The Potential of Oil Palm in the Global Carbon Cycle

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INTRODUCTION

Malaysia is one of the largest producers and exporters of palm oil in the world, accounting for 38% of the major producers and 46% of major exporters in 2009 (*Oil World*, 2010). The phenomenal growth of palm oil and palm oil products increased the total oil palm planted area in the country by 3.4% to 4.85 million hectares in 2010 (MPOB, 2010). Oil palm plantation covers one-tenth of the world's permanent croplands (FAO, 2010), and will have a significant role in the global carbon balance. Depending on the environmental and physiological factors of specific sites, oil palm plantation may contribute to carbon uptake (see Henson, 1999 for review) or carbon emission (Melling, 2007a; Yule, 2010; Koh *et al.*, 2011; Hergoualc'h and Verchot, 2011).

ECOSYSTEM CARBON CYCLE

Photosynthesis converts carbon dioxide in the atmosphere to more complex organic compounds, storing the energy from light in the bonds of these compounds. This process is called carbon fixation. Living things get the energy they need to live by consuming these more complex organic compounds, releasing this carbon again mostly as carbon dioxide. As carbon dioxide absorbs heat radiated from the earth, additional carbon dioxide in the atmosphere contributes to heating of the globe (Grace, 2004). The net impact of oil palm plantation on global warming is thus quantified in large part by how much carbon is fixed in oil palm plantation relative to how much is released back into the atmosphere over the life cycle of the oil palm crop.

Of the carbon that is fixed by the oil palm crop stands in an oil palm plantation, or gross primary production (GPP), some goes into the oil palms themselves, some into the soil, and some is released as carbon dioxide. Generally about half of GPP is respired by plants to provide energy for growth and maintenance (Grace, 2004). Net primary production (NPP) is the net carbon gain by vegetation, which is the balance between carbon gained through GPP (or photosynthesis) and carbon released by plant respiration (Chapin *et al.*, 2002). NPP is generally monitored and measured over long time intervals to capture temporal and spatial variation. Relatively accurate estimation of NPP and its components are imperative to understand the carbon dynamics and provide reliable data to evaluate environmental impacts based on the life cycle assessment (LCA).

The impact of a plantation with respect to global warming, whether positive or negative, can be quantified by the time-averaged addition or subtraction of greenhouse gases to the atmosphere by all plantation activities. There are two classes of approaches to this: one is to measure directly the transport of greenhouse gases in or out of the plantation as a function of time (the 'flux approach'); the other is to measure changes in the stocks of carbon within the plantation as a function of time (the 'stock approach').

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Flux and stock approaches are only meaningful if there is a clearly defined volume within which stocks are measured, or into and out of which fluxes are monitored. This volume is like an 'account' in the sense that carbon flowing in (gross 'income', GPP) increases the carbon in the volume, while carbon flowing out decreases the carbon in the volume. Carbon accounting for the volume means either monitoring the total net flow of carbon in and out of the volume (flux approach), or keeping track of how much carbon is in the volume (stock approach), or both. Within the volume, the carbon may be broken down into a number of different pools of carbon (like subaccounts), and fluxes may be monitored among these pools (like cash flow between subaccounts). For example, carbon is allocated to several components from plants to soil and respired by living plant leaves, stems, roots as autotrophic respiration, and decomposition of non-living organic material as heterotrophic respiration, and these can be treated separately. However, for a valid carbon accounting for a plantation, flux and stock measurements must be comprehensive, that is, all important modes of transport of carbon in or out of the plantation must be measured or estimated, and all changing stocks within the plantation must be inventoried.

The major carbon stocks in an oil palm plantation are the carbon stored in the oil palms themselves (above- and below-ground biomass), decomposing parts of the palms left on site and carbon in the soil. The major carbon fluxes in and out of a plantation are: net carbon exchange with the atmosphere; exports of carbon in groundwater; and decomposition of detritus (trunks or piled palm leaves). Completion of a plantation carbon balance is an excellent first step towards assessing the long-term effects of the plantation's carbon balance on greenhouse gases in the atmosphere, or the net greenhouse gas balance of the plantation. The net greenhouse gas balance depends on the long-term fate of the palm oil products and other removed materials, and also on emissions of nitrous oxide and methane.

The fluxes and stocks relating to carbon balance apply to plantations on both peat and mineral soils, but on all but the shallowest peat soils the soil is the largest carbon stock, while on mineral soils the oil palm biomass is the largest carbon stock. Peat soils are characterised by very high carbon content; no more than 35% and often as little as 1% of the dry mass of a peat soil remains after it is burned, the rest consisting of organic compounds that are oxidised during combustion (Page *et al.*, 2011). Mineral soils, on the other hand, have lower carbon contents. Sometimes the carbon content of mineral soils is taken to be constant, and the soil is excluded from the control volume; this may or may not be a valid assumption, depending on whether substantial amounts of carbon go into below-ground biomass. This approach cannot be taken with peat soils. The soil must be included in the control volume because often much more carbon is in the soil than is in all the above-ground biomass (*e.g.*, Melling 2007a). This point is often neglected in discussions of carbon accounting that do not consider peat soils.

Stock Approach

Biometric measurements based on destructive or non-destructive sampling and allometric modelling have been the conventional technique to assess carbon stock. On mineral soils, this means inventories of above-ground biomass throughout the plantation life cycle. This need not take long if plantations at multiple points in the life cycle are available. It is also necessary to verify that there are no significant changes in soil carbon stocks. In the case of peat soils, it is critical that soil carbon stocks are monitored (*e.g.*, Melling 2007a). This requires measurements of subsidence, bulk density, and carbon content.

An advantage to the stock approach is that it is concrete. If carbon is sequestered, it must be possible to show where the carbon is going in the long-term. If oil palm plantations act as a net sink of carbon dioxide over their life cycle, the carbon must go somewhere. It might be stored in the oil palms themselves, or in the soil, or be exported in the form of commercial products. The stock balance must be measured or estimated for the entire life cycle of the plantation, including harvesting and any fallow periods. If palms are cut down when their productivity declines, what happens to the palm stems and foliage? If they decompose on site, all the carbon stored in above-ground biomass will go back into the atmosphere and there may not be net storage. If they can be prevented from oxidising quickly, however, this could contribute to the carbon balance of the plantation.

In general, the stock approach is probably still the most practical approach for application on a broad scale. However, stock inventories cannot accurately represent daily and seasonal variation because the method may not capture many days in a year, night-time fluxes, phenology, and daily events.

Flux Approach

The flux approach means measuring the time-averaged transport of carbon dioxide in or out of the plantation. As with the stock approach, it is essential to have a clearly defined control volume into/out of which the fluxes are being measured. Again, the flux must be averaged over the entire life cycle of the plantation. Two tools for flux measurement are soil chambers and eddy covariance measurements. Soil chambers are small, portable and require less investment in infrastructure to run, and they have been deployed at many sites in tropical peatlands (reviewed in Rieley *et al.*, 2008). However, they make measurements in a small area (chambers are typically tens of centimetres in diameter) and fluxes on these spatial scales can vary widely (Hirano *et al.,* 2007). Also, when there is a canopy of vegetation, measurement of fluxes at the soil surface is not sufficient to characterise the carbon balance of the soil: the chambers measure a carbon dioxide flux out of the soil but do not measure the carbon flowing to the trees' roots from their leaves. A highly dynamic forest - with high gross primary productivity and high root respiration – could have higher soil respiration than a less dynamic forest and still have a lower net soil carbon loss (discussed in Verwer *et al.,* 2008). One way around this challenge for soil chambers is to attempt to exclude root respiration from measurements, so that the control volume excludes the plants entirely, leaving only so-called heterotrophic soil respiration (Hooijer *et al.*, 2010; see *Figure 1*). To date, various methods have been successfully used to partition soil respiration across different regions and ecosystems – mainly in boreal and temperate region (see Subke *et al.*, 2006 for review), but rarely in the tropics and especially on peat soil (but see Melling, 2007a).

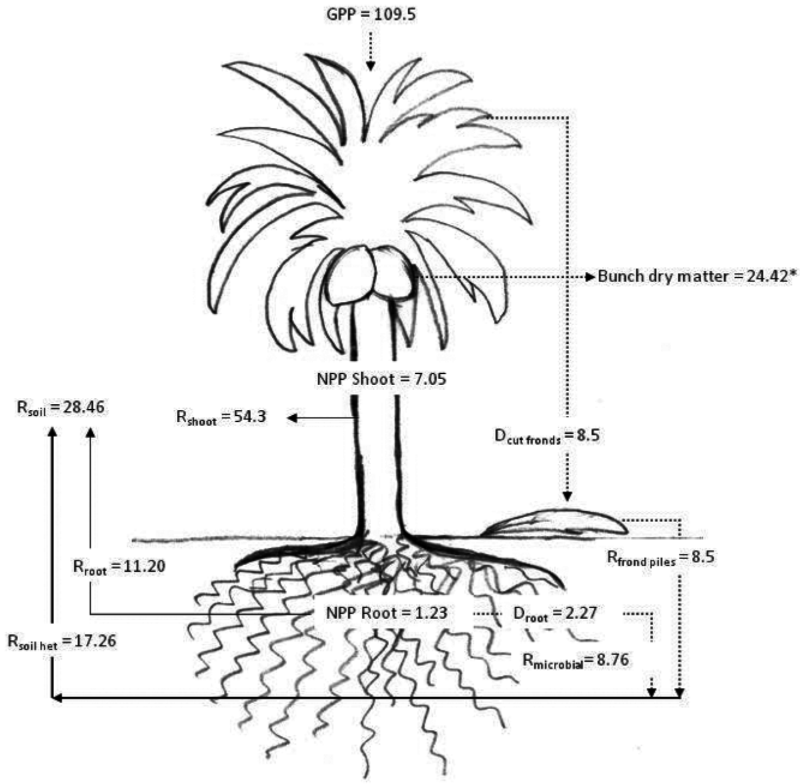
The eddy covariance approach avoids two challenges of soil chambers - coping with spatial heterogeneity and exclusion of root respiration - by effectively using a much larger control volume, and one that includes the vegetation. Eddy covariance uses instruments mounted above the plant canopy to measure the net transport of carbon dioxide between the plantation and the atmosphere, typically averaged over half-hour intervals in time and over a spatial scale of about 1 km (Baldocchi, 1988). The theory behind the measurements is well developed, and eddy covariance is deployed at a network of sites in Asia and throughout the world (Baldocchi, 2008), with a growing presence in Asia (Mizoguchi *et al.*, 2008). In addition, eddy covariance measurements yield data on surface-atmosphere exchange approximately every half-hour, and in combination with other environmental measurements can help predict how ecosystems will respond to environmental change (Grace, 2004). However, the technique is difficult and expensive to implement: instruments need to be mounted above the plant canopy, usually requiring a tower; the instruments themselves are expensive, with core instrumentation alone costing upwards of RM 300 000; and correct measurement and calibration require considerable expertise and training, meaning that there will be large long-term personnel costs to maintain an eddy covariance installation. As such, eddy covariance is probably still best regarded as a research tool rather than a workhorse methodology for monitoring fluxes.

Both soil chamber and eddy covariance approaches aim to measure fluxes between the soil or plantation and the atmosphere; however, to be comprehensive, fluxes in groundwater must also be measured or estimated, especially on peat soils (Hirano *et al*., 2009). This issue has been very little studied; the work of Baum *et al.* (2007) and on-going work by collaborators of Rieley *et al.* (2008) is the only major work to date.

The major disadvantage of the flux approach, in addition to the high cost and level of technical expertise required, is that it is possible to make major systematic (bias) errors if great care is not taken in experimental design, execution, and data analysis, and these errors will not be apparent in the data. It is possible, for example, to get the sign wrong, that is, to conclude that the system is a net sink when it is really a net source or *vice versa*. This is much harder to do with the stock approach; if carbon has been lost, there is less soil or biomass, whereas if carbon has been gained, there is more.

CARBON BALANCE OF OIL PALM

Figure 1 showed the carbon cycle of an oil palm stand. Based on a detailed study of a productive oil palm stand (9-10 years) on a coastal soil in Selangor, Henson (1999) found an average productivity of oil palm dry biomass of 9.74 Mg ha^{-1} yr^{-1}, with a steady decline suggested following peak productivity at 10 years.



Note: *Bunch dry matter are represented as Mg non-oil equivalent (Squire, 1985).

Figure 1. Figures and estimates adapted from a detailed study of carbon allocation of a coastal oil palm plantation after 9-10 years planting (Henson, 1999). Solid line indicates respiration fluxes in CO_2 and dashed line indicates detritus (D) organic matter. All values are estimated in dry biomass, with respiration (R) unit represented in Mg ha^{-1} yr^{-1} and GPP/NPP unit represented in Mg ha^{-1}.

Using these values, the average productivity was projected to be lower based on national average palm oil yield. Approximately half of the carbon metabolised is allocated to fruit bunches which contain about 35% of dry weight as oil, with two times of energy and carbon content greater than vegetative tissue (Henson, 1999). Shoot contributed the highest respiration about 70% of the total respiration.

Despite the simple and standard methods to assess biomass and productivity of oil palm (Corley *et al.*, 1971a), the NPP of oil palm is generally understudied with much uncertainty and their interactions with environmental change are poorly understood. Most studies attempted to estimate oil palm productivity focused on the above-ground productivity, young oil palm and on few limited plantation sites and often on fertile sites (Henson, 1999). In addition, below-ground biomass is usually unaccounted and assumed to be proportional to shoot growth (Khalid *et al.*, 1999; Henson and Dolmat, 2003). Henson (1999) compiled a comprehensive ecophysiology and carbon cycle review of oil palm, and explicitly comparing it with tropical forest (Pasoh Forest Reserve).

The carbon impact of oil palm plantation depends on what was there before the plantation (a reference state). Managed forest areas tend to be net sinks of atmospheric carbon dioxide, but it is not clear what their effect is relative to other land uses because forest products may decompose off-site; the only real long-term stores are soils and long-lived forest products (Grace, 2004). The carbon balance of oil palm on peat soils has the potential to be much less favourable than the carbon balance on mineral soils because the peat carbon stock is so large. On peat soils, the above-ground biomass may be less than 10% of the below-ground biomass (31-100 t C ha^{-1} *vs*. 3771 t C ha^{-1}; Melling, 2007a). Under waterlogged conditions, natural peat forest sequesters carbon over the long-term (thousands of years), at the rate of about 2 mm per year (reviewed in Rieley *et al.*, 2008). Mean drainage depths recommended by the Roundtable for Sustainable Palm Oil are 60-80 cm with a mean of 75 cm (RSPO, 2008). At these drainage depths peat will be oxidised, whether land cover is oil palm or forest, causing emission of carbon dioxide (Melling 2005; 2007; Hooijer *et al.*, 2010). Due to these effects, Falgione *et al*. (2008) calculated that conversion of natural peat forest to oil palm for biodiesel led to a payoff time of 423 years (840 years if long-term emissions were considered). RSPO recommends avoiding creation of new oil palm plantations on peat (RSPO, 2008). Payoff time for oil palm on mineral soils was better, 86 years, but in general oil palm plantation that replaces non-forest land will have a much more favourable greenhouse gas balance relative to previous land use than does oil palm replacing natural forest.

In order to improve our understanding of the carbon balance of oil palm, and model the interaction to environmental change, there is a need to expand our knowledge on the primary productivity of the ecosystem, taking into account the spatial heterogeneity. It is imperative to understand the productivity and respiration of each component and how these processes vary across different soil types and oil palm ages.

CURRENT INITIATIVES BY MALAYSIAN PALM OIL BOARD (MPOB)

To sustain the development of Malaysian oil palm industry, MPOB has undertaken various studies to understand every aspect of the oil palm and the interactions to environmental change. Few studies have been conducted to assess the productivity of oil palm since the early 1970s (*e.g*. Corley *et al.*, 1971; Corley, 1983; Henson, 1999; Henson and Harun, 2005), which also provided comprehensive knowledge on the ecophysiology of oil palm stands. However, further studies are needed to assess the variation over different palm ages, soil types and the potential interaction with environmental changes. These challenges are increasingly important due to the expansion of oil palm cultivation and the response of oil palm stands to global change at different timescales that may cause a shift in carbon allocation (Grace, 2004). MPOB is currently conducting a comprehensive monitoring and measurement of carbon stocks and fluxes on logged-over forests and oil palm plantations at the MPOB Research Station in Belaga, Sarawak. Extensive initiatives have recently shifted its focus on the monitoring and estimation of carbon fluxes using the eddy covariance measurement technique for oil palm stands planted on peat soil. Five towers equipped with eddy covariance instrument were recently erected in several oil palm plantations on peat soil (four in Sarawak and one in Peninsular Malaysia), a joint collaboration study between MPOB and Tropical Peat Research Laboratory (TPRL). In addition, continuous soil respiration are continuously measured, soil properties are being analysed, and water table are monitored to complement tower-based ecosystem measurements. These efforts are mainly to understand the carbon allocation and cycle of oil palm cultivation on peat, and to determine the relationship between carbon emission and drainage depth of peat soil.

INCREASING CARBON SEQUESTRATION BY OIL PALM

Carbon that is sequestered must be stored in some way. The most obvious mechanism for sequestration is production of palm oil and other products themselves. Where palm oil replaces petrochemicals, it is a net gain for carbon in the earth versus the atmosphere, because even when it is oxidised, it has come from the atmosphere rather than from the earth. This is a case where there is a clear agreement between management objectives, because increased net primary production could improve both carbon balance and economic output. Any management strategy that increases mean above-ground biomass over the plantation life cycle will increase net sequestration. In addition, if plant materials can be stored at end-of-life-cycle in a way that reduces their decomposition, that will also increase net sequestration. For example, management schemes where palms are killed by herbicides rather than cut down will result in higher net sequestration, because standing trunks decay very slowly.

The need for drainage of peat soils for oil palm plantation inevitably leads to carbon emissions from the soil, because peat accumulation is made possible by waterlogging (Rieley *et al.*, 2008). However, keeping mean water-tables as high as possible as recommended by RSPO (2008) will reduce emissions below those of some other agricultural uses on peatlands. In addition, careful use of fertiliser may reduce emissions of carbon and nitrous oxide, a potent greenhouse gas (Melling *et al.*, 2007b; Rieley *et al.*, 2008).

The industry has a key role to play in answering these questions, but results will need to be verified by independent bodies that are not funded by the industry to be universally accepted. Fortunately, MPOB has been working towards verifying the results and a number of independent organisations are qualified to evaluate carbon balance of different land uses.

CONCLUSION

The increasing extent of oil palm cultivation has raised many environmental issues. The oil palm landscape may be more beneficial to the environment than some other land uses, however due to limited understanding it is too early to make a plausible inference. Firstly, many earlier studies are showing the carbon uptake of mostly young oil palm stands; what is needed are analyses over the full planting cycle. Palm respiration also remains understudied. Hence, the uncertainty of net carbon budget and the potential of oil palm as carbon sink or carbon source. Clearly, the understanding of tropical peat soils are still lacking, especially complete measurements of the net carbon balance of oil palm plantation on peat with different mean water-table depths. Thus, comprehensive carbon balance needs to be estimated using a combination of techniques (*e.g.*, the eddy covariance technique together with biometric methods). These will benefit from further testing using more sites with different soil types and palm ages.

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