to the palm oil processing facility. Based upon a 0.33 seedling tonne FFB^{-1} transplantation rate, a seedling production rate of 196 seedlings $hectare^{-1}$ was calculated (Choo *et al.* 2011).

Life Cycle Assessment

The process data were calculated using the supply chain model results and were subsequently used to generate an LCI (processes used are listed in Appendix 1). An attributional LCA of environmental and human health mid-point impacts was conducted using openLCA (GreenDelta GmbH, Berlin, Germany).

Within this calculation framework, Ecoinvent v2.2 life cycle inventory data (SCLCI 2012) and the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI, Bare *et al*. 2002) impact assessment method were used to complete the LCIA. TRACI was used in an effort to make consistent comparisons with previous biomass feedstock LCA studies. LCIA data are presented as raw mid-point impacts for each allocation scenario. Impact categories include global warming impact (GW), acidification (AC), eutrophication (EU), ecotoxicity (EC), ozone depletion (OZ), photochemical oxidation (PO), carcinogenics (CA), non-carcinogenics (NC), and respiratory effects (RE).

Land use change

It was of interest to understand whether direct land use changes from the average current national land cover to oil palm plantations would significantly alter the GHG results for the EFB product to the biorefinery. The amount of land to convert was calculated based on data for the land productivity for FFB and yield of excess EFB from the palm oil extraction process.

The expected environmental impact (for greenhouse gas emissions) due to conversion of land currently covered by the national land use average to plantation forestry and intensive agriculture was calculated using emission factors from land change developed by the Inter-governmental Panel on Climate Change (Barker *et al.* 2007; IPCC 2007) and Wicke *et al.* (2008b). Many previous studies have assumed no land use change explicitly (Stichnothe and Schuchardt 2010) or have neglected to consider the impacts of land use change completely (Wood and Corley 1991; Yusoff and Hansen 2007; Pleanjai and Gheewala 2009; Yee *et al.* 2009; de Souza *et al.* 2010; de Vries *et al.* 2010; Hamilah *et al.* 2010; Tan *et al.* 2010; Zulkifli *et al.* 2010; Arvidsson *et al.* 2011; Choo *et al.* 2011; Chiew and Shimada 2013; Manik and Halog 2013; Rasid *et al.* 2013).

It should be noted that land use change for new oil palm plantations in Malaysia is thought to contribute to the reduction of biodiversity in Malaysia. New plantations being established are frequently established on drained peat land and in previously natural areas. While this study does not include further discussion about impacts to biodiversity caused by EFB supply, future studies should include quantitative measures of this.

An example calculation of land use change and the resulting GHG impact from LUC is shown in Appendix 2.

Delivered Cost

The delivered cost was calculated by summing EFB market price values from the literature, the calculated cost of loading the EFB into the transport trucks, and the cost of transporting EFB to the biorefinery for various biorefinery scales and transportation distances. Delivered cost was calculated and is presented as US$ BDMT^{-1}.

RESULTS AND DISCUSSION

Transportation Modeling

Transportation occurs (1) for FFB from harvest field to the palm oil extraction facility (assumed herein to be 50 km; Choo *et al.* 2011) and (2) for EFB from the extraction facility to the biorefinery. The total average transportation distance from the extraction facility to the biorefinery is modeled using Eq. 3,

$$T = 1.31 * \sqrt{\frac{a*0.01}{20.7 * 0.092 *b}} \tag{3}$$

where T is the average one-way transportation distance between the CPO mill and biorefinery in km, a is BDMT yr^{-1} to the biorefinery, b is the fractional covered area, and 0.01 km^2 ha^{-1} is a conversion factor. The radius of collection is estimated based upon a land productivity of 20.7 tonnes FFB ha^{-1} yr^{-1}, an EFB yield of 9.2 weight percent of EFB in FFB tonnes EFB tonne FFB^{-1} harvested, and a tortuosity factor of 1.31 tortuous km per actual km (Ravula 2007). Fractional covered area was estimated at 70% for the baseline case. Koh *et al.* (2011) have shown a clustering of plantation lands in the coastal parts of Malaysia, leading to more intensively managed oil palm plantations. Thus, sensitivity analysis was conducted around the covered area assumption, for which Low, Medium, and High covered area scenarios were generated, and for which covered area was assumed to be 50, 70, and 90%, respectively. The calculated one way trip distances were 95, 80, and 71 km, respectively. The round trip transportation distance for the delivery of EFB to the biorefinery increases with the square root of the size of the biorefinery and scales as the inverse of the square root (decreases) with an increased palm oil plantation covered area.

Mass Balance around a Palm Oil Extraction Facility

A mass balance of the average palm oil extraction facility based on literature values (Basiron and Weng 2004; Yusoff 2006; Zulkifli *et al.* 2010; Chiew *et al.* 2011; Choo *et al.* 2011; Chiew and Shimada 2013) showed that only 9.2% of the FFB, by mass, was available on a bone dry basis of EFB for sale to a biorefinery.

About 60% of the EFB collected at palm oil extraction facilities is used for CHP, and the balance of 40% is available for a biorefinery. This value was estimated by determining the total energy needs at a CPO extraction mill and diverting the appropriate amount of EFB at 45% MC (higher heating value = 19 MJ kg^{-1}) to the CHP to generate the heat and power needed (Chow *et al.* 2008; Abdullah *et al.* 2011; Hassan *et al.* 2011; Griffin *et al.* 2014). All EFB is dried to 45% MC, even the material not ultimately used in CHP. While this sounds inefficient, in actual operations a large stockpile of dried EFB is kept in order to support operations. The average biomass composition in Table 1 is used for this study. The EFB in the woodyard degrades during storage, resulting in a 5% weight loss, which is also assumed in this study. The flows in the mass balance agree reasonably well with reported literature values of actual mills, shown in Table 2. The mass balance (Figure 3) used herein shows that 25% of the mass of FFB becomes CPO, whereas the value is 20% from Table 2, though the scale of CPO facility surveyed by Vijaya *et al.* (2008) was lower and the technology older than modeled for this study. Additionally, the mass balance calculates a fiber production rate of 13%, whereas the survey by Vijaya *et al.* (2008) resulted in 10.4% fiber production.

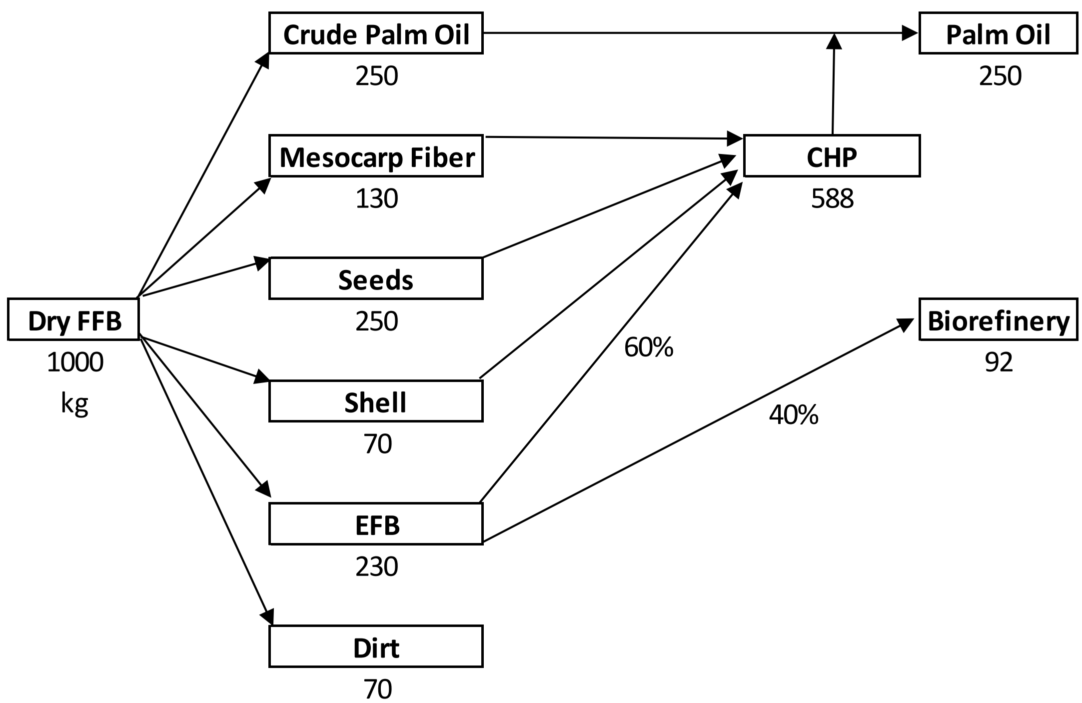

Fig. 3. A mass balance for the crude palm oil extraction process in Malaysia whereby EFB is co-produced as a waste product and utilized to some extent for combined heat and power (CHP). EFB to the biorefinery currently is either land applied, composted, or disposed. Numbers beneath each block of the mass flow diagram represent the mass (in kg) of each component.

Table 2. Malaysian CPO Extraction Mill Average *per* Metric Tonne of CPO Produced

	Average Value MT CPO produced^{-1}	Standard Deviation
FFB (t)	5.08	± 0.314
CHP energy (kWh)	102	± 6.24
Grid energy(kWh)	0.623	± 1.05
Fiber (t)	0.530	± 0.063
Mesocarp Shell (t)	0.162	± 0.087
Boiler water (l)	2.73	± 0.499
Steam to Sterilization (t)	2.62	± 0.366
Steam to Turbine (t)	2.72	± 0.498
Water consumption (t)	3.24	± 0.797

Source: Vijaya *et al.* 2008; Based upon calculated values from 12 operating palm oil extraction facilities in Malaysia.

Life Cycle Inventory

The EFB supply chain model and life cycle data from Ecoinvent v2.2 were used to develop an LCI (modelled processes listed in Appendix 1). The LCI outlines the chemical, energy, fuel, and other inputs to the FFB production system, which was used for the co-product allocation scenario during the life cycle impact assessment (LCIA).

Process data

Values to populate the supply system models were collected from the literature. Table 3 includes data used in the model for the palm oil plantation. Baseline assumptions about the empty fruit bunch loading and delivery system from the CPO extraction facility to the biorefinery include a 500,000 BDMT yr^{-1} delivery rate, a medium-sized CPO extraction facility, 70% covered area, and 60% EFB diversion to CHP (Table 4).

Table 3. Typical Data for a Malaysian Palm Oil Plantation that Produces FFB

Input/Output	**Value**	**Units**
Seeds	196	Seeds ha^{-1}
Seedlings	173	Seedlings ha^{-1}
Trees	150	Trees ha^{-1}
Fertilizers		
Nitrogen	69.1	kg ha^{-1} yr^{-1}
Phosphorus	55.4	kg ha^{-1} yr^{-1}
Potassium	228	kg ha^{-1} yr^{-1}
Magnesium	12.1	kg ha^{-1} yr^{-1}
Urea	8.12	kg ha^{-1} yr^{-1}
Irrigation	5720	L ha^{-1} yr^{-1}
Herbicides		
Glyphosate	6.69	kg ha^{-1} yr^{-1}
2,4-D	6.40E-01	kg ha^{-1} yr^{-1}
Thiocarbamate	2.00E-03	kg ha^{-1} yr^{-1}
Paraquat	1.79	kg ha^{-1} yr^{-1}
Bipyridylium	2.15	kg ha^{-1} yr^{-1}
Fungicide		
Dithiocarbamate	1.90E-02	kg ha^{-1} yr^{-1}
Pesticide		
Pyrethroid	4.30E-01	kg ha^{-1} yr^{-1}
Organophosphate	1.27	kg ha^{-1} yr^{-1}
Unspecified Pesticide	41.3	kg ha^{-1} yr^{-1}
Fuel and Energy		
Transport Diesel	994	L ha^{-1} yr^{-1}
Motor Oil	11.3	L truck^{-1} yr^{-1}
Ag machinery diesel usage	49.1	L ha^{-1} yr^{-1}
Electricity	2.26	kWh ha^{-1}
Transportation		
Diesel truck (<3.5 tonnes)	518	tonnes*km
FFB Harvested	20.7	tonnes ha^{-1} yr^{-1}

Sources: Chiew *et al.* 2011; Choo *et al.* 2011; Chiew and Shimada 2013

A project term of 25 years was used (2012-2037), assuming that year 1 of the study is the seedling nursery operation, years 2 to 3 are plantation growth with no harvest, years 4 to 23 are plantation growth, regular harvest and plantation maintenance years, and years 24 to 25 are plantation growth and harvest without any maintenance such as fertilization or pest management (Syahrinuddin 2005; Zulkifli *et al.* 2010; Chiew *et al.* 2011; Chiew and Shimado 2013). All oil palms on the plantation are cut down at the end of year 25. Thus, a 25 year rotation length was assumed for oil palm trees (Yusoff 2006; Wicke *et al.* 2008a).

Table 4. Assumptions about the Empty Fruit Bunch Loading and Delivery System from the CPO Extraction Facility to the Biorefinery, Assuming 500,000 BDMT *per* Year Delivered, a Medium-Sized CPO Extraction Facility, and 60% EFB Diversion to CHP

Parameter	Value	Units
EFB delivery quantity	500,000	BDMT yr^{-1}
CPO mills necessary	30	mills yr^{-1}
Planted area necessary	722,200	Hectares
CPO mill up-time	350	days yr^{-1}
EFB produced per CPO mill	20,421	tonnes $mill^{-1}$ yr^{-1}
EFB moisture content	45	%
Dry EFB Produced per CPO mill	16,669	BDMT yr^{-1} $mill^{-1}$
FFB to EFB	23	%
EFB to CHP	60	%
EFB to Biorefinery	40	%
Loader operating time	16	hrs day^{-1}
Operator raw rate	15.9	US$ hr^{-1}
Lorry biomass capacity	20	tonnes
Average FFB collection radius	25	km
Distance between CPO mills	50	km
Distance (one-way) to biorefinery	80	km
Tortuosity factor	1.31	tortuous km direct km^{-1}

Sources: Ravula 2007; Corley and Tinker 2008; Begum *et al.* 2009; Stichnothe and Schuchardt 2010; Zulkifli *et al.* 2010.

Life Cycle Impact Assessment

The environmental and human health (net life cycle and stage-wise) burdens were calculated in the openLCA calculation framework using Ecoinvent v2.2 life cycle data, process data from the EFB supply chain model, and the TRACI impact assessment method. Appendix 1 lists the modules used in openLCA to model the LCI. Nine impact categories from the TRACI method were used, including: GW, AC, EU, EC, OZ, PO, CA, NC, and RE. These mid-point impacts can be grouped roughly into two major impact groups: environmental burdens and human health burdens. It is important to consider all of these impacts and not focus only on GW. These human health and environmental burdens were calculated for the four allocation scenarios and appear in Table 5.

Mass allocation of the FFB burdens (26.9%) is the central allocation assumption used throughout this study, in agreement ISO methods (Table 5). The GW impacts from using mass allocation shows a -1474 kg CO_2 BDMT of EFB^{-1} to the refinery, which indicates that the net carbon uptake from plant growth allocated to the EFB to the refinery is greater than all the allocated net burdens of producing and shipping the EFB to the refinery gate. Land use change is not considered here but is calculated and discussed later in the paper.

Table 5. Results of the LCA for the Four Allocation Scenarios *per* BDMT of EFB to Biorefinery

Impact Category	Units	No Burden	Economic Allocation	Mass Allocation	Full Burden
GW	kg CO_2-eq	-1629	-1619	-1474	-1029
AC	moles of H^+-eq	6.9	8.4	28	86
EU	kg N-eq	1.0E-02	1.2E-02	0.05	0.14
EC	kg 2,4-D-eq	2.7	3.8	18	59
OZ	kg CFC-11-eq	2.5E-06	4.2E-06	2.7E-05	9.4E-05
PO	kg NO_x-eq	1.5E-01	1.8E-01	5.7E-01	1.7
CA	kg benzene-eq	1.2E-02	1.6E-02	7.3E-02	2.4E-01
NC	kg toluene-eq	54	74	354	1171
RE	kg $PM_{2.5}$-eq	1.6E-02	2.0E-02	7.3E-02	2.3E-01

Mass allocation assigns 26.9% and economic allocation assigns 1.67% of the FFB production burdens to the EFB to the biorefinery. Carbon sequestered in plant growth corresponding to EFB sent to a biorefinery is assigned fully to the EFB to the biorefinery (Daystar *et al.* 2014).

Whereas the No Burden, Economic Allocation, and Mass Allocation scenarios can be considered reasonable allocation of FFB production burdens, the Full Burden scenario cannot, as it unfairly allocates all FFB production burdens to a waste stream. Thus, the Full Burden scenario is not included in Figure 4, where the impacts of each allocation scenario are shown, normalized to 100% of the greatest impact for each impact category.

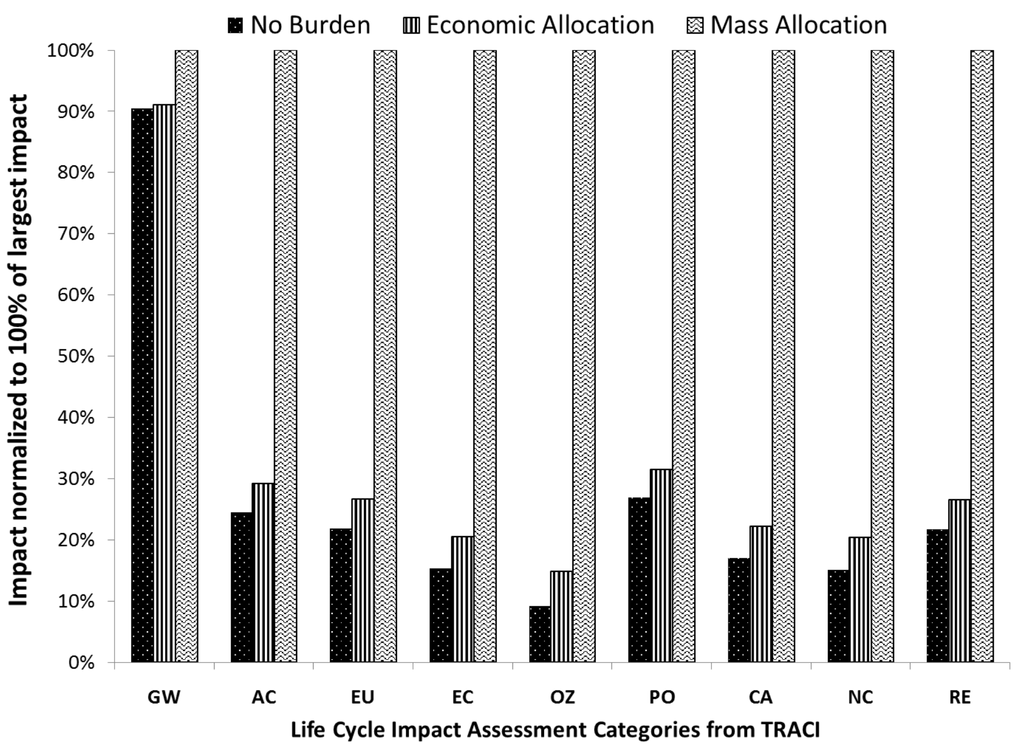

Fig. 4. Impacts using TRACI for the three allocation scenarios normalized to 100% of the largest impact for each impact category, assuming 500,000 BDMT year^{-1} delivered to a biorefinery from a medium-sized CPO extraction facility in Malaysia. Mass allocation assigns 26.9% and economic allocation assigns 1.67% of the FFB production to the EFB to the biorefinery. GW = global warming impact; AC = acidification; EU = eutrophication; EC = ecotoxicity; OZ = ozone depletion; PO = photochemical oxidation; CA = carcinogenics; NC = non-carcinogenics; RE = respiratory effects. Note: y-axis break alters the perceived scale of GW for the Mass Allocation scenario.

It is also interesting to compare the net and stage-wise GW impacts for other various functional groups including kg CO_2-eq ha^{-1} yr^{-1} and kg CO_2-eq MT^{-1} carbohydrates, which may be more pertinent to the FFB plantation owner or the bio-sugar platform owner, respectively (Table 6). Direct land use change (LUC) burdens were also included and were calculated for the three functional units using the Forest Industry Carbon Assessment Tool (FICAT). These calculations assumed that tropical forests were converted to intensively managed forest land in the tropics (herein, considered palm plantation). Also in Table 6 are literature GHG emission values changing land use in Malaysia from *peatland* to intensively managed oil palm plantation land (Khalid *et al.* 2000; Harsono *et al.* 2012; NCASI 2012; Rasid *et al.* 2013), a drastically different practice shown as a potential worst case scenario for comparison.

Table 6. The GHG for Cradle-to-Gate FFB Production by Life Cycle Stage by Mass Allocation Method

Life Cycle Stage	**GHG Emissions (kg CO_2-eq. ha^{-1} yr^{-1})**	**GHG Emissions (kg CO_2-eq. $BDMT^{-1}$ EFB)**	**GHG Emissions (kg CO_2-eq. MT $carbs^{-1}$)**
Establishment	0.22	0.14	0.18
Biomass Growth	-2625	-1650	-2200
Maintenance	206	130	173
Harvest	45.0	28.3	37.7
FFB Transportation	1.78	1.12	1.49
EFB Loading	2.10	1.32	1.76
EFB Transportation	24.4	15.3	20.4
Subtotal	-2346	-1474	-1965
LUC from FICAT	5.5	3.5	4.6
LUC Harsono *et al*. 2012	212	133	178
LUC Rasid *et al.* 2013	340	214	285
Total (Including LUC from FICAT)	-2340	-1471	-1961

Conversion factors are 0.63 BDMT EFB ha^{-1} yr^{-1} and 1.33 BDMT EFB MT $carbs^{-1}$.

Net GHG emissions are dominated by biomass growth with significant contributions from maintenance of the oil palm plantation, the harvest of the FFB and the transportation of the EFB. It is shown that the GHG emissions from LUC calculated using the FICAT model represent less than 2% of the total emissions, not including CO_2 uptake during biomass growth. Note that there is a significant difference in LUC values between our result based on preferable land conversion practices and the LUC values from Harsono *et al.* (2012) and Rasid *et al.* (2013) which reflect, at least in part, the practice of peatland conversion for oil palm plantations.

Hassan *et al.* (2011) suggested that failing to allocate for co-production (of CPO and EFB) results in only a slight overestimation of net burdens for the primary product of study, which is clearly not the case as the allocation of burdens on a mass basis in the present study relative to no burdens or economic allocation is significantly different.

A comparison of the GHG burdens of FFB production, not including plant carbon uptake, versus other studies is shown in Table 7. As an order-of-magnitude test, this comparison shows that the results of the study herein (yield adjusted) fall within the range of previous literature for the production of CPO and co-production of EFB in Malaysia. There is a significant spread in the data. It appears that several lower GHG burdens have been reported in recent times. These results are expected to be different because of differing FFB yield assumptions, oil palm plantation practices, land cover assumptions, and LCA methods. Thus, the exact magnitude of GHG emissions should be used with considerable caution.

It is clear from this comparison against previous literature that the net cradle-to-CPO facility gate GHG emissions are lower for this study than reported literature values. There is also not, as might be expected with increases in production efficiency, yield, or calculation accuracy, a correlative decrease in net GHGs or increase in yield with an increase in publication year.

Table 7. The Life Cycle Stage-Specific GHG Burdens (kg CO_2 –Eq. Ha^{-1} $Year^{-1}$) for this Study Compared against Previous LCA Studies of FFB Production in Malaysia

Authors	Year	GHG CO_2-eq. ha^{-1} yr^{-1}	Yield (MT FFB ha^{-1} yr^{-1})	Yield Adjusted GHGs (kg CO_2-eq. BDMT FFB^{-1})
Wood and Corley	1991	1268	19	66.7
Yusoff and Hansen	2007	2160	19	113.7
Wicke *et al.**	2008	3312	25	132.5
Yee *et al.*	2009	2659	19	139.9
Pleanjai and Gheewala	2009	3784	17	222.6
de Souza *et al.*	2010	1437	20	70.6
Hassan *et al.*	2011	4000	19	210.5
Choo *et al.*	2011	2463	21	119.0
Harsono *et al.*	2012	1436	23	63.8
Kaewmai *et al.*	2013	2213	21	105.4
Rasid *et al.*	2013	1560	88**	17.7
This study	2014	981	21	47.4

Yield is included to facilitate yield-equivalent comparison. Carbon capture during plant growth is not included in this data. *Wicke *et al.* 2008b **Rasid *et al.* referred to Chiew and Shimada (2013) for yield, who did not provide a yield value.

It is also of interest to compare the relative environmental and human health impacts of EFB as compared to other biomass feedstocks using a standardized methodology. Table 8 compares EFB to several North American biomasses studied in a consistent manner (Daystar *et al.* 2014). The GW impact, though a net negative impact for the cradle-to-gate study scope, is greater for EFB than for all other biomasses considered except for sweet sorghum, largely due to a higher burden from plantation maintenance and harvest. For most other burdens, including EU, AC, OZ, PO, and NC, EFB is approximately equivalent with the other woody biomass feedstocks and lower than that of agricultural feedstocks. For EC, CA and RE, EFB is higher than other woody feedstocks but equivalent to or lower than the agricultural feedstocks.

Table 8. Comparison of EFB Cradle-to-Gate Environmental and Human Health Impacts *per* BDMT against Feedstocks from Daystar *et al.* (2014), Assuming 500,000 BDMT yr^{-1} Delivered to a Biorefinery, using Ecoinvent v2.2 Data, Mass Allocation and the TRACI Impact Assessment Method (Bare *et al.* 2002; Bare *et al.* 2003)

Impact Category	Units	Empty Fruit Bunch	Loblolly Pine	Eucalyptus	Unmanaged Hardwood	Forest Residues	Switchgrass	Sweet Sorghum
GW	kg CO_2-eq	-1474	-1833	-1753	-1797	-1793	-1517	-1423
AC	mol of H+-eq	28	24	28	27	24	45	25
EU	kg N	4.6E-02	3.0E-02	4.0E-02	3.0E-02	2.0E-02	4.8E-01	4.3E-01
EC	kg 2,4-D-eq	18	13	16	1	9	21	13
OZ	kg CFC-11-eq	2.7E-05	1.29E-03	1.86E-03	4.30E-07	1.78E-07	9.62E-03	5.36E-03
PO	kg NO_x-eq	5.7e-01	5.4E-01	6.1E-01	6.1E-01	5.3E-01	6.2E-01	3.6E-01
CA	kg benzene-eq	7.3E-02	3.0E-02	4.0E-02	2.0E-02	2.0E-02	1.1E-01	6.0E-02
NC	kg toluene-eq	354	359	432	351	323	1105	8700
RE	kg $PM_{2.5}$-eq	7.3E-02	3.0E-02	4.0E-02	3.0E-02	3.0E-02	1.2E-01	6.0E-02

Sensitivity Analysis

Sensitivity analysis was conducted for several supply chain and CPO operations assumptions. Figure 5 provides a sensitivity plot for the change in net GHG burdens as some sensitivity factors are changed. From these sensitivity analyses, it is possible to see that the assumption about carbon sequestration by EFB during FFB growth has the largest positively-correlated impact on the net GHG emissions per BDMT of EFB biomass to the biorefinery. GHG emission accounting was less sensitive to the assumptions about mass allocation procedure and, importantly, biorefinery size. This is important because there may be trade-offs for higher capacity biorefineries between lower GHG emissions and improved financial returns (due to a well-established economic advantage to larger scale biorefineries).

Alternatively, analysis of the sensitivity of the net GHG calculation to the assumption that the percent plantation covered area value in Malaysia is 70% shows a negatively correlated impact to GHG emissions. This is due to a lower transportation distance and an assumed increase of CPO facility proximities with higher plantation covered area.

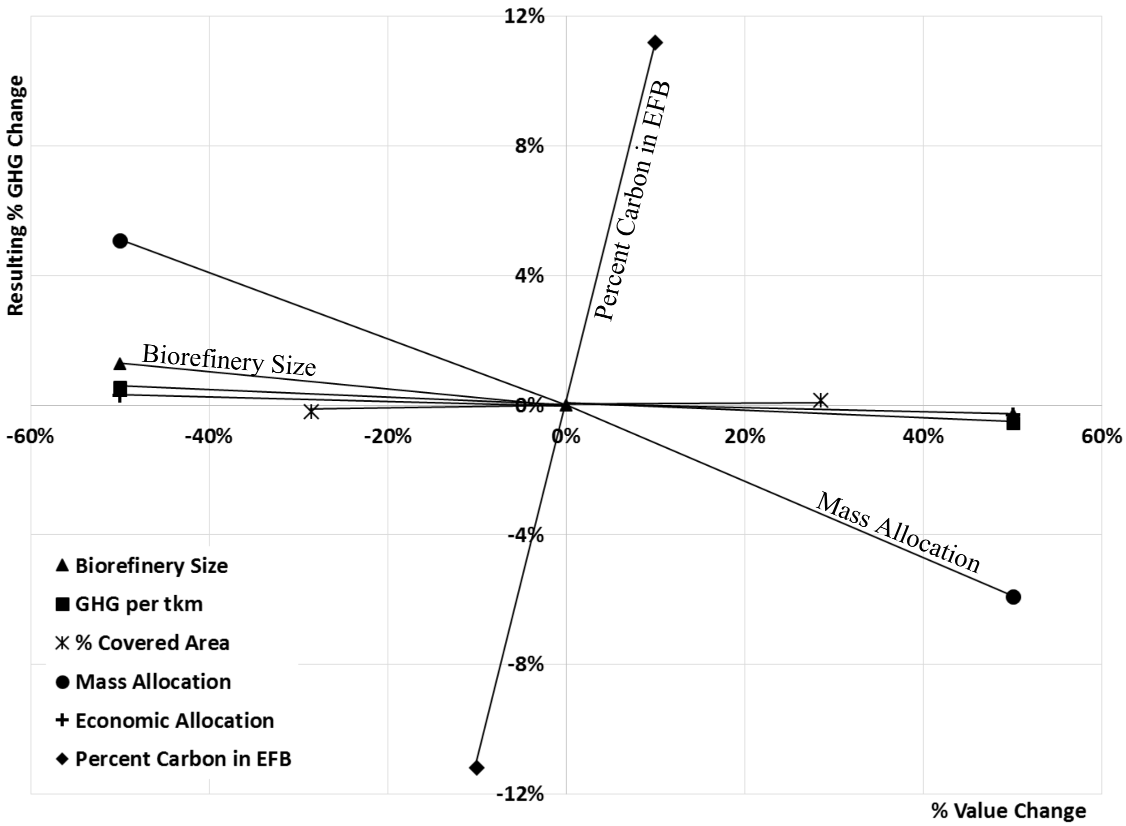

Fig. 5. The sensitivity of net GHG burdens (kg CO_2 –eq. BDMT^{-1}) to changes in major study assumptions

GHG burdens are most sensitive to the assumption surrounding the carbon sequestered during growth of the biomass. A ± 50% sensitivity analysis for the mass allocation ratio (basepoint 26.9%) and ± 25% for the economic allocation ratio (basepoint 1.67%) resulted in a ±5% and ±0.03% impact to net GHGs, respectively. It is clear that the GHG value is sensitive to the mass allocation procedure, but not as sensitive to the economic allocation procedure. Changing the transportation emissions per tkm ± 50% had little impact on net GHGs. Factors to which the net GHG burdens were relatively insensitive included (data not shown): (1) % of EFB to CHP in the CPO facility, (2) composition of the EFB, (3) transport truck size, (4) degradation due to storage time, (5) FFB moisture content, and (6) FFB to EFB yield.

Delivered Cost

Delivered cost of EFB to the biorefinery included the sales price of the EFB, the loading costs, and the transportation cost. The EFB sales price of $12.02 BDMT^{-1} was determined as the average price per kilogram of $0.000 (Lange and Pellegrini 2013), $0.006 (Chiew *et al.* 2011), $0.007 (Tay *et al.* 2011), $0.022 (Begum *et al.* 2009), and $0.022 (Harsono *et al.* 2013), and then adjusted for inflation to base-year 2014 dollars (Table 9). The oil palm seedling operations, oil palm tree plantation establishment and maintenance, transportation of the FFB and palm oil extraction activities were not included in the cost calculation of the delivered EFB since those costs are either accounted for in the purchase price or are allocated to the palm oil and not the waste EFB stream. The loading cost of EFB was calculated using industry-average rental rates and agricultural worker raw wage rates for Malaysia (Table 10). The loading costs are reported on a per BDMT basis, a value which scales linearly with biorefinery size. Thus, the loading costs were not listed for the other biorefinery sizes (250,000 and 750,000 BDMT yr^{-1}).

Table 9. Literature Values of Purchase Prices of EFB Biomass

EFB $/kg		EFB Price Sources
$	0.0242	Begum *et al.* 2009
$	0.0061	Chiew *et al.* 2011
$	0.0077	Tay *et al.* 2011
$	0.0000	Lange and Pellegrini 2013
$	0.0222	Harsono *et al.* 2013
$	0.012	Average
$	12.02	per tonne

Table 10. Cost of Loading EFB Biomass into a 20-Tonne Truck at the CPO Extraction Facility

		500,000 BDMT yr^{-1}
Labor		
	Palm Oil Extraction Facilities	30
	Number of Loader Operators	30
	Labor Cost (US $/hr)	$15.90
	Total Labor Cost per year (US $)	$2,671,200
Materials		
	Loaders per year	30
	Hours operated per loader per year	5,600
	Loader Cost (US $/day)	$6.63
	Total Loader Cost per year (US $)	$69,615
	Loading cost US$ $BDMT^{-1}$ EFB	$5.48

It is assumed that 40% of the cost for loading is allocated to EFB to a biorefinery, whereas 60% of the cost of handling EFB is involved with EFB being fed to the CHP process within the CPO extraction facility.

Following the loading of the EFB into the 20 tonne truck, it is transported from the CPO extraction facility to the biorefinery. The transportation distance was calculated (Table 11) for three different covered area value assumptions and the transport distance (round-way) for 70% covered area (assuming highly intensive plantation growth of oil palm trees). This methodology is similar to that used by other recent biomass supply studies by the same authors (Gonzalez 2011; Daystar *et al.* 2012, 2013, 2014). A tortuosity factor of 1.31 was assumed (Ravula 2007). EFB transport costs were calculated using a standard industry value for transport costs in Malaysia of $0.1737 $t{*}km^{-1}$. Hassan (2012) suggested a range of $0.1114 to $0.23 $t{*}km^{-1}$. A joint report commissioned by the Malaysian and Danish governments (Eco-Ideal Consulting and Mensilin Holdings 2006) reported an industry average transport cost of $0.26 $t{*}km^{-1}$ (using a 3.24 RM:USD April 2014 exchange rate and a 2.28% inflation rate). The required area, total transport distance, tortuous transport distance, and total delivered cost for each biorefinery scale and covered area assumption can be found in Table 12.

Table 11. Transport Distance (Round-Trip), Required Area, and Total Delivered Cost per Bone Dry Metric Tonne using Three Different Covered Area Assumptions across Three Biorefinery Scales

	Biorefinery Scale (BDMT yr^{-1})			
Covered Area	**250,000**	**500,000**	**750,000**	**Units**
50%	2625	5251	7876	Collection area (km^2)
	102	145	177	Direct km
	134	190	233	Tortuous km
	$40.83	$50.49	$57.90	Delivered cost (USD)
70%	1875	3751	5626	Collection area (km^2)
	87	122	150	Direct km
	113	160	197	Tortuous km
	$37.21	$45.38	$51.64	Delivered cost (USD)
90%	1459	2917	4376	Collection area (km^2)
	76	108	132	Direct km
	100	142	173	Tortuous km
	$34.89	$42.09	$47.61	Delivered cost (USD)

While there is an economy of scale inherent in the CAPEX and operating cost assumptions surrounding the bio-sugar conversion facility, there is not an observed economy of scale for the transportation distance and the cost per delivered BDMT of biomass feedstock, though the related increase or decrease in cost is not linearly related to scale-up or scale-down. From Table 12 it is clear that any increase in biorefinery scale results in an increase in the cost per BDMT delivered, though at a square root rate of scale increase.

Table 12 provides a breakdown of the delivered cost to which labor costs and transport costs contribute. The other independent variable for this sensitivity analysis is the assumption about covered area. While there was an observed increase in cost per BDMT as the biorefinery scale increased, there was a decrease in cost per BDMT as the covered area value was increased. The lowest delivered cost calculated ($34.89 BDMT^{-1}) was at a 250,000 BDMT yr^{-1} biorefinery scale assuming 90% covered area, which resulted in a 100 km tortuous round-trip transport distance. The highest delivered cost calculated ($57.90 BDMT^{-1}) was at a 750,000 BDMT yr^{-1} biorefinery scale, assuming 50% covered area, which resulted in a 233 km tortuous round-trip transport distance. This $23.01 BDMT^{-1} delivered cost range was associated with a 133 km tortuous round-trip transport distance range and a 500,000 BDMT yr^{-1} transport range. While any hypothetical bio-sugar platform in Malaysia is assumed to fall within this scale range and the plantation lands from which EFB is grown is assumed to fall within this covered area range, reducing the covered area to 10% for the 500,000 BDMT yr^{-1} scale resulted in a US $91.25 BDMT^{-1} delivered cost and a tortuous round-trip transport distance of 425 km, which can then be compared against previously-studied North American feedstocks holding these variables constant.

Since it is not appropriate to reduce covered area assumption for Malaysian feedstocks to artificially make them more comparable to North American feedstocks, the 70% covered area assumption for the 500,000 BDMT yr^{-1} biorefinery scale was used for that comparison. From this comparison it is evident that the EFB feedstock results in the lowest delivered cost, though no regard for convertibility has been taken into account for this analysis. The greatest cost driver contributing to this delivered cost (~61% of the cost) is the transportation of EFB from the CPO facilities to the centralized biorefinery gate. The EFB price, while substantially lower than the equivalent production cost or stumpage price for the North American feedstocks (Daystar *et al.* 2014), equates to ~27% of the EFB delivered cost. The most minimal cost driver is the loading costs, which contribute only ~12% of the delivered cost.

Table 12. Delivered Cost of the EFB Feedstock for 500,000 BDMT yr^{-1} Assuming a 70% Covered Area and the Breakdown of Delivered Cost by Major Cost Drivers. EFB Delivered Cost is Also Compared against Six North American Feedstocks (Daystar *et al.* 2014)

Component	Value (US$ $tonne^{-1}$)	% of Total Delivered Cost
EFB Price	12.02	26.5%
Loading Cost	5.48	12.1%
Transport Costs	27.87	61.4%
Total EFB Costs	45.38	
Feedstock	**Value (US$ $tonne^{-1}$)**	**% Difference from EFB**
Empty Fruit Bunch	45.38	0.0%
Loblolly Pine	65.90	45.2%
Eucalyptus	59.10	30.2%
Unmanaged Hardwoods	69.30	52.7%
Switchgrass	82.00	80.7%
Sweet Sorghum	69.80	53.8%
Forest Residues	53.40	17.7%

In comparison of EFB against the North American feedstocks, EFB is closest in delivered cost to Forest Residues due in part to the fact that both feedstocks are waste biomass feedstocks and much of the production costs are attributed to other co-products and only carry over to the bio-sugar biomass feedstock co-product as a purchase price. All other feedstocks result in a more than 15% increase in delivered cost, including Switchgrass, which results in an 81% increase in delivered cost as compared to EFB. If the 10% covered area assumption (which is not appropriate for EFB in Malaysia) is utilized for calculating delivered cost, then EFB has the highest delivered cost, at \$91.25 $BDMT^{-1}$.

This delivered cost calculation and sensitivity analysis shows that the delivered cost is highly sensitive to transportation distance, a highly uncertain parameter, especially as only a single literature source was found for the initial analysis. From a joint Malaysian-Dutch feasibility study (Eco-Ideal Consulting and Mensilin Holdings 2006), a total delivered cost of RM 150 was estimated, which, using the April 2014 exchange rate of RM 3.24 per US\$, is equivalent to \$46.29 $BDMT^{-1}$. Griffin *et al.* (2014) determined the availability, cost, and environmental impact of various lignocellulosic residues co-

combustion for electricity in Malaysia. They confirm an availability of between 7 and 11 million metric tonnes per year in Malaysia, and suggest a delivered cost of US$ 25.23 green $tonne^{-1}$ ($45.87 $BDMT^{-1}$), assuming 45% moisture content and no biomass pulverization is necessary. These values, along with other values from literature, validate the total delivered cost value calculated here of $45.38 $BDMT^{-1}$ (in US 2014 dollars) and an availability of approximately 7 million dry tonnes of EFB per year.

Biomass Supply Feasibility

Based upon the mass balance, approximately 7 million dry tonnes of EFB will be available for use by biorefineries in Malaysia in 2015. This calculated availability was checked against recent governmental reports from the Malaysia Palm Oil Board (MPOB 2014), the Roundtable on Sustainable Palm Oil (RSPO 2011), United Nations Development Programme (UNDP 2007), and Griffin *et al.* (2014), which all reinforce this estimation of EFB availability in Malaysia.

Additionally, a feasibility study was conducted for businesses intending to invest in a bio-sugar platform in Malaysia from oil palm EFB. It is expected that a substantial quantity (approximately 7,100,000 BDMT) of EFB biomass from palm oil extraction facilities is available (after CHP use) each year in Malaysia (MPOB 2014). The results of this analysis show that, for the three studied biorefinery scales (250,000, 500,000 and 750,000 BDMT yr^{-1}), approximately 28, 14, and 9 biorefineries could be built, respectively.

Bio-based Chemical Platform Feasibility

As this research proposes a biomass-to-monomeric sugars platform for bio-based chemical production, a deeper analysis of sugar yield from the biochemical conversion of EFB is necessary in order to fully understand the convertibility of EFB biomass and to understand how a bio-sugar platform using EFB might compare to platforms using other feedstocks. Based upon a 75% carbohydrate content and known monomeric saccharide yields from literature a calculation of feedstock cost for this monomeric sugar can be achieved.

Tan *et al.* (2013) suggested a 91% monomeric sugar yield from polysaccharides in EFB using acid (H_2SO_4) hydrolysis, while Katinonkul *et al.* (2012) showed an average conversion yield of 48% using ionic liquid pre-treatment and enzymatic hydrolysis. Based upon these values (91% and 48%) the delivered cost of EFB $BDMT^{-1}$ monomeric sugar produced (not including biorefinery costs) would be 49.87 and 94.54 US$, respectively. Net GHG values would be -1336 and -705 kg CO_2-eq. $BDMT^{-1}$ monomeric sugar produced, respectively, not including biorefinery burdens.

CONCLUSIONS

1. At the 250,000 BDMT yr^{-1} scale, the highest plantation management intensity and the highest covered area, the cost of feedstock production is lowest.
2. Transportation of the EFB to the biorefinery has a large impact on financial burdens.
3. As compared to the North American feedstocks previously studied by these authors, EFB in Malaysia has a similar GW impact than North American switchgrass and sweet sorghum but slightly higher GW impact than woody biomass. The EFB has

approximately the same AC, EC, OZ, PO, CA, NC, and RE, and lower EU than the North American biomasses.

4. For bio-sugar production, the use of EFB would reduce some environmental burdens and greatly reduce the delivered cost of the feedstock as compared to the same biorefinery using a North American feedstock.
5. The major reasons for the exceptionally low EFB delivered cost are the low transportation distance, the low purchase price of EFB, and the fact that it is a waste stream for which a co-product is responsible for all production costs.
6. For biorefinery scales of 250,000, 500,000 and 750,000 BDMT yr-1, approximately 28, 14, and 9 biorefineries, respectively, could be supplied with excess EFB from CPO production facilities. It is estimated that about 40% of the total EFB generated currently at CPO facilities is available as biomass feedstock to a biorefinery.
7. The conversion of different types of land has a significant impact on the net GHG burdens assigned to the EFB to a biorefinery.

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*Note: Changes to the final revised version include the GW impact for EFB and the editing of that value in Table 5, Fig. 4, Table 6, Table 8, and Fig. 5. The conclusions regarding feasibility, cost, and environmental impact did not change appreciably.

Appendix 1. Life Cycle Inventory

The life cycle inventory (LCI) for this study was developed in openLCA using data from Ecoinvent v2.2. When developing life cycle inventories and conducting life cycle assessments it is important to be explicit with the input processes used, as assumptions about the appropriate process or product system to use can vary between LCA practitioners. Thus, a comprehensive list of life cycle stages, the processes used for each product system, and the database from which these processes were taken are provided in Table A1.1.

Table A1.1. LCA Processes Used in openLCA to Model each Life Cycle Stage of EFB Production and the Database Source for each Record

Life Cycle Stage	Process	Source
Establishment	Diesel, low-sulfur, at refinery	Ecoinvent v2.2
	Electricity, bituminous coal, at power plant	Ecoinvent v2.2
	Fungicides, at regional storehouse	Ecoinvent v2.2
	Glyphosate, at regional storehouse	Ecoinvent v2.2
	Herbicides, at regional storehouse	Ecoinvent v2.2
	Nitrogen fertilizer, production mix, at plant	Ecoinvent v2.2
	Pesticide unspecified, at regional storehouse	Ecoinvent v2.2
	Phosphorus fertilizer, production mix, at plant	Ecoinvent v2.2
	Potassium chloride, as K2O, at regional storehouse	Ecoinvent v2.2
	Transport, van <3.5t	Ecoinvent v2.2
	Urea formaldehyde resin, neat, 65% solids	Ecoinvent v2.2
	Water, irrigation	Ecoinvent v2.2
Maintenance	Diesel, low-sulfur, at refinery	Ecoinvent v2.2
	Electricity, bituminous coal, at power plant	Ecoinvent v2.2
	Fungicides, at regional storehouse	Ecoinvent v2.2
	Glyphosate, at regional storehouse	Ecoinvent v2.2
	Herbicides, at regional storehouse	Ecoinvent v2.2
	Lubricating oil, at plant	Ecoinvent v2.2
	Magnesium oxide, at plant	Ecoinvent v2.2
	Nitrogen fertilizer, production mix, at plant	Ecoinvent v2.2
	Pesticide unspecified, at regional storehouse	Ecoinvent v2.2
	Phosphorus fertilizer, production mix, at plant	Ecoinvent v2.2
	Potassium chloride, as K2O, at regional storehouse	Ecoinvent v2.2
	Transport, lorry 7.5-16t, EURO4	Ecoinvent v2.2
	Urea formaldehyde resin, neat, 65% solids	Ecoinvent v2.2
Harvesting	Diesel, low-sulfur, at refinery	Ecoinvent v2.2
	Electricity, bituminous coal, at power plant	Ecoinvent v2.2
	Lubricating oil, at plant	Ecoinvent v2.2
	Transport, lorry 7.5-16t, EURO4	Ecoinvent v2.2
FFB Transport	Transport, lorry 7.5-16t, EURO4	Ecoinvent v2.2
EFB Loading	Diesel, combusted in industrial equipment	Ecoinvent v2.2
EFB Transport	Transport, lorry >16t, fleet average	Ecoinvent v2.2

Appendix 2. Land Use Change

For land use change (LUC) calculations it is important to distinguish between direct land use change (DLUC) and indirect land use change (ILUC). ILUC refers to the unintended consequences of changing the land use and is not considered here. DLUC refers to measurable and predictable emissions and impacts due to moving from a pre-conversion land use scheme to a post-conversion land use scheme. Land use is partially a result of the change in land cover, partially a result of conversion activities and soil disturbances, and partially the long-term avoided emissions or sequestered nutrients and carbon from land cover growth.

The International Panel on Climate Change (IPCC) has provided emission values and multipliers for GHG equivalency that other works have used to create specific calculations, which can be used to calculate the emissions and other impacts due to land use change. In this research Equation A2.1 was used:

$$LUC_{emissions} = 3.7 * \left[\frac{LUCC}{T_{LUC}Y} - \frac{C_{uptake}}{T_{plant}Y}\right], \qquad \text{Eq. A2.1}$$

where $LUC_{emissions}$ is the net emissions from LUC (kg CO_2- eq. $BDMT^{-1}$ FFB), 3.7 is the molecular weight ratio of CO_2 to C (dimensionless), LUCC is the loss of carbon from LUC (kg C ha^{-1}), C_{uptake} is the carbon uptake by oil palm during the lifetime of the plantation (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 mass yield (BDMT FFB ha^{-1} yr^{-1}). T_{LUC} is assumed here to be equal to plantation lifetime. For further reading about DLUC emission calculations, please refer to previous literature (Lasco 2002; Syahrinudin 2005; Barker *et al.* 2007; IPCC 2007; Wicke *et al*. 2008b; Wicke *et al.* 2011; Harsono *et al.* 2012).

In addition to standardized accounting methodologies for calculating DLUC emissions, standard impact factors have been generated on a regional-basis according to the literature, such that region- and even nation-specific studies of DLUC emissions can be conducted, such as in Malaysia assuming a change from peatland to intensively managed plantation oil palm land through draining and drying of the peatland (Table A2.1).

Table A2.1. Input Table for Calculations of GHG Emissions due to Land Use Change from Various Pre-Conversion Scenarios to Palm Oil Plantation Land in Malaysia

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.

Sources: Lasco (2002); Syahrinudin (2005); Barker (2007); IPCC (2007); Wicke *et al.* (2008b); Wicke *et al.* (2011); Harsono *et al.* (2012).