Review of carbon flux estimates and other greenhouse gas emissions from oil palm cultivation on Tropical peatlands - Identifying the gaps in Knowledge

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ABSTRACT

Caspar Verwer , Peter van der Meer & Gert-Jan Nabuurs, 2008. *Review of carbon flux estimates and other greenhouse gas emissions from oil palm cultivation on Tropical peatlands - Identifying the gaps in Knowledge.* Wageningen, Alterra, Alterra-rapport 1731. 44 blz.; .8 figs.; 1 tables.; 66 refs.

This report provides an independent review that clarifies current confusion on carbon dioxide emissions resulting from oil palm cultivation on tropical peatlands in Malaysia, that was brought about by two recent publications. It describes the processes of carbon flow in forests, degraded forests and oil palm plantations on peat and depicts uncertainties in existing datasets. The report identifies the gaps of knowledge and offers recommendations for further research to be commissioned by the Joint Committee on Carbon Emissions (JCCE), Malaysia-The Netherlands.

Keywords: tropical peat, oilpalm cultivation, land conversion, carbon balance, Malaysia

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Preface

This study was commissioned by the Dutch Ministry of Housing, Spatial Planning and the Environment (VROM) in conjunction with the Malaysian Ministry of Plantation Industries and Commodities (MPIC). It was coordinated by the bi-lateral Joint Committee on Carbon Emission (MY-NL) and executed by Alterra, research institute of Wageningen University and Research Centre.

The study was greatly supported by Herbert Diemont, Henk Wösten and Jan Verhagen representing the EU funded CARBOPEAT project and by Bart Kruijt. We owe particular thanks to Lulie Melling for her extensive and thoughtful comments on earlier versions of the report and we also acknowledge Goh Kah Joo for improving our conceptual model on carbon stocks.

Executive Summary

Establishment of oil palm plantations on peatland areas in Malaysia is currently debated, in part because of CO_2 emissions related to land conversion. Several recent reviews indicate that the conversion of intact peat swamp forests to oil palm plantations results in high CO_2 emissions (e.g. Hooijer et al., 2006). However, Melling et al. (2005) found that soil CO_2 emissions of a primary peat swamp forest were higher than the soil CO_2 emissions of an oil palm plantation. These seemingly contradicting findings led to confusion on the CO_2 emission status of tropical peatlands and especially on the (CO_2-)effects of draining and converting these ecosystems to agriculture areas.

This report assesses the sources of confusion by reviewing the carbon balance of primary and degraded peat swamp forests and oil palm plantation. In the undisturbed situation, primary peat swamp forests sequester carbon by accumulation in peat and biomass. Over time this ecosystem is a net sink of carbon because of carbon accumulation in peat. Drainage and degradation of primary peat forests in Malaysia results in carbon losses mainly through increased decomposition of the peat. Other pathways of carbon loss from the site are biomass removal, methane emissions from anaerobic decomposition, fire and leaching. Conversion of peatlands to oil palm plantations requires drainage of 60-80 cm below soil surface which enhances peat decomposition. Emissions of CO_2 have been measured in several (agro-)ecosystems on peat. These fluxes are highly variable due to variations in hydrology, land use and topography.

Results of soil CO_2 flux measurements as described in the literature can be confusing because of a limited description of the system and the context. Measurements of forest soil CO_2 flux in Melling et al. (2005) appear to have been measured in an isolated forest patch that was disturbed and influenced by drainage as well. High soil emissions as reported by them can therefore probably be assigned to drainage effects. The Hooijer et al. (2006) series of measurements portray a large cloud of soil CO_2 efflux measurements indicating a considerable uncertainty in the relationship. As a result, upscaling to arrive at a regional carbon budget is hampered by considerable uncertainty as indicated in their report.

Currently the carbon budgets of peatlands are still poorly understood because most research focuses on CO_2 emissions from the peat soil only, without incorporating the carbon uptake by vegetation and additional carbon flows such as anaerobic decomposition and leaching. Recommendations for further research include (1) studies on the full ecosystem carbon balance of various peatland ecosystems (e.g. undisturbed forest, degraded forest, oil palm plantations), (2) detailed estimates of carbon stocks of peat and vegetation, (3) the relation between drainage and CO_2 emissions, and (4) research on additional measures (like REDD) which may further assist sustainable use of peatlands.

1 Introduction

1.1 Context

Worldwide tropical peatlands cover some 30-45 million ha, which is approximately 10-12% of the global area of peatlands (Rieley et al., 2008). Most of the tropical peatlands are in Southeast Asia (26 million ha), with about 20 million ha in Indonesia and 2.73 million ha in Malaysia (Rieley et al., 1996). Contrary to boreal and temperate peat, most tropical peat has been formed by the accumulation of organic material produced by peat swamp forests. The peat and the associated forest vegetation are largely interdependent (Page et al., 1999; see Box 1 for more details)

Tropical peatlands are important reservoirs of carbon, water and biodiversity (e.g. Hooijer, 2004). They provide direct functions such as water flow regulation (water storage, filtration and supply), protection from natural forces (erosion prevention, flood mitigation), macro-climate stabilization, education and recreation and production of food and other resources for local communities (Rieley, 2008). Peat swamp forests are a source of vital products such as drinking water, fuel wood, timber and medicines. Indirect functions include sediment retention, carbon balance, nutrient detention and micro-climate stabilization. Intact tropical peat swamp forests make an essential contribution to regional and global biodiversity, providing an important habitat for many endemic and endangered species, including birds, fish, and mammals like the red banded langur (*Presbytis melalophos cruciger*) in Sarawak (Shahbudin, 2005).

Since the 1970s vast areas of tropical peat swamp forest in Southeast Asia have been converted for urban development, forestry and agriculture, including oil palm plantations (McMorrow & Talip, 2001). In Malaysia, there has been rapid development of new oil palm plantations on peatlands (Mantel et al., 2007; Reinders & Huijbregts, 2008; Fargione et al., 2008) and the accelerating global demand for biofuels is likely to put further pressure on peat swamp forest areas.

1.2 Problem description

Although efforts have been made by the Roundtable on Sustainable Palm Oil (RSPO) to define criteria for sustainable palm oil production (RSPO, 2005), oil palm plantations on peatlands are currently debated, in part because of CO_2 emissions related to land conversion. On the one hand, several reviews indicate that the conversion of intact peat swamp forests to oil palm plantations results in high CO_2 emissions (Wösten & Ritzema, 2001; Hooijer et al., 2006; Germer & Sauerborn, 2007). On the other hand Melling et al. (2005) found that soil CO_2 emissions of a primary peat swamp forest were about 1.4 times as much as the soil CO_2 emissions of an oil palm plantation. These seemingly contradicting findings led to confusion on the CO_2 emission status of tropical peatlands and especially on the effects of draining and converting these systems to agriculture.

The objective of this study is to clarify these issues by unraveling the key concepts of the carbon balance in tropical peatlands and reviewing relevant publications on CO_2 emissions from tropical peatlands under different land use types.

Chapter 2 of this report describes the state of the art of Malaysian and more generally, South East Asian peatlands. Chapter 3 proposes a full system approach of tropical peatland ecosystems. Chapter 4 describes the points of confusion raised by the publications of Melling et al. (2005) and Hooijer et al. (2006) and places these publications within the full system approach described in chapter 3. Based on the first four chapters, chapter 5 describes the main gaps of knowledge, followed by the conclusions and recommendations which are given in chapter 6.

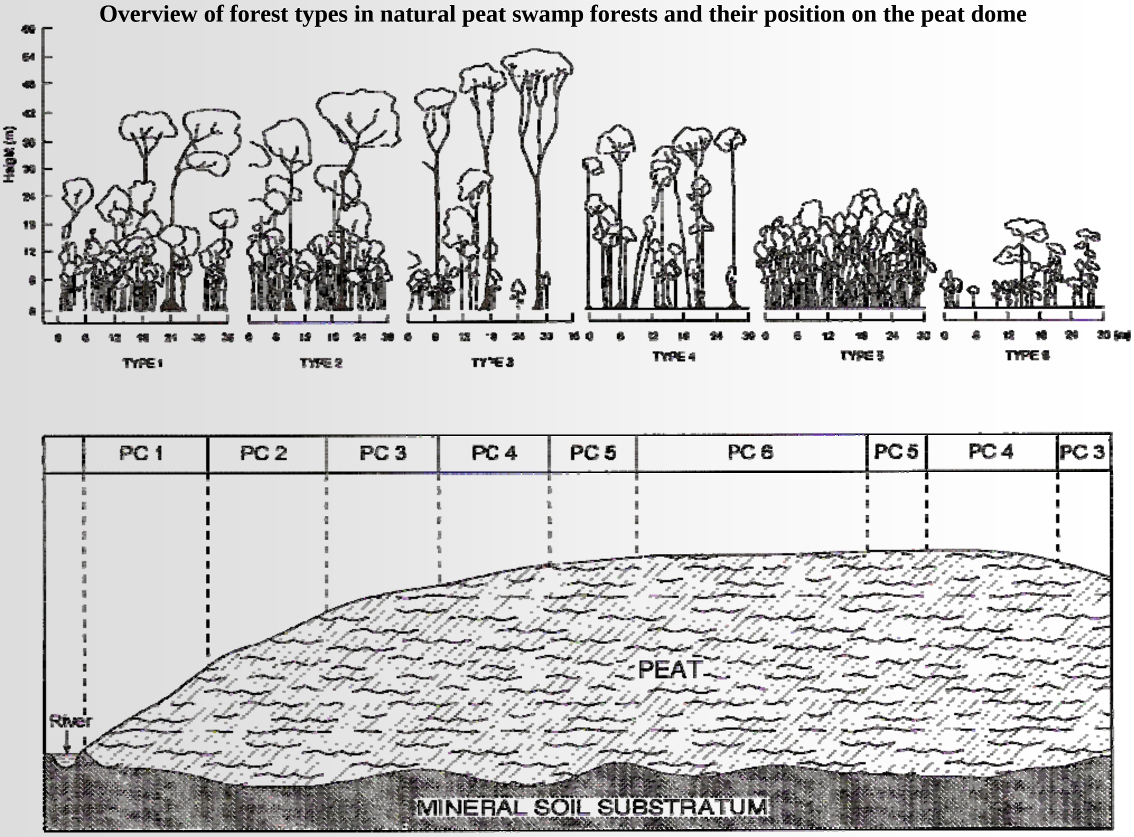
Box 1
Interdependency of peat and forest

Most tropical peatlands are located in coastal regions, often on the inland edge of mangroves, where prolonged flooding retards the breakdown of organic material. Peat formation initially starts on the marine sediments that are generally rich in nutrients. As the peat accumulates and peat depth increases, those nutrient rich mineral sediments become inaccessible for plant roots and mineral supply to the vegetation starts to depend completely on the minerals in rainwater and the available nutrients of decaying vegetation in the surface layer. As organic material continues to accumulate, nutrients become increasingly scarce and a dome-shaped peat formation starts to form. Eventually the peat-forming plant community derives all its water, and hence dissolved nutrients, from rainfall and other precipitation as opposed to watercourses or below-ground drainage (i.e. the forest becomes ombrogeneous). In general mangrove forests develop directly along the coast and (going inland) these are gradually replaced by peat-swamp forest. Anderson (1961) distinguished six different vegetation zones (or phasic communities) in Sarawak based on their floristic composition and vegetation structure. These vegetation zones are related to different zones on the peat dome, with from perimeter to core:

- PC1: Mixed swamp forest (*Gonystylus-Dactylocladus-Neoscortechinia* association);
- PC2: Alan forest (*Shorea albida-Gonystylus-Stemonurus* association);
- PC3: Alan bunga forest (*Shorea albida* association);
- PC4: Padang alan forest (*Shorea albida-Litsea-Parastemon* association);
- PC5: *Tristania- Parastemon-Palaquium* association;
- PC6: Padang keruntum (*Combretocarpus-Dactylocladus* association).

The occurrence of different forest types depends on the hydrology, chemistry and organic matter content of the peat, but these factors are in turn determined by vegetation and may differ remarkably between forest types (Melling et al. 2007a), hence resulting in the interdependency of forest type and peat characteristics (Page et al., 1999).

Overview of forest types in natural peat swamp forests and their position on the peat dome



Modified after: Paramananthan, unpublished

2 Carbon storage and land use change

2.1 Carbon storage in Southeast Asian peatlands

Tropical peatlands play a vital role in biospheric carbon dynamics. Tropical peatlands are among the largest reservoirs of biospheric carbon, which have resulted from thousands of years of organic matter accumulation. Globally tropical peat soils store about 70 billion tonnes of carbon, which is equal to 20% of global peat soil carbon and 2% of global soil carbon (Sabine et al., 2004). The amount of carbon stored in peatlands depends on area, peat thickness, bulk density and the origin of peat deposits (i.e. forest vs *sphagnum* dominated peats). There is still limited data available on peat thickness in tropical peatlands. In Sarawak more than half of the peat area is over 3 m thick (Lee & Chai, 1996) with a maximum depth ranging from 17-20 m (Melling et al., 2007a). Peat thickness varies from less than 1 m to over 12 m in Indonesia (Sumatra, Kalimantan and Papua) (Hooijer et al., 2006). Extrapolating the average bulk density found in Bornean peatlands - i.e. each cubic meter of peat stores 57 kg carbon at a bulk density of 0.1 g cm^{-3} (Page et al., 2002) - Hooijer et al. (2006) estimated that South East Asian peatlands store over 42 billion tonnes of carbon of which 5.26 billion tonnes in Malaysia. The uncertainty is however large as peat depth and carbon densities are as yet poorly described.

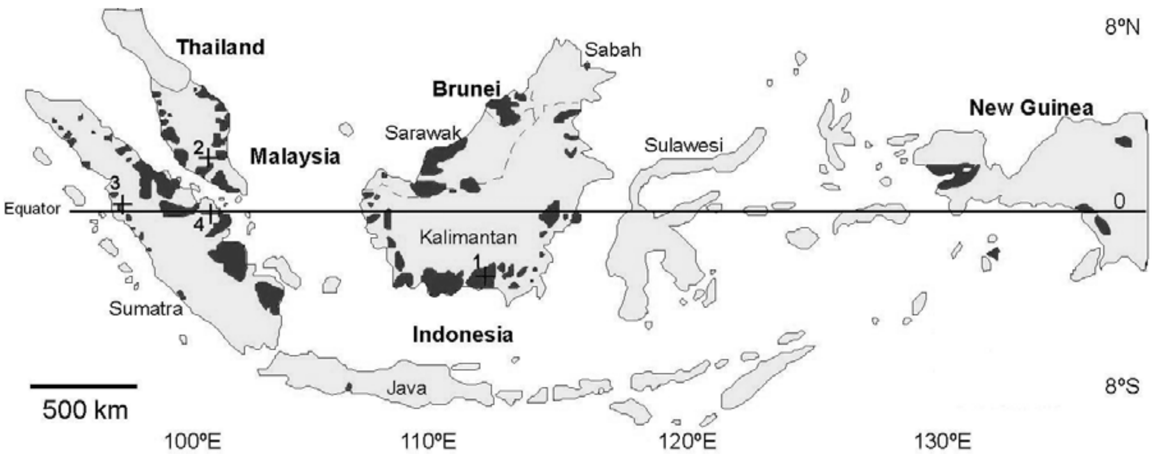


Figure 1. Distribution of peatlands (dark grey) in Southeast Asia (after: Rieley et al., 2008)

2.2 Changes in land use

Since the early 1950s commercial logging in the peat swamp forests has been an important economic activity in Sarawak. By 2003 logging activity in the peat swamp forest still generated a royalty income of RM38 million from a production volume of 1.37 million m^3 (Lee, 2004). Only recently the development of peatlands includes large scale conversion of peat swamp forests to agriculture, especially oil palm plantations and urban development. Oil palm development is currently an important source of economic benefits in Malaysia (Corley, 2005), but the accelerating demand for agricultural crops and biofuels forms one of the main threats to the remaining peat swamp forests (e.g. Sawal, 2005) and may contribute to the 1.2% annual deforestation rate in Malaysia (FAO, 2005). Figures provided by the Sarawak Forest Department's GIS unit indicate that as at 30 June 2004 over 58% of the peat swamp forest area within the Permanent Forest Estate of Sarawak were excised for conversion to agriculture plantations and other non-forest land use (Lee, 2004). Table 1 shows the development of forest cover on peatlands in Sarawak. A large part of the deforested areas has been converted into oil palm plantations (Lee, 2004). Remote sensing data indicate that as at 2005 some 0.448 million ha of Malaysian peatlands may have been planted with oil palm (Henson, 2005).

Table 1 Reduction in peat swamp forest areas in Sarawak between 1979 and 2004 (after Lee 2004).

Year	Area of peat swamp forest (ha)	Reference
1979	1,455,000	Lee (1979)
1990	1,140,000	Anon. (1990)
2000	1,054,800	Wong (2003)
2004	320,161*	Lee (2004)

* Figure relates only to the Permanent Forest Estate (other figures include Permanent Forest Estate as well as Stateland)

The area of Malaysian oilpalm plantations is likely to increase as an expansion of Malaysian diesel production with 5% of biofuel is expected (Reijnders & Huijbregts 2008). Indonesia and Malaysia account for 86% of global palm oil production (Basiron, 2007). By 2005 oil palm plantations in Asia covered 12 million ha, of which over 4 million ha were located in Malaysia (Malaysian Palm Oil Board, Malaysian Rubber Board). In the same year Malaysia produced about 44% of the world's palm oil (Basiron, 2007). Figure 2 shows the increase in the quantity of palm oil produced by the two main producing countries Malaysia and Indonesia. Note that this increase is without a strong pull of the emerging biofuel market yet.

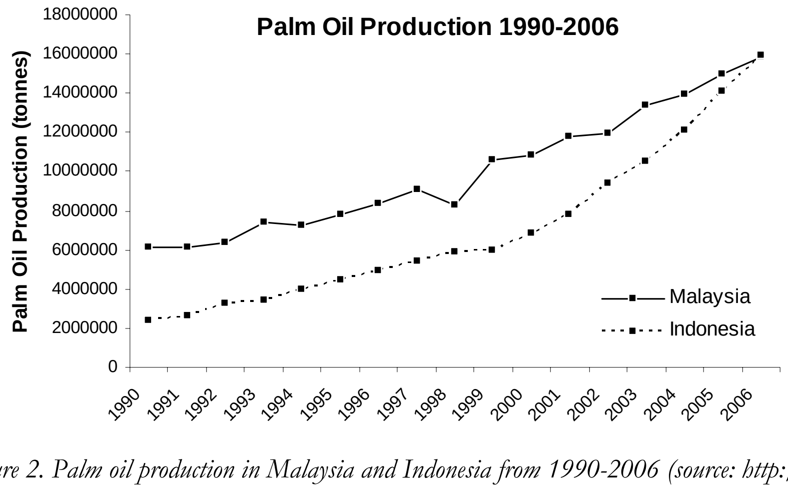


Figure 2. Palm oil production in Malaysia and Indonesia from 1990-2006 (source: http://faostat.fao.org)

Scientists argue that conversion of tropical swamp forest result in large emissions of CO_2 caused by drainage of the peat soil (e.g. Fargioni, 2008; Rieley et al., 2008). CO_2 emissions from tropical peatlands are increasingly recognized to form a significant part of the global terrestrial carbon emissions (Hooijer et al., 2006; Inubushi et al., 2003; Melling et al., 2005a). The rate at which CO_2 is released from the ecosystem depends on a variety of interrelated processes (e.g. drainage, logging, consolidation, compaction, leaching, fertilization) that affect a wide variety of factors (e.g. bulk density, peat profile morphology, soil moisture content, water table depth, soil temperature). It is these factors that in turn determine microbial activity in the peat soil and subsequent greenhouse gas emissions. To completely understand the peat ecosystem it is crucial to study the complex relations among and between those processes and factors.

3 The Full carbon balance in tropical peatlands

Terrestrial carbon dynamics are characterized by long periods of small rates of carbon uptake, interrupted by short periods of rapid and large carbon releases during natural disturbances or harvests (IPCC, 2007). It depends on the stage of the individual forest patch and its hydrology whether it acts as a carbon source or sink. In the long term, the total amount of carbon in the ecosystem will be approximately in balance or slightly increasing in time as peat accumulates (the phase 'primary forest' in figure 3.1. with large carbon stocks retained in biomass and peat).

When comparing results of carbon balance studies it is important to understand the whole system and its temporal dynamics. In analyzing the results attention should be given to the different system components and at what point in time they have been measured. Therefore we first describe the full carbon cycle in the three stages of undisturbed forest, degradation phase and oil palm plantations as depicted in the conceptual diagram in figure 3.1.
The ratio between carbon content in living biomass and peat depends on the peat depth, bulk density and carbon content of the peat on the one hand and on the vegetation or crop on the other. A review study of Indonesian sites showed that aboveground biomass estimates range from 254-390 t C ha^{-1} in natural peat swamp forest, 148.2-245 t C ha^{-1} in logged forest and 31-101 t C ha^{-1} in oil palm plantation (Lasco 2002). In contrast, the belowground carbon storage may greatly exceed this in peatlands, depending on peat depth and bulk density. Estimates by Melling (2008) show for example a peat carbon content of 3771 t C ha^{-1} on deep peats in Sarawak. If we assume an average carbon content of 60 kg C m^{-3} (Page et al., 2002), a peat layer of 3 m thick would contain 1800 t carbon ha^{-1} and a 6 m thick peat layer 3600 t C ha^{-1}. Belowground carbon storage in living biomass (course and fine roots, mycorrhizas) remains largely unknown for tropical peatlands. Figures on carbon pools and fluxes in primary and degraded peat swamp forests and oil palm plantations are included in Appendix 1.

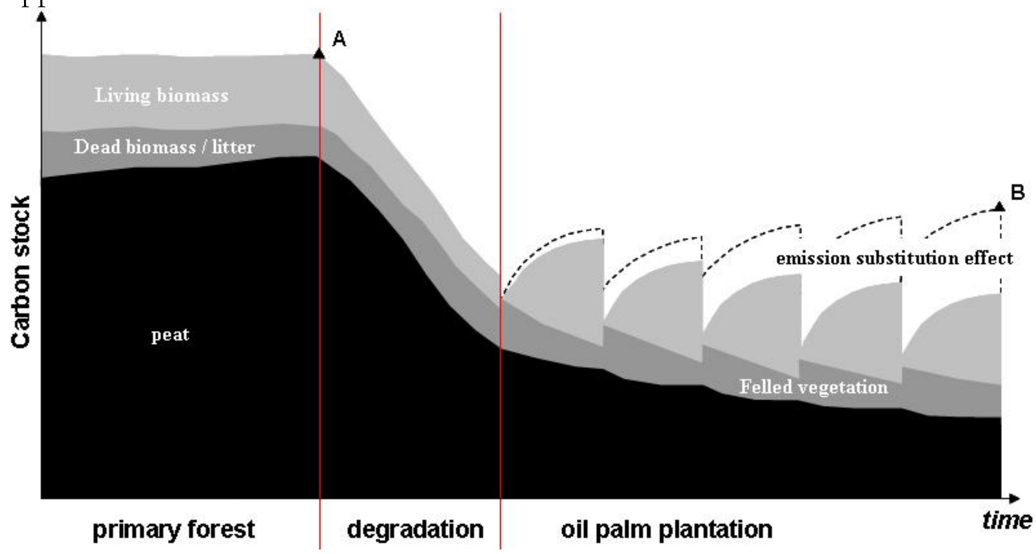


Figure 3.1 Conceptual diagram of temporal evolution of on-site carbon stocks in living biomass (pale grey), dead biomass (dark grey), peat (black) and the cumulative emission substitution effect (dashed line) during the conversion from primary peat forest through a degradation and drainage phase and five rotations of oil palm. Carbon stored in logged timber and harvested products are not incorporated as these are removed from the site.

3.1 The primary peat swamp forest

Primary peat swamp forests are wetlands that are characterized by a high water table. Depending on the forest type (Box 1) they are often waterlogged. In a primary peat swamp forest, atmospheric CO_2 is being fixed through photosynthesis (gross primary production, GPP) (Figure 3.2). Some of the fixed carbon is released back to the atmosphere in the parallel process of plant respiration (autotrophic respiration, R_A), but the surplus is stored in plant biomass (net primary production, NPP). Part of this NPP is released by respiration of consumers and decomposers as plant parts are consumed and decomposed (heterotrophic respiration, R_H). The resultant of this, the annual net rate of biomass accumulation in live plants and soil organic matter is termed net ecosystem production (NEP). In a primary peat forest ecosystem (with undisturbed hydrology) the long term NEP is slightly positive. The stock of carbon in living biomass may be fairly constant over time (straight horizontal line in the phase 'primary forest' in figure 3.1), but in primary peat swamp forest the decomposition of dead organic material is generally limited due to anaerobic and acid conditions which result in organic matter accumulation and growth of the peat layer, hence increasing the peat carbon stock. The amount of carbon sequestered in the vegetation and allocated partly to accumulating peat is high in climax peat swamp forest, although 80-90% of annual biomass produced is decomposed quickly and is unavailable for peat accumulation (Rieley et al., 2008). Higher rates of plant productivity do not necessarily drive peat formation (Chimner & Ewel, 2005). For example, leaves generally contribute a high proportion of total plant productivity, but their rapid decomposition allows little carbon to be available for peat accumulation. By contrast, fine roots only contributed about 10% to plant productivity (Chimner & Ewel, 2005), but their slow decomposition allows them to accumulate as peat. Page et al. (2004) reported that carbon accumulated at an average rate of 0.92 t C ha^{-1} yr^{-1} at the Sebangau peatland in Central Kalimantan. Peat accumulation data for several tropical peatlands implies that, over their life-time, tropical peat deposits can act naturally as both carbon sinks and carbon sources, although the accumulated peat represents net carbon storage (i.e. NEP>0) over thousands of years. Factors that influence the rate of organic matter accumulation include hydrological setting, type of vegetation and climate and environmental changes associated with them (Rieley et al., 2008). Estimates of of carbon accumulation rates in intact tropical peat forests range from 0.59 – 1.45 t C ha^{-1} yr^{-1}, exceeding those in boreal and subarctic ombrotrophic bogs of 0.3 and 0.35 t C ha^{-1} yr^{-1} (Turunen, 2003). Field measurements indicate that peat accumulation rates vary from 2.2 mm yr^{-1} in tropical peats (Sebangau peatland, Page et al., 2004) to 0.2-1 and 0.2-0.8 mm yr^{-1} in temperate and boreal peats respectively (Gorham, 1991 and Aaby & Tauber, 1975).

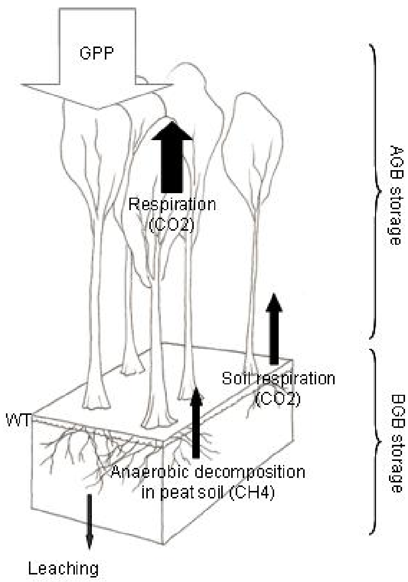


Figure 3.2 Land based carbon fluxes in a primary (undrained) peat swamp forest ecosystem. The white arrow indicates the CO2 uptake by the ecosystem through photosynthesis (gross primary production, GPP). Black arrows indicate carbon emissions from the system. The arrow width indicates the proposed extent of the carbon flux. AGB = above ground biomass, BGB = below ground biomass, WT = average water table.

In addition to plant and soil respiration, carbon is to some extent lost from the ecosystem through anaerobic decomposition. Specific for the undrained situation is the release of methane (CH_4). Methane is a product of organic matter decomposition under waterlogged (anaerobic) conditions. It is a potent greenhouse gas with a relative global warming potential 23 times that of carbon dioxide over a time horizon of 100 years (IPCC, 2001). However CH_4 emissions from the peat surface in peat swamp forest are relatively small and are in the range of 0.25-1.75 kg C ha^{-1} yr^{-1} (Inubushi, 2003; Jauhiainen et al,. 2005; Melling et al,. 2005b). Melling et al. (2005b) reported CH_4 fluxes to be higher in a peat swamp forest compared to an oil palm plantation, indicating that the oil palm plantation was a net sink of CH_4 whereas the forest acted as a CH_4 source. Some CH_4 can also be released by vascular plant tissues but this flux needs further research.

Carbon may finally escape the forest system through leaching, but the extent of leaching in primary peat swamp forests is still not known.

3.2 The degradation phase

Timber harvest and further development of peat swamp areas including drainage have various consequences for the carbon cycle of peat swamp forest areas. Harvesting of forest products (mainly timber) results in the direct loss of carbon and other nutrients from the system as biomass is removed, consequently reducing above ground carbon storage. For instance during logging operations in Sarawak the average commercial yield in Peat Swamp Forest was about 85 m^3 ha^{-1}, with typically some 40% of the above ground biomass removed during logging operations (Lee 1977). It depends on the product's life cycle when this carbon is released back to the atmosphere. When trees were harvested selectively the forest is able to recover and sequester carbon again. Depending on the type of concession and the plans afterwards, the removal of woody biomass can be gradual (leaving sufficient trees to regrow), or rather abrupt, with a land use change as a result. In the years following such a disturbance, the losses from decay of residual dead organic matter generally exceed the carbon uptake by regrowth.

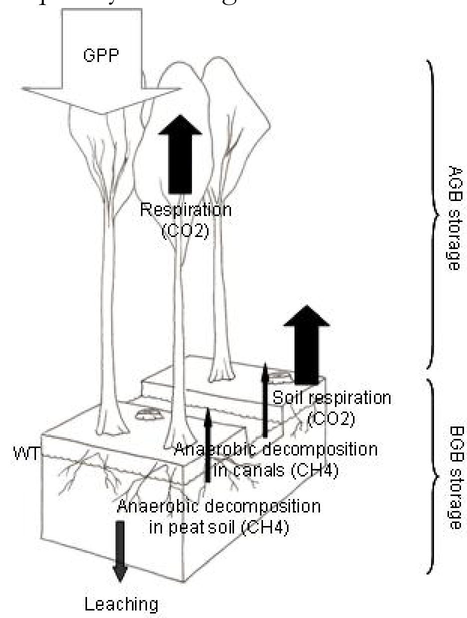


Figure 3.3 Land based carbon fluxes in a drained and partly logged peat swamp forest ecosystem. Symbols are as in Figure 3.2. AGB = above ground biomass, BGB = below ground biomass, WT = average water table.

When peatlands are further developed for agriculture they require optimum water levels to maximize crops yields which vary greatly with different crops (e.g. 40-50 cm for sago, 60-80 cm for oil palm; DID, 2001). The optimum water table is reached by artificial drainage. Drainage increases soil aeration, which enhances soil respiration rates (i.e. CO_2 release) by increasing the available oxygen for soil micro-

organisms (e.g. Furukawa et al., 2005; Melling et al., 2005a). Several studies confirm that the amount of CO_2 emitted from tropical peatland soils strongly depends on the depth of the water table (Wösten et al., 1997; Inubushi et al., 2003; Hooijer et al., 2006). A lower water table results in oxidation and shrinkage (i.e. peat subsidence) (Salmah et al., 1994; Aminuddin, 1994; Andriesse, 1994). Peat subsidence starts as soon as originally water-logged peat swamp forests are drained. In the first few years after drainage subsidence is mainly due to consolidation during which permanently saturated peat layers are mechanical compressed and it can be as much as 50 cm per year (Welch and Nor, 1989; Wösten et al., 1997). After about 2 years subsidence is mainly due to oxidation (microbiological breakdown of peat resulting in CO_2 emission) and shrinkage (irreversible drying of peat without CO_2 emission). Long term measurements in Western Johore show that peat subsidence reduced from about 15 cm per year in the 2-10 years after drainage to about 5 cm per year in the 10-20 years after drainage, (decreasing peat stock line in Figure 3.1. in the phase of 'degradation') and to about 2 cm per year thereafter. Peat subsidence may finally result in disappearance of the peat and surfacing of potential acid sulphate soils, and limited agricultural use of peatlands as they subside towards the drainage basis of the system (Wösten and Ritzema, 2001). However, the rate at which CO_2 is released can be highly variable between locations depending on several factors such as the bulk density (see Box 2), soil moisture content, water table, peat profile morphology, soil temperature and chemical composition of the peat. Soil respiration in drained and degraded peat swamp forests may range from 9-35 t C ha^{-1} yr^{-1}, depending on microclimate and physical properties of the peat (Jauhiainen et al., 2005; Hadi et al., 2001). In addition, leaching of (dissolved) organic material through drainage canals and increased methane emission from drainage canals may increase the system's carbon loss (Figure 3.3).
In the degradation phase the top layers of the peat become highly susceptible to fire which sometimes is also used as a land clearing technique. Fire can in two ways affect the rate of CO_2 released to the atmosphere: 1) directly by combustion of organic material in both the living biomass and the peat and 2) indirectly as dense smoke emitted from large fires reduces photosynthesis of the vegetation thus resulting in lower ecosystem production (Hirano et al., 2007), the latter being of minor importance in the long term carbon balance. The risk and frequency of peatland fires is greatly accelerated by deforestation, drainage and extreme weather events resulting from for example the El Niño Southern Oscillation (Page et al., 2002).

Carbon sequestered in organic material may leach to the water system in the form of particulate organic matter (POM) or as dissolved organic carbon (DOC) and leave the peatland ecosystem either in this form or as CH_4 through anaerobic decomposition. Leaching of organic material is probably very small in undrained peat swamp forests but increases when the system is drained and eroded organic material can easily flow away through drainage canals (see Figure 3.3). The magnitude and fate of this lateral carbon transport through drainage has yet to be quantified for different land uses.

Box 2
Humification and peat quality

The amount of CO_2 released from each centimeter of peat subsidence is related to the bulk density of the peat (Wösten, 2006a; Hooijer et al., 2006). Bulk density in turn is related to the degree of humification of the peat layer. Three main phases of humification can be distinguished (Esterle et al., 1992): *Fibric peat* contains > 66% fibers (15 mm in either diameter or length) by weight and has a bulk density of approximately 0.1 g cm^3. It denotes good preservation but due to its low bulk density the water holding capacity is low and peat is easily drained and consolidated. Fibric peat is mainly found under forests; *Hemic peat* contains 33-66% fibers and has a bulk density of approximately 0.2 g cm^3; *Sapric peat* is the most decomposed of the three and consists of < 33% fibers. Its bulk density is about 0.3 g cm^3. Sapric peat has the highest water holding capacity and is mainly found in plantations. The degree of humification depends on the time since land conversion took place. Over time drainage of peat generally results in the conversion of fibric peat via hemic to sapric peat. Along this pathway peat subsidence usually decreases, however bulk densities increase with as possible net effect a fairly constant CO_2 emission. Another effect occurring along this pathway is the shift in peat quality, i.e. easily decomposable material is rapidly decomposed whereas organic material with a high content of hardly decomposable materials (such as lignin) remains. It seems crucial to take into account the time since land conversion took place as well as the peat quality in assessing the sustainability of land use types on peat.

3.3 Oil palm plantation phase

Oil palm plantation development on cleared peatlands requires ground water levels of 60-80 cm below soil surface (DID, 2001). A higher water table is not appropriate as oil palms cannot survive in waterlogged conditions. As described in the previous paragraph this drainage enhances decomposition rates and CO_2 emissions to the atmosphere. Soil respiration rates in oil palm plantations were found to be less variable compared to those from forests (Figure 3.4), possibly due to the more homogeneous terrain or because of controlled drainage in oil palm plantations. Soil respiration rates in oil palm plantations are about 15 t C ha^{-1} yr^{-1} (Murayama & Bakar, 1996; Melling et al., 2005a), but heavy fertilization may on the other hand stimulate decomposition (Kawahigashi & Sumida, 2006). In addition, mean soil temperatures are generally higher in plantations compared to forest (Melling, 2005a) which may further enhance microbial activity. Thus it seems logical that the peat C stock under oil palm continues to decrease (Figure 3.4), although the rate of carbon loss may be slower compared to degraded forests (Melling et al. 2005a). The carbon losses are to some extent balanced by biomass uptake in oil palms. In relatively short rotations of about 25 years, palm tree biomass builds up (see 'living biomass' C stock in phase 'oil palm' in figure 3.1) which increases the (temporal) above ground carbon storage in both living biomass and products.

In a recent study Melling (2005b) found that CH_4 emissions in an oil palm plantation were lower than those from a peat swamp forest. She suggests that these lower emissions result from aeration (methane oxidation) and soil compaction which reduces gas permeability of the soil. Current research indicates however that CH_4 emissions can be very high in drainage canals and may therefore form a substantial part of the greenhouse gas emissions in tropical peatlands that are converted to plantations (Jauhiainen, pers. comm.). Although this flux of CH_4 from water surfaces has yet to be quantified, it is likely to play an important role in plantations on peat as the water surface from drainage canals may account for 3-5% of the total plantation area. For the same reason carbon losses through leaching seem to be prominent in oil palm plantations as well since organic material can easily flow away through drainage canals. However, to date the quantity of leaching remains largely unknown.

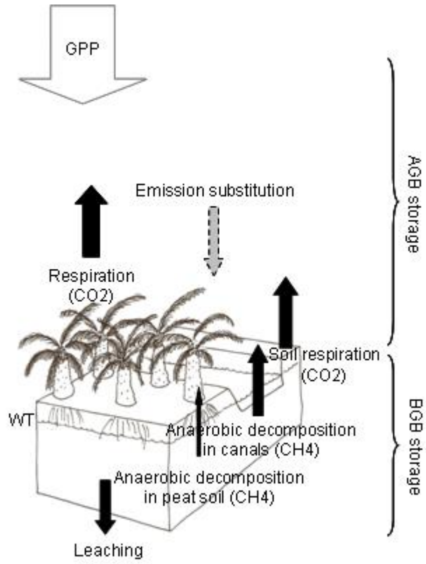


Figure 3.4 Land based carbon fluxes in an oil palm plantation on peat. Grey arrow indicates the emission substitution effect of the oil palm crop. Other symbols are as in Figure 3.2. AGB = above ground biomass, BGB = below ground biomass, WT = average water table.

Carbon losses through fire are limited in Malaysia relative to Indonesia. In Malaysia, fire risk in oil palm plantations on peat is generally reduced because 1) artificial soil compaction during land preparation to reduce the incidence of leaning and toppling of palms due to poor anchorage, also increases the soil moisture content and 2) fire is intensively monitored and controlled. Burning is not allowed. Instead, most plant materials are stacked on the site and left to slow decomposition process (Paramananthan, unpublished.).

Considering the increasing biofuel demand, it is likely that conversion of peat swamp forests will be in part for the production of biofuels. The use of palm oil for biofuel production is a substitute for fossil fuel burning. Each litre of biofuel produced from palm oil thus avoids the need for one litre of fossil fuels (see component 'emission substitution effect' in phase 'oil palm' in figure 3.1). This is a cumulative effect after each harvest of oil seeds. Fargione et al. (2008) estimate that each rotation cycle of palm oil results in an annual emission substitution effect of about 1.9 t C ha^{-1} , assuming an average palm biodiesel yield of 0.9 t C ha^{-1} yr^{-1} (Fargione et al., 2008). By adding the palm oil yield and substitution effect to the land based emissions caused by peat drainage, Fargione et al. (2008) calculated that it would take more than 420 years to repay the carbon losses caused by habitat conversion. Until then, producing and using palm biodiesel from peatlands would cause greater CO_2 emissions than would be saved by refining and using an energy-equivalent amount of petroleum diesel. Fargione et al. (2008) estimated the carbon debts (i.e. the amount of CO_2 released during the first 50 years of land conversion) of nine different scenario's for biofuel production and showed that South East Asian peatlands have the highest carbon debts and the longest repayment time with palm biodiesel production, although oil palm yield is among the highest of the oil crops (Basiron, 2008) (Figure 3.5). Conversion of degraded and abandoned agricultural lands on the other hand causes little or no carbon debt and can offer immediate and sustained greenhouse gas advantages (Germer & Sauerborn, 2007; Fargione et al., 2008). In this context development of oil palm plantations may form an important way to rehabilitate degraded land and sequester carbon (Diemont et al., 2001; Corley, 2005).

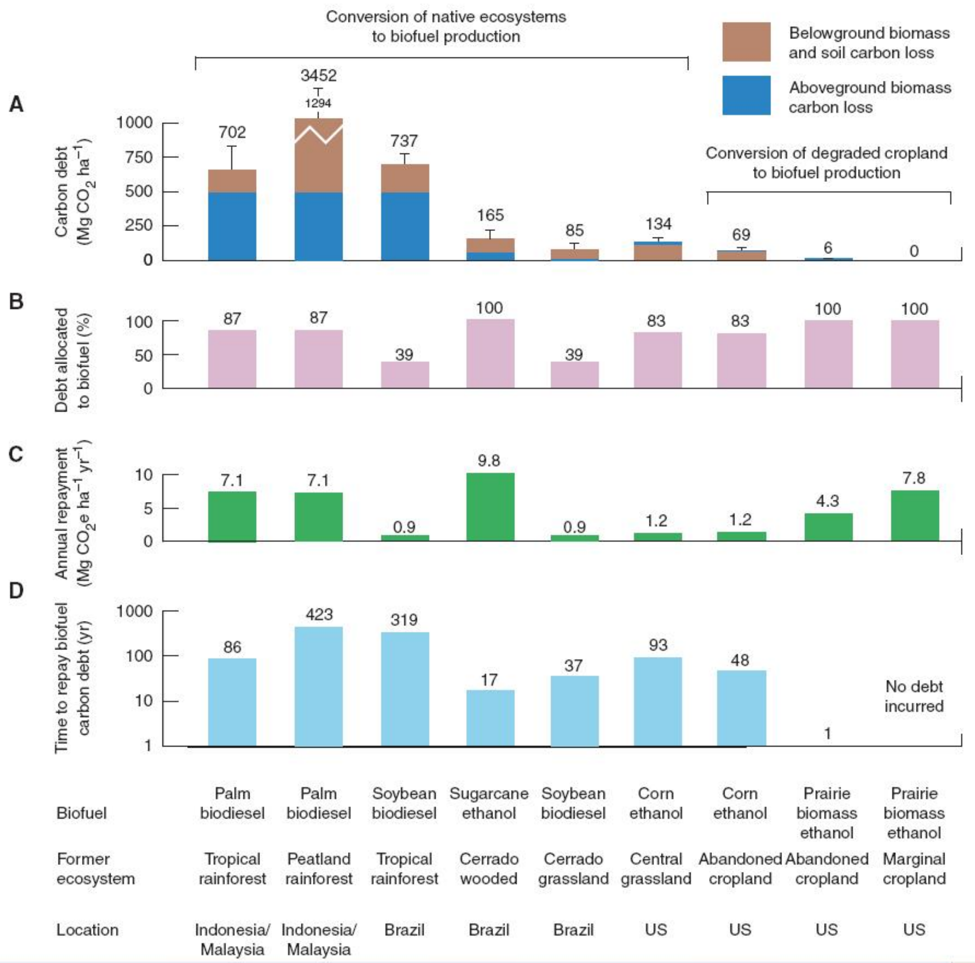


Figure 3.5 Carbon debt, biofuel carbon debt allocation, annual carbon repayment rate, and years to repay biofuel carbon debt for nine scenarios of biofuel production, as was recently published in Science (Fargione et al., 2008). (A) Carbon debt, including CO2 emissions from soils and aboveground and belowground biomass resulting from habitat conversion. (B) Proportion of total carbon debt allocated to biofuel production. (C) Annual life-cycle GHG reduction from biofuels, including displaced fossil fuels and soil carbon storage. (D) Number of years after conversion to biofuel production required for cumulative biofuel GHG reductions, relative to the fossil fuels they displace, to repay the biofuel carbon debt.

4 Sources of confusion

The impact of oil palm plantations on peat in terms of greenhouse gas emissions has been the subject of an ongoing debate. The most important publication fuelling this debate is the article of Melling et al. (2005) in Tellus, which shows that under peat swamp forests the CO_2 emissions may exceed those under oil palm plantations. Another recent review by Hooijer et al. (2006) concludes that the conversion of peat swamp forests is a globally significant source of CO_2. Although results of both studies may seem contradictory, they are not. There are, however, some major points of confusion that are outlined below.

4.1 Necessity to consider the complete system

Both studies merely focus on soil CO_2 efflux and do not perform a full system analysis, including biomass regrowth, and emission reduction effect of palm oil. The soil CO_2 flux represents just one of the carbon fluxes within the carbon cycle of an ecosystem (see Figures 3.2-3.5). Additional information on vegetation growth, respiration, decomposition, leaching and fire is necessary to estimate NEP, i.e. whether a system acts as carbon source or as carbon sink and to what extent.

4.2 Definition of primary forest

Very limited CO_2 emission data are available for peat swamp forests with undisturbed hydrology. Most data is from secondary, selectively logged forests that are influenced by drainage. Melling et al. (2005) claims to have sampled in 'mixed peat swamp forest which represents the climax vegetation of tropical peatland'. This description suggests that the peat swamp forest ecosystem was undisturbed and not drained. However, satellite imagery suggests that all forests surrounding Mukah were disturbed and (partly) degraded at the time of sampling (Wong, 2003). As reported by Melling et al. (2005), the mean water table depth in this forest ecosystem was 45.3 cm, which was lower than the drained sago plantation (27.4 cm) and slightly higher than the oil palm plantations (60.2 cm), indicating that the forest area is likely to have been influenced by drainage of the surrounding peatlands.

4.3 Definition of soil CO_2 efflux

Further confusion exists on the definition of soil CO_2 efflux. Total soil CO_2 efflux is formed by the sum of autotrophic and heterotrophic soil respiration (i.e. respiration by roots, mycorrhizas and soil (micro-)organisms). In forest ecosystems the belowground root respiration is generally higher due to higher belowground biomass compared to agricultural land use. The higher soil emissions measured by Melling et al. (2005) may consequently relate to more CO_2 released from the root system. In several of the CO_2 flux measurements reported in literature it is unclear whether and to what extent the emission includes root respiration, but high data variability suggests that measurements were done under varying conditions.

4.4 Variability in flux data

Part of the debate on CO_2 emissions from tropical peatlands originates from the limited amount of CO_2 flux measurements in undisturbed peat swamp forest. Over fifteen scientific papers are currently available that deal with gas flux measurements of CO_2 using the closed-chamber method in tropical peatlands (Crill, 1991; see Box 3). Only few of them measured in undisturbed primary peat swamp forest (e.g. Yoshioka et al., 2002). The others were performed in secondary, selectively logged forests, rice paddy's, plantations and crop fields. Hooijer et al. (2006) combined these measurements of soil CO_2 emissions with data on peat subsidence rate, peat carbon content and bulk density that were gathered in several land use types in Central Kalimantan, Sarawak, Sumatra and Southern Thailand. Based on this they show a significant positive linear relationship between drainage depth and the emission of CO_2. Thus, each centimeter of lowering the water table yields an additional CO_2 emission of about 1 t CO_2 ha^{-1} yr^{-1} (Figure 4.1). This relationship has been debated because variability was high and because it may not be linear over the full range of water table depths, i.e. CO_2 emissions are likely to be reduced under very wet conditions (water tables in the range of 0-20 cm below surface) while they also seem to reach a maximum under deep drainage (water tables deeper than 80 cm below surface).

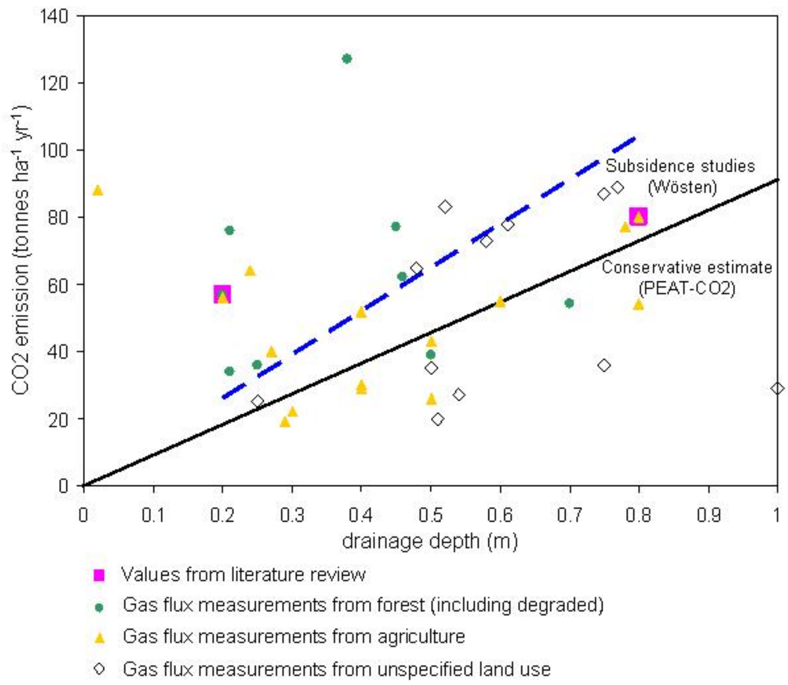


Figure 4.1. Relation between drainage depth and CO2 emissions from decomposition in tropical peatlands, as published in Hooijer et al (2006). The dashed line shows the linear relation derived from the data points. This relationship was based on 15 different studies (table 2), including Melling et al. (2005). The solid black line shows the estimate used for further calculations in the Peat-CO2 report by Hooijer et al. (2006).

The closed-chamber technique can yield precise measurements of the soil CO_2 flux, given that the soil surface is not too porous for chamber installation (Hirano et al., 2007). However, results of gas flux measurements should be dealt with carefully because CO_2 fluxes from tropical peats are highly variable in time and place (Hirano et al., 2007). The closed-chamber technique involves a point measurement in the ecosystem. This point measurement does not necessarily represent soil carbon flux of the entire ecosystem. For instance, peat layers often consist of hummocks (slightly elevated terrain for example around tree stumps) and hollows (slight depressions). CO_2 fluxes may be very different between the two terrain types because of differences in water availability, soil temperature and bulk density (Jauhiainen et al., 2005). High variability in the gas flux dataset used by Hooijer et al. (2006) may result from land use (forest root respiration compared to crop root respiration), the time since land conversion (i.e. the degree of humification), site variability (i.e. microclimatic differences such as soil and air temperature), nutrient status (fertilized versus non-fertilized) and the variability of measuring time (i.e. seasonal changes in soil respiration).

4.5 Other GHG emissions from tropical peats

Emissions of another greenhouse gas (nitrous oxides, mainly N_2O), from peatlands receives increasing attention in determining the climate change effect of peatland conversion (Hadi et al., 2005; Inubushi et al., 2003). Undrained, ombrogeneous peat swamp forest is naturally poor in nutrients, but the consequences of forest conversion on nitrogen emissions are poorly understood. Drainage and development of oil palm on peat increases the rate of peat decomposition and also the process of peat mineralization by increasing the amount of available N, which indirectly will contribute to higher N_2O emissions (Melling, pers. comm.). The mean annual N_2O emission from a secondary peatland forest in Kalimantan was nearly 0.014 t N ha^{-1} yr^{-1}, which was high compared to the N_2O emission from a paddy field and a rice-soybean rotation field (Hadi et al., 2005). However, conversion of secondary peatland forests to agriculture may significantly enhance the N_2O emissions (Hadi et al., 2000; Hadi et al,. 2001). It seems likely that the application of nitrogen fertilizers in oil palm plantations could accelerate both the release of N_2O and CO_2, although under high ammonium concentrations nitrification may be hindered (Hadi et al., 2001). It is unknown to what extent the effect of excess nitrogen released in drained forests or plantations on vegetation growth rates (i.e. more carbon storage in aboveground biomass) could neutralize the carbon losses through continued decomposition of peat.

Currently it is believed that the emissions of methane (CH_4) from tropical peat swamp areas only form a minor contribution to the greenhouse effect compared to the emissions of CO_2. Nevertheless, the extent of CH_4 emissions from open water surfaces in drained peatlands and the production of CH_4 by termites remain unknown and therefore its importance may be as yet underestimated.

5 Gaps of knowledge and recommendations for further research

5.1 Gaps of knowledge

5.1.1 Full ecosystem carbon balance

The pathways of carbon loss from (agro-) ecosystems on peat are poorly understood. They have to be further quantified and analyzed in order to estimate their consequences for the total carbon balance. For example leaching of organic carbon and anaerobic decomposition (especially from drainage canals) could be important sources of carbon loss in degraded forests or oil palm plantations. Effects of artificial soil compaction in oil palm plantations may significantly reduce greenhouse gas emissions from the soil by decreasing pore size and thereby increasing soil moisture content.

In addition, there is a lack of data and knowledge on long-term rates of carbon accumulation in tropical peatlands. This knowledge is needed when investigating the carbon cycle in peatlands and its relationship to climate change.

5.1.2 Estimates of carbon content

Limited knowledge of carbon fluxes within disturbed and undisturbed peatland ecosystems is available, causing confusion in the debate about the net greenhouse effect of oil palm plantation on former tropical peat forests. More information and data are needed, especially because Malaysian peatlands are still poorly described in terms of peat profile morphology, peat depth, peat chemistry, peat classification, peat variation and its associated vegetation. These factors are essential to achieve better estimates of carbon content and potential greenhouse gas emissions. The current figures of peat carbon stocks (Hooijer et al., 2006) result from a few major assumptions concerning peat depth, bulk density and carbon content. Small variations in these parameters can largely influence the estimated amount and hence more precise estimates are needed. As peat characteristics are highly spatial variable and change also over time (like the conversion from fibric to hemic peats) it is essential to clarify these processes and their effects on carbon emissions.

5.1.3 Relation between drainage and CO_2 emission

The empirical relation between drainage level and CO_2 emission is highly variable. It is poorly understood to what extent this relation is influenced by factors such as soil temperature, chemistry, moisture content etc. Melling et al. (2005) demonstrates that it strongly depends on the type of ecosystem which of the factors is the most important determinant of soil CO_2 emission. For example the effects of fertilizer application in oil palm plantations on CO_2 and N_2O emissions are not clear. In addition, most of the studies that measured CO_2 fluxes were localized in degraded forests that were somehow influenced by drainage. CO_2 emissions from natural, undisturbed peat swamp forests in Malaysia are as yet unclear. Spatial and temporal variation seems to be very high so it may not be legitimate to extrapolate carbon fluxes over large areas.

5.2 Recommendations for further research

5.2.1 Full ecosystem carbon balance

To understand carbon dynamics of peatlands more data is needed to determine to what extent carbon accumulation still occurs in peatland ecosystems and to what extent peat formation is limited under oil palm plantations. The full ecosystem carbon balance for different land use types can be estimated quite precisely with the use of Eddy Covariance Flux measurements located in undrained pristine peat swamp forests, disturbed forests and agricultural ecosystems. The Eddy Covariance measurements are done above the forest canopy (Hirano et al., 2007), thus incorporating carbon fluxes of both respiration and decomposition (see Box 3).
These measurements should be done in combination with:
- remotely sensed data interpretationand;
- ground truth field inventories of carbon stocks;
- full greenhouse gas balances of the oil palm system, including alternative management and processing systems of the palm oil.

To reduce the high variability and uncertainties in the data of separate carbon fluxes the following measurements are needed:
- Additional CO_2 flux data, especially for undrained peat swamp forests;
- Insight in the magnitude of carbon leaching and lateral transport via canals and rivers;
- Quantification of CH_4, CO_2 and N_2O emissions from peat basins.

5.2.2 Estimates of carbon content

An improved understanding of the magnitude of the tropical peatland carbon content is essential given the current interest in greenhouse gas emissions from drained and degrading tropical peatlands and the role that tropical peatlands play in carbon offset and carbon trading agreements. To improve estimations of peatland carbon content and emissions the following is needed:
- Gathering data on peat thickness that represent the actual situation in Malaysia;
- Precise measurements of peat bulk density and carbon content.
- Estimates of above ground carbon content in both undisturbed and degraded peat swamp forests

5.2.3 Relation between drainage and CO_2 emission

The major uncertainties in the relationship between drainage depth, subsidence rate and CO_2 emission as proposed by Hooijer et al. (2006), should be reduced by:

- Defining separate relations for different land use types to account for the effects of vegetation cover and land management;
- Incorporating the time since land conversion in the relation thus distinguishing sites that were converted only recently and sites that have long been converted.

Such a reduction of data variation is crucial since the current estimates of carbon emission from drained peat largely depend on this relation. Stratified sampling is needed so that additional flux measurements are representative for varying peat areas. A prerequisite for making progress on this item is that a database is created capturing all georeferenced, measured CO2 flux data as reported in the literature together with information on groundwater level, land use type, time after land conversion etc. Statistical analyses of these data will result in improved relationships between CO2 emissions and drainage.

5.3 Additional research on sustainable use of peatlands

Above mentioned information combined with high resolution land use cover data can form the input for scenario based modeling of individual peatland areas, rather than projections for the whole of South East Asia. Climate change projections such as increased drought in Sarawak are relevant to be incorporated in these models in order to assess the impact of future climate change. It may be relevant for these scenarios to evaluate the potential reduction of greenhouse gas emissions through restoration of the water tables in degraded peatland areas as well.

Both satellite imaginary and GHG flux measurements indicate that greenhouse gas emissions from drained peatland areas may contribute significantly to anthropogenic climate change. This underlines the function of intact peat swamp forests in the global carbon cycle.

The conservation of intact peat swamp forests is important for a number of other ecosystem functions such as biodiversity, genetic reservoir, water retention, provision of clean drinking water, flood prevention, coastal protection and tourism. The challenge for long term sustainable development is to find ways to integrate the different goods and services which are provided into landscape systems that combine financial, socio-cultural and environmental benefits. It is crucial that these values are strongly recognized in the decision making process in order to achieve sustainable development of peatlands.

New initiatives such as payments for reduced emissions from avoided deforestation and forest degradation (REDD) may form a useful instrument in the development of new strategies for sustainable use and conservation of the remaining peat swamp forest areas. At the same time these new mechanisms also require more in-depth knowledge of carbon stocks and flows of peat land systems.

Box 3
Measuring C-fluxes

NEP is defined as the net carbon exchange between the ecosystem and the atmosphere. It can be estimated by measuring separate carbon fluxes within the ecosystem and adding those fluxes, or by measuring incoming and outgoing carbon fluxes above the canopy.

Soil CO_2 fluxes are generally measured with the closed chamber method which involves placement of an open ended stainless steel cylinder over the top layer of the soil. Gas is subsequently extracted from the headspace of the cylinder into an airtight bag and analyzed in the laboratory.

Eddy Covariance Towers are equipped with measurement apparatus for incoming and outgoing greenhouse gas fluxes. Because Eddy Covariance measurements are made continuously above the forest canopy they give a reliable estimate of the ecosystem production and carbon dynamics, although lateral or downward carbon fluxes such as leaching are not incorporated in the measurements.

Leaching can be estimated using surface water samples from the catchment area and extracting the organic material.

6 Conclusions

Full system carbon balances of forest ecosystems are complex and show a large variety both in time and space. This is because the net balance is determined by several gross fluxes, each controlled by many factors, both natural and anthropogenic. The gross fluxes originate from all compartments of the carbon cycle, being living biomass, dead wood, (peat) soils, wood products, and emission substitution. The anthropogenic influences are determined by land use (change) decisions that not only have the carbon balance as the prime goal, but that are driven by decisions concerning income, food and fiber production and/or poverty alleviation and biodiversity conservation. The natural influences are related to the different plant communities associated with peatland hydrology. Changes in precipitation regime or other disturbances of the hydrology will have an impact on this fragile system. Increased temperatures will increase decomposition rates of organic material. This is the complex system of many fluxes, carbon compartments and human influences. It is this system on which we try to shed light on the uncertainties, the various estimates, and the relevance of some of the estimates in literature.

Based on this review we can conclude the following:

- Results of soil CO_2 flux measurements as described in the literature are confusing because of a limited description of the system and the context:
    - Measurements of forest soil CO_2 flux in Melling et al. (2005) appear to have been measured in an isolated forest patch that was disturbed and influenced by drainage as well. High soil emissions as reported by them can therefore probably be assigned to drainage effects;
    - The Hooijer et al. (2006) series of measurements portray a large cloud of soil CO_2 efflux measurements indicating a considerable uncertainty in the relationship. As a result, upscaling to arrive at a regional carbon budget is hampered by considerable uncertainty as indicated in their report.
- Soil CO_2 flux only forms one part of the Net Ecosystem Production. All carbon fluxes within the (agro)ecosystem should be defined in order to assess the net uptake/emission of CO_2 in these systems.
- Soil CO_2 fluxes may be highly variable due to heterogeneous peat characteristics, land use type, degree of humification, microclimatic variations such as soil and air temperature and seasonal variability.
- Primary forests on undrained peat sites hold the largest stocks of carbon, both in biomass as well as in the peat.
- Peat swamp forests areas which are artificially drained are most likely net emitters of CO_2. Soil CO_2 emissions in such forests are likely higher compared to oil palm plantations because of 1) the degree of humification of the peat layer and 2) higher root respiration due to more belowground biomass in forests compared to plantations. However, this last argument is still being debated.

- Drainage depth of > 50cm below soil surface is required for the establishment of oil palm plantations. With such a drainage depth the process of peat accumulation stops and the peat starts to decompose due to oxidation.
- The substitution potential of palm oil is about 7.1 Mg CO_2 ha^{-1} y^{-1}, but establishing palm oil plantations on pristine forest areas will result in large carbon emission most likely offsetting future gains in substitution of fossil fuel. It will take a very long time to compensate for the carbon losses that were caused by land conversion. Therefore oil palm plantations should be established (where possible) on already marginal or degraded sites.
- Research recommendations include Eddy Covariance measurements of net ecosystem production in undisturbed and converted peat swamp forests and in oil palm plantations; the assessment of carbon losses through leaching and methane emissions from drainage canals; measurements of peat depth and bulk density and estimates of above- and belowground carbon content.

Literature

Aaby, B., Tauber, H. 1975. Rates of peat formation in relation to humification and local environment, as shown by studies of a raised bog in Denmark. Boreas 4:1-17

Aminuddin, B.Y. (Editor). 1994. Tropical Peat; Proceedings of the International Symposium on Tropical Peatland, 6-10 May 1991, Kuching, Sarawak, Malaysia.

Anderson, J.A.R. 1961. The ecology and forest types of the peat swamps forests of Sarawak and Brunei in relation to their silviculture. Ph.D. Thesis, University of Edinburgh, U.K.

Andriesse, J.P. 1994. Constraints and opportunities for alternative use options of tropical peat land. In: B.Y. Aminuddin (Editor), Tropical Peat; Proceedings of the International Symposium on Tropical Peatland, 6-10 May 1991, Kuching, Sarawak, Malaysia.

Anon. 1990. Mission Report submitted to the ITTC by Mission established pursuant to Resolution I(VI) 'The Promotion of Sustainable Forest Management: A Case Study in Sarawak Malaysia'.

Basiron, Y. 2007. Palm oil production through sustainable plantations. European Journal of Lipid Science and Technology 109, 289-295

Chimner, R.A., Ewel, K.C. 2005. A tropical freshwater wetland: II. Production, decomposition, and peat formation. Wetlands Ecology and Management 13:671–684

Corley, R.H.V. 2005. Is the oil palm industry sustainable? In: Proceedings of agriculture, biotechnology & sustainability conference. Technological breakthroughs and commercialization - The way forward. PIPOC 2005, International Palm Oil Congress, 25-29 September 2005. P1, pp. 89-107

Crill, P.M. 1991. Seasonal patterns of methane uptake and carbon dioxide release by a temperate woodland soil. Global Biogeochemical Cycles 5, 319-334

Department of Irrigation and Drainage (DID). 2001. Water management guidelines for agricultural development in coastal lowlands of Sarawak. Department of Irrigation and Drainage, Sarawak.

Diemont, W.H., Joosten, H., Mantel, S., Murdiyarso, D., Noordwijk, M.v., Rieley, J.O., Veldsink, J.W., Verhagen, A., Wakker, E., Wind, J., Setiadi, B., Limin, S.H. 2001. Poverty alleviation and wise use of peatlands in Indonesia. International Peat Journal: 11: 79-87

Esterle, J.S., Calvert, G., Durgi, D., Tie, Y.L., Supardi. 1992. Characterization and classification of tropical wood peats from Baram River, Sarawak and Jambi, Sumatra. In: Proceedings of the International Symposium on Tropical Peatlands. Kuching, Sarawak, Malaysia, 1991. MARDI, Ministry of Agriculture, Malaysia. Pp. 33-48.

Fargione, J., Hill, J., Tilman, D., Polasky, S., Hawthorne, P. 2008. Land Clearing and the Biofuel Carbon Debt. Science 319(29): 1235-1238

FAO. 2005. State of the worlds forests 2005, Food and Agricultural Organization of the United Nations

Furukawa, Y., Inubushi, K., Ali, M., Itang, A.M., Suruta, H. 2005. Effects of changing groundwater levels caused by land use changes on greenhouse gas fluxes from tropical peatlands. Nutrient Cycling in Agroecosystems 71: 81–91

Germer, J., Sauerborn, J. 2007. Estimation of the impact of oil palm plantation establishment on greenhouse gas balance. Environment, Development and Sustainability. 14 February 2007. 10.1007/s10668-006-9080-1

Gorham, E. 1991. Northern peatlands: role in the carbon cycle and probable responses to climatic warming. Ecological Applications 1(2): 182-195

Hadi, A., Haridi, M., Inubushi, K., Purnomo, E., Razie, F., Tsuruta, H. 2001. Effects of land-use change in tropical peat soil on the microbial population and emission of greenhouse gases. Microbes and Environment 16(2): 79-86

Henson, I.E., 2005. Plantations on peat: How sustainable are they? Environmental aspects of developing peat lands for agriculture. In: Proceedings of agriculture, biotechnology & sustainability conference. Technological breakthroughs and commercialization - The way forward. PIPOC 2005, International Palm Oil Congress, 25-29 September 2005. AP34, pp. 1020-1045

Hirano, T., Segah, H., Harada, T., Limin, S., June , T., Hirata, R., Osaki, M. 2007. Carbon dioxide balance of a tropical peat swamp forest in Kalimantan, Indonesia. Global Change Biology 13: 412–425

Hooijer, A., Silvius, M., Wösten, H., Page, S. 2006. Peat-CO2, Assessement of CO2 emissions from drained peatlands in SE Asia. Delft Hydraulics report Q3943 (2006)

Hooijer, A., 2004. Hydrology of tropical wetland forests: recent research results from Sarawak peatswamps. In: M. Bonell and L.A. Bruijnzeel (Editors), Forests, water and people in the humid tropics: past, present and future hydrological research for integrated land and water management. Cambridge University Press., Cambridge, UK, pp. 447-461.

Inubushi, K., Furukawa, Y., Hadi, A., Punomo, E., Tsuruta, H. 2003. Seasonal changes of CO2, CH4 and N2O fluxes in relation to land-use change in tropical peatlands located in coastal area of South Kalimantan. Chemosphere 52: 603-608

IPCC, 2001. Climate change 2001: the scientific basis, in: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Xiaosu, D. 1452 L. Melling et al. / Soil Biology & Biochemistry 37 (2005) 1445–1453 (Eds.), Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jauhiainen, J., Takahashi, H., Heikkinen, J.E.P., Martikkainen, P.J., Vasanders, H. 2005. Carbon fluxes from a tropical peat swamp forest floor. Global Change Biology 11, 1788–1797

Kawahigashi, M., Sumida, H. 2006. Humus composition and physico-chemical properties of humic acids in tropical peat soils under sago palm plantation. Soil Science & Plant Nutrition 52 (2), 153–161

Lasco, R.D. 2002. Forest carbon bugets in Southeast Asia following harvesting an land cover change. Science in China (Series C): Vol. 45 Supp., 55-64;

Lamade, E., Bouillet, J-P. 2005. Carbon storage and global change: the role of oil palm. Oléagineux, Corps Gras, Lipides 12(2): 154-160

Lee, H. S. 1977. "Manipulation and regeneration of the mixed swamp forest in Sarawak." Malayan Nature Journal 31(1): 1-9.

Lee, H.S. 1979. Natural regeneration and reforestation in the peat swamp forests of Sarawak. Tropical Agriculture Research Series No. 12, Tropical Agriculture Research Center, Ministry of Agriculture, Forestry and Fisheries, Yatabe, Tsukuba, Ibaraki 300-21, Japan.

Lee, H.S. 2004. Improving biodiversity and sustainability of peat swamp forests of Sarawak. Joint Working Group Malaysia-The Netherlands: Sustainable Management of Peat Swamp Forests of Sarawak with Special Reference to Ramin. JWG/RAW/12

Lee, H.S., Chai, F. 1996. Production functions of peat swamp forests in Sarawak. In: Maltby, E., Immirzi, S.P. and Safford, R.J. 1996. Tropical Lowland Peatlands of Southeast Asia, Proceedings of a Workshop on Integrated Planning and Management of Tropical Lowland Peatlands held at Cisarua, Indonesia, 3-8 July 1992. IUCN, Gland, Switzerland.

Mantel S., Wösten H., and Verhagen J. 2007. Biophysical Land Suitability for Oil Palm in Kalimantan, Indonesia. Report 2007/01, ISRIC – World Soil Information, Alterra, Plant Research International, Wageningen UR, Wageningen.

McMorrow, J., Talip, M.A. 1999. Decline of forest area in Sabah, Malaysia: Relationship to state policies, land code and land capability. Global Environmental Change 11, 217-230

Melling, L., Hatano, R., Goh, K.J. 2005a. Soil CO2 flux from three ecosystems in tropical peatland of Sarawak, Malaysia. Tellus 57B, 1-11

Melling, L., Hatano, R., Goh, K.J. 2005b. Methane fluxes from three ecosystems in tropical peatland of Sarawak, Malaysia. Soil Biology & Biochemistry 37 (2005) 1445–1453

Melling, L., Goh, K.J., Uyo, L.J., Sayok, A., Hatano, R. 2007a. Byophysical characteristics of tropical peatland. In: Jol, H., Joo, G.K., Ishak, C.F., Melling, L., Ahmed, O.H., Jalloh, M.B., Sayok, A., Balasundram, S. (editors), Proceedings of the Soil Science Conference of Malaysia, 17-19 April 2007, Mukah, Sarawak.

Melling, L., Hatano, R., Goh, K.J. 2007b. Nitrous oxide emissions from three ecosystems in tropical peatland of Sarawak, Malaysia. Soil Science and Plant Nutrition 53, 792–805

Melling, L., Goh, K.J., Beauvais, C., Hatano, R. 2008. Carbon flow and budget in a young mature oil palm agroecosystem on deep tropical peat. The Planter 84(982): 21-25

Murayama, S., & Bakar, Z. A. 1996. Decomposition of tropical peat soils. 2. Estimation of in situ decomposition by measurement of CO2 flux. Japan Agricultural Research Quarterly 30: 153-158

Murdiyarso, D., Wasrin, U.R. 1995. Estimating Land Use Change and Carbon Release from Tropical Forests Conversion Using Remote Sensing Technique. Journal of Biogeography 22(4/5): 715-721

Page, S.E., Rieley, J.O., Shotyk, O.W. & Weiss, D. 1999. Interdependence of peat and vegetation in a tropical peat swamp forest. Philosophical Transactions of the Royal Society of London B, 354, 1-13

Page, S.E., Siegert, F., Rieley, J.O., Boehm, H v., Jayak, A., Limink, S. 2002. The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature 420, 61-65

Page, S.E., Wüst, R.A.J., Weiss, D. et al. 2004. A record of late Pleistocene and Holocene carbon accumulation and climate change from an equatorial peat bog (Kalimantan, Indonesia): implications for past, present and future carbon dynamics. Journal of Quaternary Science 19, 625–635

Paramananthan, S. Tropical lowland peats: to conserve or develop them? Param Agricultural Soil Surveys (M) Sdn. Bhd. Petaling Jaya, Selangor, Malaysia

Reijnders. L., Huijbregts, M.A.J. 2008. Palm oil and the emission of carbon-based greenhouse gases. Journal of Cleaner Production 16: 477-482

Rieley, J.O., Ahmad-Shah, A-A., Brady, M.A. 1996. The extent and nature of tropical peat swamps. Maltby, E., Immirzi, C.P., Safford, F.J. (eds). Tropical Lowland Peatlands of Southeast Asia, Proceedings of a Workshop on Integrated Planning and Management of Tropical Lowland Peatlands held at Cisarua, Indonesia, 3-8 July 1992. IUCN, Gland, Switzerland.

Rieley, J.O., Wüst, R.A.J., Jauhiainen, J., Page, S.E., Wösten, H., Hooijer, A., Siegert, F., Limin, S.H., Vasander, H., Stahlhut, M. 2008. Tropical Peatlands: carbon stores, carbon gas emissions and contribution to climate change processes. Chapter 6: pp:148-18.In: Strack, M. (editor). 2008. Peatlands and climate change. International Peat Society.

RSPO. 2005. Roundtable on Sustainable Palm Oil: Principles and Criteria for Sustainable Palm Oil Production. Version 3. 22 September 2005

Sabine, C.L., Heimann, M., Artaxo, P., Bakker, D.C.E., Chen, C.-T.A., Field, C.B., Le Gruber, N., Quéré, C.L., Prinn, R.G., Richey, J.E., Lankao, P.R., Sathaye, J.A., Valentini, R. 2004. Current status and past trends of the global carbon cycle. In: Field, C.B., Raupach, M.R. (Eds.), The Global Carbon Cycle, Island Press, Washington, pp. 17–44

Salmah, Z., Spoor, G., Zahari, A.B. and Welch, D.N. 1994. Importance of water management in peat soil at farm level. In: B.Y. Aminuddin (Editor), Tropical Peat; Proceedings of the International Symposium on Tropical Peatland, 6-10 May 1991, Kuching, Sarawak, Malaysia.

Sawal, P. 2005. Threats to Peat Swamp Forests of Sarawak. Sarawak Forest Department, Sarawak Forestry Corporation. Kuching. (JWG/RAM/02).

Shahbudin, M.S. 2005. Development and management of Maludam National Park, Betong Division Sarawak. Completion Report. Forest Department Sarawak, Kuching.

Suzuki, S., Ishida, T., Nagano, T., Waijaroen, S. 1999. Influences of deforestation on carbon balance in a natural tropical peat swamp forest in Thailand. Environmental Control Biology 37: 115-128

Tansey et al. 2004. A global inventory of burnt areas at 1 km resolution for the year 2000 derived from spot vegetation data. Climatic Change 67: 345-377

Turunen, J. 2003. Past and present carbon accumulation in undisturbed boreal and subarctic mires: a review. Suo 54(1): 15-28

United Nations Development Program. 2006. Malaysia's Peat Swamp Forests, Conservations and sustainable use. UNDP Malaysia

Welch, D.N. and Nor, M.A.M. 1989. Drainage works on peat in relation to crop cultivation – a review of problems. Mal. Soc. Soil Sci., National Seminar on Soil Management for Food and Fruit Crop Production, 28-29 March 1989, Kuala Lumpur.

Wong, J. 2003. The Status of Peat Swamp Forest in Sarawak. Final Report for The Sustainable Management of Peat Swamp Forest in Sarawak with special reference to ramin (Gonystylus bancanus) Project, Forest Department, Kuching, Sarawak, Malaysia.

Wösten, J.H.M., van den Berg, J., van Eijk, P., Gevers, G.J.M., Giesen, W.B.J.T., Hooijer, A., Aswandi Idris, Leenman, P.H., Dipa Satriadi Rais, Siderius, C., Silvius, M.J., Suryadiputra, N. and Iwan Tricahyo Wibisono. 2006a. Interrelationships between hydrology and ecology in fire degraded tropical peat swamp forests. Water Resources Development, Vol. 22, No. 1, 157-174.

Wösten, H., Hooijer, A., Siderius, C., Rais, D.S., Idris, A. and Rieley, J.O. 2006b. Tropical peatland water management modelling of the Air Hitam Laut catchment in Indonesia. International Journal of River Basin Management, vol. 4, no. 4, pp. 233-244.

Wösten, J.H.M., Clymans, E., Page, S.E., Rieley, J.O., Limin, S.H., 2008. Peat – water interrelationships in a tropical peatland ecosystem in Southeast Asia. Catena 73, 212-224.

Wösten, J.H.M. and Radjagukguk, B. (eds.) 2007. The role of tropical peatlands in global change processes. Open Science Meeting 2005. Science and Society: new challenges and opportunities. 27-29 September 2005, Yogyakarta, Indonesia. Alterra, ISBN: 978-90-327-0357-8

Wösten, J.H.M., A.B. Ismail and A.L.M. Van Wijk. 1997. Peat subsidence and its practical implications: a case study in Malaysia. Geoderma 78, 25-36

Wösten, J.H.M. and H.P. Ritzema. 2001. Land and water management options for peatland development in Sarawak, Malaysia. International Peat Journal 11, 59-66.

Yoshioka, T., Ueda, s., Miyajima, T., Wada, E., Yoshida, N., Sugimoto, A., Vijarnsorn, P., Boonprakub, S. 2002. Biogeochemical properties of a tropical swamp forest ecosystem in southern Thailand. Limnology 3, 51–59

Appendix 1 Carbon pools and fluxes

Carbon budgets of undisturbed peat swamp forest degraded peat swamp forest and oil palm plantation in several sites in Southeast Asia, based on a preliminary literature review. Belowground carbon storage is not included because it depends strongly on peat depth and is only to a lesser extent determined by land use.* = comparative data of non-peat areas; ? = value not found in literature.

Peat swamp forest (avg >-25cm watertable)	Value	Unit	Source	Site
Aboveground c storage:	323*	t C/ha	Lasco, 2002	Avg for tropical forest
	250	t C/ha	Murdiyarso & Warsin, 1995	Sumatra
CO_2 emissions from soil:	?			
CO_2 emissions from soil and root respiration:	9.55	t C/ha/yr	Jauhiainen et al., 2005	Central Kalimantan
	10.64	t C/ha/yr	Muruyama & Bakar, 1996	Western Johore
	9.28	t C/ha/yr	Jauhiainen et al., 2005	Recovering forest
NPP	25	t C/ha/yr	Murdiyarso & Warsin, 1995	Tropical swamp forest
NEP:	5.32	t C/ha/yr	Suzuki, 1999	primary PSF, Thailand
	5.22	t C/ha/yr	Suzuki, 1999	secondary PSF, Thailand
	1.62	t C/ha/yr	Henson, 2005	Undisturbed PSF

Peat swamp forest (avg <-20cm watertable)	Value	Unit	Source	Site
Aboveground c storage:	181*	t C/ha	Lasco, 2002	Avg for disturbed tropical forest
CO_2 emissions from soil:	?			
CO_2 emissions from soil and root respiration:	21	t C/ha/yr	Melling et al., 2005	Sarawak
GPP:	34.34	t C/ha/yr	Hirano et al., 2007	Central Kalimantan
NEP:	-4.33	t C/ha/yr	Hirano et al., 2007	Central Kalimantan

Oil Palm Plantation on peat (avg 60-80 cm drainage)	**Value**	**Unit**	**Source**	**Site**
Aboveground c storage:	69.1*	t C/ha	Lasco, 2002	Avg for oil palm, Malaysia
CO_2 emissions from soil:	11.15	t C/ha/yr	Melling et al., 2008	Sarawak (deep peat)
CO_2 emissions from soil and root respiration:	14.74	t C/ha/yr	Murayama & Bakar, 1996	Western Johore
	15.02	t C/ha/yr	Melling et al. 2005	Sarawak
	15.4	t C/ha/yr	Melling et al., 2008	Sarawak (deep peat)
GPP:	?			
NPP:	12.01	t C/ha/yr	Melling et al., 2008	Sarawak (deep peat)
	20.14	t C/ha/yr	Lamade & Bouillet, 2005	Avg for oil palm, Malaysia
NEP:	1.06	t C/ha/yr	Melling et al., 2008	Sarawak (deep peat)
	-5.41	t C/ha/yr	Henson, 2005	Sarawak