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Carbon Mobilization in Oil Palm Plantation and Milling Based on a Carbon-Balanced Model – A Case Study in Thailand

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Abstract

Damage to agricultural areas and household properties occurs more frequently all year round from extreme weather, which is believed to be due to climate change caused by the increase of greenhouse gases – particularly, CO_2. In order to help reduce its concentration in the atmosphere, palm oil is a renewable energy which can be used for this purpose. In this study, the carbon mobilization of palm oil was investigated, from oil palm plantation process to the milling process, so as to determine the associated Carbon Equivalence (CE) and the effects on human and land space. A carbon-balanced model (CBM) is proposed herewith to indicate the main paths of carbon emission, fixation, and reduction. The net equivalent carbon emission was found to be 56 kg CE per ton of Crude Palm Oil (CPO) produced, resulting in the emission flux of 175 kg CE/ha-y. The plantation activity that emits the highest CO2 levels is fertilizer application, accounting for about 84% of the total. All bio-residues produced from CPO production were found to be utilized for human use, thereby decreasing the carbon emission. Their use ranged from biogas and electricity generation to soil conditioning, and the utilization of the bio-residues resulted in total carbon reduction of 212 kg CE per ton of CPO. Carbon fixation as a main product (CPO) was found to be an average of 812 kg CE per ton of CPO, equivalent to 2543 kg CE/ha-y. Overall, as the total fixation is 14 times higher than that of the total emissions, the production of CPO generates and introduces a very small amount of waste into the environment. To satisfy the need for palm oil as renewable energy and other end-user products the expansion of the plantation areas may result in competition of agricultural land with other cash crops.

Keywords: biomass; carbon-balanced model; carbon emission; carbon equivalence; palm oil

1. Introduction

Plantation of oil palm trees is increasing every year so as to support the demand of end-user products in the market. Two main end-user palm oil products in Thailand, at present, are cooking oil (68%), and biodiesel (15%) (DOA, 2006). Among these, biodiesel is the most popular one being promoted for use as a substitute energy for use in running diesel-engine motor vehicles, replacing the original wholly fossil-based diesel fuel. As the Ministry of Energy enforced a mandatory measure on B3-biodiesel (3% of B100 in the diesel fuel), instead of conventional diesel fuel effective from 1 June 2010, the use of B100-biodiesel was estimated at about 1.6 million liters per day. In addition, the government plans to implement B10-biodiesel in 2022. This measure encourages the production of about 4.5 million liters of B100-biodiesel per day to meet the national demand (DEDE, 2010). Presently, the total planted area of palm trees in Thailand is about 0.62 million hectares, allowing the production of about 8.16 million tons of fresh fruit bunches and 1.48 million tons of crude palm oil (4.58 million liters per day) in 2009 (OAE, 2010). Several issues have been of interest to energy related bodies of the Thai government because palm oil is the biomass resource having the highest yield among oil yielding plants. Accordingly, researchers have been keen on studying energy balance in the milling process and greenhouse gas emissions from biodiesel production, using the Life Cycle Assessment (LCA) method (Chavalparit *et al*., 2006; de Souza *et al*., 2010; Papong *et al*., 2010; Pleanjai and Gheewala, 2009; Yee *et al*., 2009). However, carbon is the main substance in the biosphere, and its organic forms support the lives of almost all heterotrophs (Stanier *et al*., 1986). Whereas, if there is too much inorganic CO_2 in the atmosphere, it causes the problem of global warming (IPCC, 2007). Therefore, this work was carried out with the objectives of (1) indentifying the main paths of carbon transfer on oil palm plantations and production of crude palm oil following a carbon-balanced model, and (2) quantifying the equivalent carbon emission from the resources used.

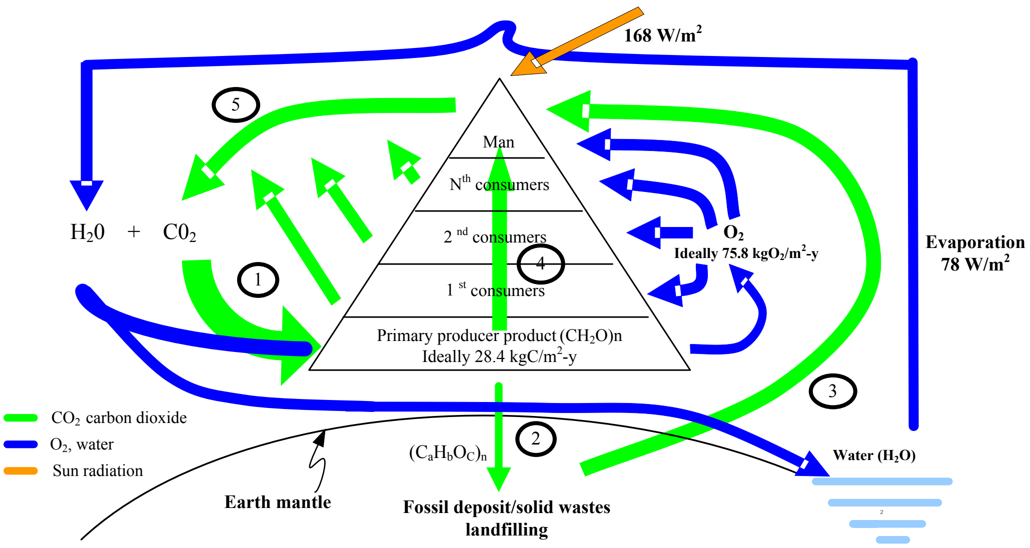

Figure 1. Carbon cycle of the globe (modified from Polprasert and Chaiyachet, 2007)

2. A carbon-balanced model

The carbon cycle of the earth (modified from Polprasert and Chaiyachet, 2007) is illustrated in Fig. 1, and it indicates the circulation of carbon and water, both of which are activated by radiated sun energy. Beginning with the sun energy radiated to the earth at the rate of 342 Watts per square meter (W/m^2), only an average of 168 W/m^2 can reach the earth's surface, and almost half of it is used to lift the water through the processes of physical evaporation and evapo-transpiration by plants. From the average worldwide rainfall data (~1m/y) at the surface temperature of 15°C, the energy used for water evaporation can be calculated to be equal to 78 W/m^2 (Masters, 1998) or equivalent to 1.23×10^4 GJ/ha-y for the sun radiation of 12 hours per day.

To recognize the importance of carbon in the form of fuel, the atmospheric carbon dioxide (CO_2) is presumed to be the energy captor reacting with H_2O to form the organic compound (CH_2O) in the chlorophyll-catalyzed photosynthetic reaction, shown as pathway 1 circled. The energy stored in the freshly formed organics, often referred to as primary producers, is transferred up to the top of the pyramidal food web along pathway 4. When both plants and consumers are dead, most of them decay and return to the original substances (CO_2 and H_2O) with the help of bacterial decomposition reactions. But some of them persist and accumulate underneath the earth surface (pathway 2). The formation of petroleum following pathway 2 occurred about 2 billion years ago in the Precambrian era, in which photosynthesis was abundant worldwide and accumulation of organic carbon was less than 0.1 percent (Tissot and Welte, 1984). At present, only solid waste landfilling is the human activity of carbon sequestration.

In order to obtain numerical figures of the substantial amounts involved with the photosynthesis, the change of the reaction enthalpy can be calculated, using the chemical thermodynamic data (Stumn and Morgan, 1996) as follows.

$$CO_2\,(g) + H_2O\,(g) \leftrightarrow CH_2O\,(g) + O_2\,(g)$$
$$\Delta H_f°;\ \ -393.5 \qquad -241.8 \qquad -116.0 \qquad 0 \qquad ;\ KJ/mol.$$
$$\Delta H° = (-116.0 + 0) - (-393.5 - 241.8) \qquad (1)$$
$$= +519.3\ KJ/mol.$$

Since ΔH° value is positive, the reaction is endothermic, thereby absorbing the energy content and forming the organic carbon at the proportion of 43.3 KJ/g C. Meanwhile, from the reaction (1), the O_2 product is generated at the maximum rate of 75.8 Kg O_2 per square meter per year (pathway 3). It is, then, used by all aerobic, heterotrophic consumers, including man, in respiration to get the energy and produce CO_2 releasing it back into the atmosphere, following the reverse of reaction (1) or pathway 5. The carbon cycle in Fig. 1 can be scrutinized further so as to reveal the major human activities of carbon interchange between earth's atmosphere and lithosphere, a process often known as Carbon-Balanced Model (CBM) shown in Fig. 2. In most tropical countries, like Thailand, products of photosynthesis serve as not only food, but also as important key economic drivers in every market, both local and international. Apart from the forest areas, agricultural lands in Fig. 2 are grouped, based on types of photosynthetic products, into three - lands for the production of staple food (rice grain), non-staple food (fresh fruits, cassava, and sugarcane), and non food (palm fruit and Para rubber). The amounts of products in excess of domestic consumption

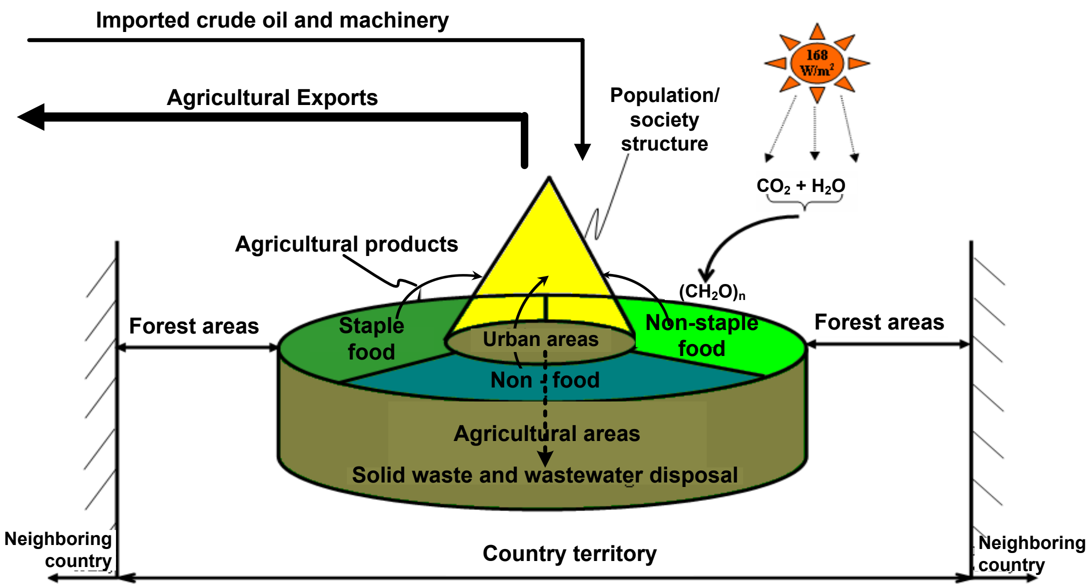

Figure 2. A carbon-balanced model in agricultural countries

are exported in exchange for the imported crude oil and machinery from abroad. Such imported fossil energy is used mostly by both industrial sectors and domestic households in urban areas. Therefore, understanding the CBM would enhance the public's participation in reducing carbon emissions, thereby leading to a win-win approach - not only mitigating the global warming problem, but also saving more foreign currency from reduced crude oil import.

3. Methodology

3.1. Field survey and data collection

The majority (98%) of oil palm plantations and palm oil mills are located in the South of Thailand (DIW, 2006). Therefore, a field survey was carried out with questionnaires and interviews in order to obtain all necessary information from 40 plantation sites and 9 mills in Surat Thani, Krabi, Nakhon Si Thammarat, and Songkhla provinces. Sample size was calculated, using a simplified formula (Yamane, 1973) to determine the sample size for 80% confidence level and precision = 0.2. Data information on quantities of energy, fertilizer and herbicides used and main product and residues produced in oil palm plantation and milling were collected. To ensure that accurate information was obtained, some of it was randomly verified by on-site measurement. The results were not found to be different between interviewing and onsite data. The data values on material input and output were interpreted in terms of Carbon Equivalence (CE) and categorized into carbon emission, fixation, and reduction.

3.2. Conversion factors of carbon equivalence

From the concept of CBM, conversion factors of CE of all materials can be calculated as follows.

3.2.1. Fossil materials

CE conversion factor of fossil fuels can be directly calculated from the amount of carbon molecules present in the chemical formulas, such as diesel ($C_{12}H_{23}$) and benzene (C_8H_{17}). The equation for carbon equivalence estimation is shown in Equation (2).

$$CE_f = \frac{n \times C}{MW} \quad (2)$$

Where CE_f is the conversion factor for fossil fuel (kg C/kg fuel), n is the number of carbon atoms in the chemical formula (#), C is the atomic weight of carbon (12 g C/mol), and MW is the molecular weight of the fuel (g/mol).

Chemical fertilizer and herbicides are fossil-based materials that are characterized as part of the indirect energy consumption process on the oil palm plantation. Indirect energy consumption differs from direct consumption, such as those used for the operation of tractors, threshers, irrigation pumps, and other types of agricultural equipment, in that the majority of the energy consumption associated with chemical fertilizer and herbicide are accomplished away from the farm. Therefore, CE conversion factors of these materials are calculated, using the energy consumption for its production divided by the thermodynamic conversion factor (Equation (1), 43.3 KJ/gC) as shown in Equation (3).

$$CE_{fb} = E / 43.3 \qquad (3)$$

Where CE_{fb} is the CE conversion factor, (kg C/kg fossil-based material) and *E* is energy consumption for fossil-based material production (MJ/kg).

Energy consumption for fossil-based material production consists of the energy required for the production of fertilizer plus that required for post-production, which consists of transportation of minerals to the production facilities, supply center, and the site of application. Most of the data on the energy requirements for production of these types of materials are based on U.S. facilities (West and Marland, 2002). In this study, the CE conversion factor of fertilizer was obtained from energy requirements for fertilizer production, packaging, transportation, and application. Energy requirements for fertilizer transportation include transport from overseas to the fertilizer compounding plant in Thailand. The average distance from overseas to Thailand was estimated to be 13,586 km (one-way) and energy consumption for shipping was 0.086 MJ/ton-km. In domestic transport, the distance from the compounding plant to the distribution center and to the farmers was estimated at 865 km (one way) (Papong *et al*., 2009). Trucks generally consume 0.0125 liters of diesel per ton per kilometer (LTAT, 2010). As a result, the CE conversion factor for transportation is equal to 0.035 kg CE/kg fertilizer. Estimates of the average energy requirement for N, P_2O_5, and K_2O production are 55.48 MJ/kg N, 7.70 MJ/ kg P_2O_5, and 6.38 MJ/kg K_2O, respectively (West and Marland, 2002; Mudahar and Hignett, 1987). CE conversion factors of N, P_2O_5, and K_2O in this study can, therefore, be calculated, using Equation (3), as summarized in Table 1. Herbicide with a 48% glyphosate content was mostly used to kill unwanted grasses and weeds in the plantation area. Energy consumption for glyphosate production of about 454 MJ/kg as reported by Green (1987) was used in this study.

3.2.2. Biomass formation

Nowadays, biomass is increasingly used as renewable energy to reduce the use of fossil fuel. Burning of biomass resources contributes no new carbon dioxide to the atmosphere because replanting harvested biomass ensures that CO_2 is absorbed and returned for a cycle of new growth (Mckendry, 2002). If the energy content or calorific value of the biomass is known, it can be used to determine the CE conversion factor by substituting it as E in Equation (3). If not, the CE conversion factor of the freshly-formed organics is taken from the molecular weight proportion of carbon in CH_2O (Equation (1)) to be equal to 0.4 kg C/kg.

3.2.3. Electricity

The conversion factor of carbon equivalence from electricity generation was calculated, using the emission factor from the Environmental Division, Electricity Generating Authority of Thailand (EGAT, 2010), equal to 0.58 kg CO_2/kWh with the ratio of C to CO_2 molecular weight of 0.27. Therefore, 0.16 kg CE/kWh was the conversion factor used to determine the carbon equivalence from electricity consumption. In this study, the electricity generation process from

Table 1. CE conversion factor in oil palm plantation and crude palm oil production

Variable	CE conversion factors (kg CE/ kg)			
	This study	West and Maland (2002)	Lal (2004)	De Souza *et al.* (2010)
Diesel	0.86	0.98	0.94	1.06
Gasoline	0.85	1.01	0.85	-
Glyphosate	10.48	-	9.10	-
N-fertilizer	1.28	0.86	1.30 ± 0.3	1.31
P_2O_5 -fertilizer	0.18	0.17	0.20 ± 0.06	0.55
K_2O- fertlizer	0.15	0.12	0.15 ± 0.06	0.14
Fresh Fruit Bunches	0.40	-	-	-
Electricity	0.16a	0.18	0.075	0.02
Crude Palm Oil	0.81	-	-	-
Palm fiber	0.41	-	-	-
Palm shell	0.43	-	-	-
Empty Fruit Bunch	0.0032	-	-	-
Biogas from POME[b]	0.53	-	-	-

Remark: [a] derived from EGAT, b data express in kg CE/m^3

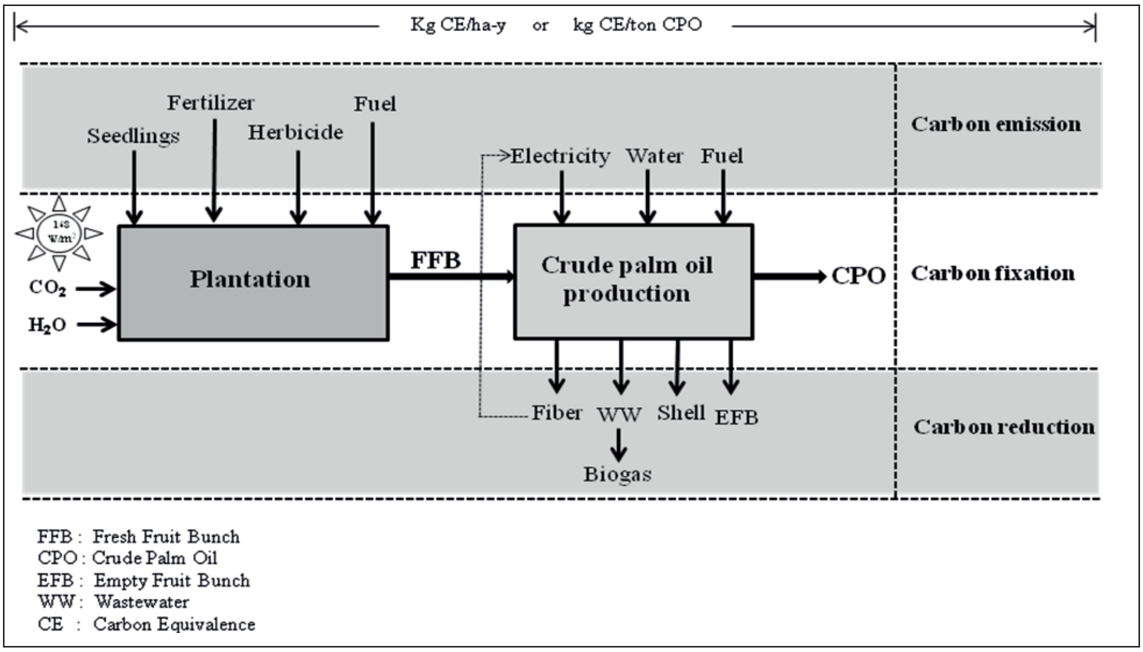

Figure 3. Schematic flow diagram of carbon transfer for oil palm plantation and milling

the grid was considered as a source of carbon emission, while electricity generation from fiber and biogas was considered as carbon reduction.

3.2.4. Man-power

The authors consider the world's human population as a carbon mobilizer that causes carbon movement to satisfy their need. Therefore, it is not included in the determination of carbon equivalences.

4. Results and Discussion

4.1. Main paths of carbon mobilization

From the field survey, data information on material input and output from oil palm plantation and milling were interpreted into CE value by multiplying with conversion factor and categorized into three main paths - carbon emission, fixation, and reduction. The schematic flow diagram of carbon transfer in the CBM for oil palm plantation and milling is illustrated in Fig. 3.

Details of each path can be described as follows.

- Carbon emission comes from the anthropogenic use of fossil energy and other fossil energy derived materials. As shown in Fig. 1, fossil matter underneath the earth surface is dug up and used as energy to facilitate human activities. After this, it remains in the atmosphere as the incremental CO_2.
- Carbon fixation is the product of photosynthetic reaction in which atmospheric CO_2 is combined with H_2O to form organic carbon. It will be, then, mobilized horizontally to satisfy human need. Finally after being consumed by humans, it returns to the atmosphere, resulting in no emissions in this pathway.
- Carbon reduction is the amount of carbon involved with any recovery, recycling, and reuse of waste. It is considered as a carbon reduction because it helps reduce the use of natural raw materials and fossil energy (Pimentel *et al.*, 2010).

4.1.1. Carbon emission from oil palm plantation and milling

Total carbon emissions from plantation (starting from land tillage to harvest and transport to the mill) was found to be an average of 167 ± 40 kg CE/ha-y. The most significant emissions came from a fertilizer application, which contributed to 88% of total emissions. This is because oil palm trees require intensive fertilization throughout the period of Fresh-Fruit Bunch (FFB) production (25 years). In contrast, land tillage emits very low levels of carbon emissions, about 1.7% of total emissions, as this is done only once during the life time of the tree (Fig. 4). As oil palm trees require a large amount of fertilizer for growth, the annual average application rate per hectare of 75 kg N, 57 kg P_2O_5, and 200 kg K_2O was needed. Accordingly, carbon emissions from N, P_2O_5 and K_2O-fertilizer applied were estimated at 98, 12, and 37 kg CE/ha-y, respectively. A significant

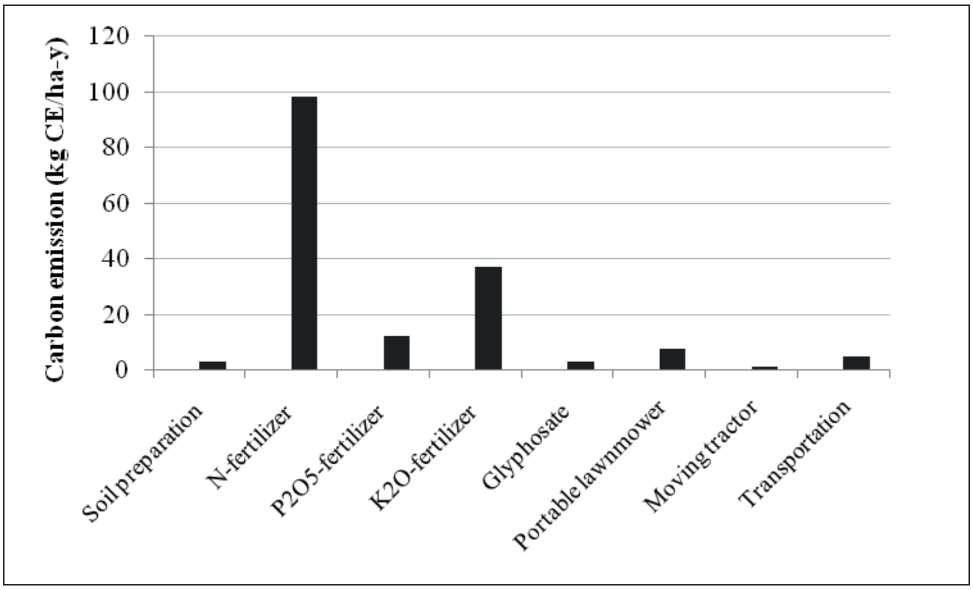

Figure 4. Carbon emission from oil palm plantation

source of carbon emissions from fertilizer applications derives from N-fertilizer, which takes into account 67% of all emissions from fertilizer.

Carbon emissions from the weed control process is estimated at about 11.9 kg CE/ha-y from the herbicide and the fuel consumption of the weed cutting machine. Glyphosate was used as an herbicide which was sprayed during the early period of the palm trees' lives (1-3 y); whereas portable lawnmowers and moving tractors were used in the mature period (4-25 y) of the palm tree. The carbon emissions come from the above-mentioned weed control practices 2 times a year. The lowest level of emissions belonged to that of portable lawnmower operation with a rate of 10 kg CE/ha-y. The highest emissions was from glyphosate spraying and was found to be a rate of 31 kg CE/ha-y. This indicates that production of chemical herbicides produce high levels of carbon emissions. Therefore, it is suggested that only portable machines should be used for weed control in oil palm plantation so as to avoid health risk from contact with the chemical (Glyphosate), which is considered a toxic chemical (Cox, 2004).

Carbon emissions from the transportation process was estimated at about 4.7 kg CE/ha-y, equivalent to 29.2 kg CE per ton of FFB-km. The amount depends on the distance from plantation to mill. Most of the plantation areas surveyed were located near the mill, around 1-20 kilometers.

Excluding machinery and other durable equipment used in the milling process, all input and output materials were found to be fully utilized, thereby not discharging any waste into the environment. Because most of the energy input came from the recycling of bio solid residues for electricity generation, carbon emission was very small and negligible. The amount of emissions was found to be 7.7 kg CE/ha-y or 2.5 kg CE per ton of CPO, owing to consumption of diesel fuel and electricity from the grid. In general, diesel fuel was used for initial start-up of the production process and for the operation of wheel loaders and forklifts in the mill. Although most of electric power can be generated from the solid residues left after oil extraction, about 3% of it was still brought from the outside grid network - particularly, for use in the process start-up.

The net carbon emission of 56 kg CE per ton of CPO from plantation to milling process is depicted in Fig. 5, in which fertilizer application contributes the most (84%) to these emissions. A few approaches to help reduce the emissions could be recommended; i.e., use of compost mixed with fertilizer and replacing the use of the fossil diesel with biodiesel.

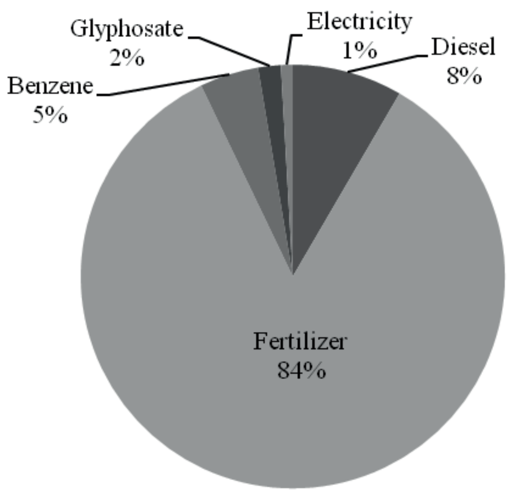

Figure 5. Percentage carbon emission in each activity of oil palm plantation and milling

4.1.2. Carbon fixation

Carbon fixation is the main process for plant production via photosynthetic reaction. The average production yield of FFB and CPO was found to be 19.2 tons FFB/ha-y and 3.1 tons CPO/ha-y, corresponding to the carbon fixation from oil palm plantation and crude palm oil production of 7.7 tons CE/ha-y and 0.8 tons CE per tons of CPO, respectively. Additionally, photosynthesis efficiency can be estimated, using Equation (4).

$$Photosynthesis\ efficiency\ (\%) = \frac{Energy\ input}{Energy\ output} \times 100 \quad (4)$$

From the net input of sun energy radiated to the earth mantle versus the energy output of energy content in the biomass, the energy transfer efficiencies based on total biomass and CPO were found to be 9.8 and 2.6% as summarized in Table 2. These values are relatively high, compared with those of other plants grown in the tropics; for example, energy-capturing efficiency in the range of 4.4-6.0% was obtained from papyrus grown in constructed wetland (Perbangkhem and Polprasert, 2010).

4.1.3. Carbon reduction

Carbon reductions were found to be an average of 212 kg CE per ton of CPO which came from the utilization of fiber, shell, Empty-Fruit Bunch (EFB), and palm oil mill effluent (POME). All of the fiber generated by the mills was used internally as fuel in the boiler for steam and electricity generation. Total electricity consumption of all electric machines used in the process was estimated at 18.70±5.42 kWh per ton of FFB, while the quantity of electricity generated on-site was found to be an average of 18.25±5.27 kWh per ton of FFB, contributing to 97% of total consumption. The remaining 3% of the electricity was brought in from the grid outside. In the conventional process, one ton of fiber was found to be able to produce 171±48 kWh, which was equivalent to a carbon reduction of 17.9±5.1 kg CE per ton of CPO. The majority of shell generated was sold to other industries as biomass fuel. Since EFB contains 0.16% N, 0.08% P_2O_5, and 0.70% K_2O, it was used as a soil conditioner, resulting in carbon reduction of 4.6 kg CE per ton of CPO. Furthermore, high-strength wastewater (BOD = 30,000 mg/L) generated from the milling process was fed into an anaerobic reactor to produce methane gas, which was subsequently used for electricity generation and selling back to the grid. Typically, 1 m^3 of POME can produce 12-16 m^3 of biogas. Moreover, 1 m^3 of biogas generally can generate around 1.0-1.2 kWh of electricity (DIW, 2006). If biogas is used to generate electricity, it can reduce emissions 8.0 kg CE per ton of CPO. Summary of all materials and carbon equivalence in oil palm plantation process and milling is presented in Table 3.

4.2. Land area available for oil palm plantation

Thailand's Department of Agriculture (1998) had suggested the suitable land area for oil palm plantation be only in the South of Thailand with the maximum available land area about 2.17 million hectares. Total planted area and harvested area of palm oil were about 0.62 and 0.51 million hectares in 2009, respectively. From the above-stated conditions, a mathematical equation of the logistic-growth model (Equation 5) seems appropriate for use in predicting the future expansion of the plantation area as follows (Masters, 1991):

$$\frac{dA}{dt} = rA\left(1 - \frac{A}{K}\right) \quad (5)$$

Table 2. Biomass production and photosynthesis efficiencies of oil palm tree

Materials	Biomass yield (Ton/ha-y)	Energy content (MJ/kg)	Energy produced (GJ/ha-y)
CPO	3.13	35.16 [a]	110.14
Fiber	2.62	17.62 [b]	46.13
Shell	1.33	18.46 [b]	24.57
Empty Fruit bunches	4.20	17.86 [b]	75.09
Palm kernel	1.15	18.90 [c]	21.75
Trunk	3.02	10.00 [d]	30.20
Fronds	10.98	9.83 [a]	107.89
Total energy output			415.77
Total energy input (168 W/m^2, 12 h/d)			4238.44
Photosynthesis efficiency based on total biomass (%)			9.81
Photosynthesis efficiency based on CPO (%)			2.60

Derived from: [a] Permchart and Tanatvanit (2007), [b] prasertson (2006), [c] Shuit (2009), and [d] Yusoff (2006)

Table 3. Unit measurement and carbon equivalence in oil palm plantation and milling

Process	Unit measurement		Carbon equivalence (kg CE per ton of CPO)
	Value	Unit per ton of CPO	
Oil palm plantation			
Soil preparation			
- 1st tilling	0.66 ± 0.11	L diesel	0.48 ± 0.08
- 2nd tilling	0.33 ± 0.07	L diesel	0.24 ± 0.05
- 3rd tilling	0.24 ± 0.05	L diesel	0.18 ± 0.04
Sub-total carbon emission from soil preparation	1.22 ± 0.16	L diesel	0.89 ± 0.12
Fertilizer application			
- Nitrogen (N)	23.82 ± 6.41	kg N	31.32 ± 8.43
- Phosphorus (P_2O_5)	18.15 ± 5.31	kg P_2O_5	3.90 ± 1.14
- Potassium (K_2O)	63.79 ± 20.73	kg K_2O	11.79 ± 4.42
Sub-total carbon emission from fertilizer application	105.90 ± 32.15	kg fertilizer	47.00 ± 12.63
Weed control			
- glyphosate	1.98 ± 0.49	L glyphosate	0.96
- portable lawnmower	5.22 ± 1.47	L benzene	2.50
- moving tractor	4.99 ± 1.15	L diesel	0.32
Sub-total carbon emission from weed control			3.78
Transportation from field to mill	2.07 ± 2.09	L diesel	1.51 ± 1.52
FFB production	6.12 ± 1.77	ton FFB	2450 ± 707
(a) Carbon emission from plantation			53.32 ± 12.77
Crude palm oil production			
Electricity from grid	3.06 ± 0.80	kWh	0.50 ± 0.12
Diesel consumption (for starting turbine and all machines)	2.69 ± 0.73	L diesel	1.96 ± 0.55
CPO production	1000 ± 61.23	kg	812.16 ± 49.71
Palm shell production	425.15 ± 129.06	kg	181.41 ± 55.10
EFB production (for soil conditioner)	1342.19 ±107.07	kg	4.30 ± 0.34
Palm-fiber production	836.04 ± 183.80	kg	-
Electricity generation from palm-fiber	111.74 ± 32.27	kWh	17.88 ± 5.14
Palm oil mill effluent (POME)	3.25 ± 0.86	m3	-
Biogas from palm oil mill effluent*	45.50	m3	-
Electricity generation from biogas	50.05	kWh	8.01
(b) Carbon emission from milling			2.46 ± 0.67
Total carbon emission (a + b)			**55.78**
Total carbon fixation			**812.16**
Total carbon reduction			**211.60**

* Calculated from 1 m^3 of POME in which 12-16 m^3 of biogas are produced (DIW, 2006)

Where A is area size, t is time, r is a growth rate, and K is saturated area (carrying capacity). The growth rate (r) in this study already includes all factors influencing the use of palm oil such as economics, promotion, trading, and environmental factors. At present, other oil producing plants are not competitive with the oil palm because their yields per unit area are very low, compared with palm oil. The area for plantation is predicted to reach the 90% of maximum available land area in 2054 from the growth rate of 5.4% as shown in Fig. 6. In 2054, the area of 1.95 million hectares (90% of maximum available land area) will be used to produce 37.4 million tons of FFB and 6.1 million tons of CPO.

From the renewable energy development plan of the country, which promotes the use of B10-biodiesel in 2022, the required oil palm plantation area will be 1.03 million hectares with the production of 19.7 million tons of FFB, and 3.2 million tons of CPO. This amount of CPO can be used to produce 3.0 million tons of B100-

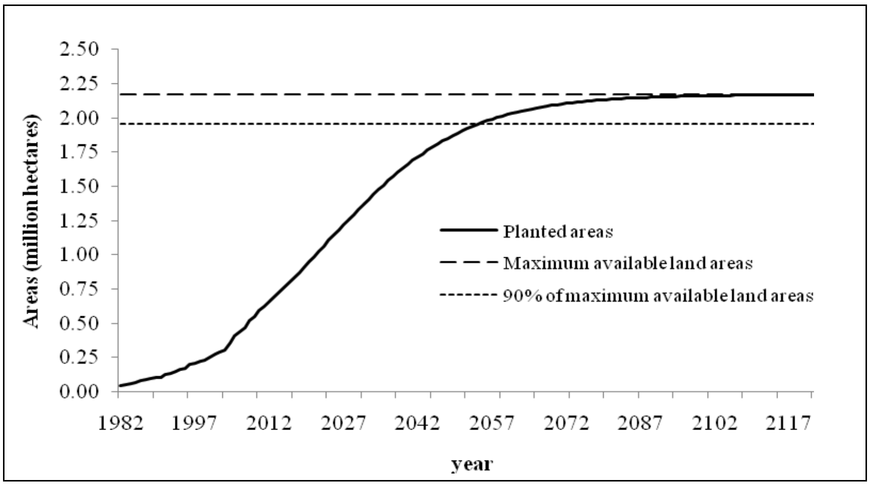

Figure 6. Available land areas and oil palm plantation areas predicted in the south of Thailand

biodiesel, indicating the adequacy for B10-biodiesel implementation in 2022, which requires 1.5 million tons of B100 (4.5 million liters per day). However, this area (1.03 million hectares) is not only used for biodiesel production, but also for cooking oil and other end-user products of palm oil. Accordingly, further expansion of oil palm plantation areas may result in competition of agricultural land with other cash crops in the south.

5. Conclusion

In the photosynthetic reaction of oil palm trees, carbon fixation as the main product of CPO was found to be an average of 2543 kg CE/ha-y with the energy transfer efficiency of 2.6%. The equivalent carbon emission in oil palm plantation and milling was about 175 kg CE/ha-y. The highest emissions comes from fertilizer application at the average flux of 147 kg CE/ha-y, which was 84% of total emissions. The production of CPO generates a very small amount of wastes into the environment because all bio-residues after CPO extraction are used for electricity generation and soil conditioning in plantation, resulting in carbon reduction of 649.3 and 13.5 kg CE/ha-y, respectively.

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