CHAPTER 6:

TROPICAL PEATLANDS: CARBON STORES, CARBON GAS EMISSIONS AND CONTRIBUTION TO CLIMATE CHANGE PROCESSES

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6.1. Introduction

6.1.1 Background

Peatlands worldwide play a vital role in biosphere biogeochemical processes (Immirzi *et al.*, 1992). The majority of the world's peatlands by area occur in boreal and temperate zones where they have formed in low-relief (poorly draining) environments under high precipitation-low temperature climatic regimes. In the humid tropics, however, regional environmental and topographic conditions have enabled peat to form under high precipitation-high temperature conditions (Rieley & Page, 1997). In lowland Southeast Asia, peatlands form part of the mosaic of rain forest types that includes mangrove, lowland dipterocarp, heath, montane and cloud forests (Rieley *et al.*, 1996; Page *et al.*, 1999). Most tropical peatlands are located at low altitudes where peat swamp forest occurs on top of a thick mass of organic matter, to which it has contributed over thousands of years, forming accumulated deposits up to 20 m thick (Anderson, 1983). Other areas of peatland in the tropics occur at high altitude, some of which are forested, while others contain *Sphagnum* mosses (Gore, 1983).

Tropical peatlands can be valued according to their functions, which are either, direct or indirect, products or attributes (Maltby, 1997; Joosten & Clarke, 2002). Direct functions include water flow regulation (water storage, filtration and supply), protection from natural forces (erosion prevention, flood mitigation), macro-climate stabilization, recreation and education, and production of food and other resources for local communities. Indirect or ecological functions of peatlands include sediment retention, nutrient detention, carbon (C) balance and storage, and micro-climate stabilization. Peatland products include provision of water to other ecosystems and human communities, forest resources ranging from fuel wood, timber and bark to resins and medicines, wildlife resources, agricultural and horticultural resources, and energy resources (Page & Rieley, 1998). Attributes of tropical peatland are values, other than products, that can be derived directly from the ecosystem or functions that are related closely to the maintenance of environmental quality (Joosten & Clarke, 2002). These include biological diversity since tropical peatlands are important genetic reservoirs of many animals and plants, unique locations for culture and heritage and habitats for the life cycles of flora and fauna. Many of the trees found in tropical peat swamp forest are endemic to the ecosystem, while it is the preferred habitat of some animals, for example, orang utan, often because it is the only location remaining for their survival (Morrough-Bernard *et al.*, 2003).

Tropical peatlands have long provided goods and services for local communities to fulfill their daily, basic requirements, for example, hunting grounds and fishing areas, food and medicines and construction materials. In the marginal areas surrounding tropical peatlands subsistence dry land agriculture has been practised by indigenous people for generations. More recently, timber extraction has been carried out, particularly in the peat swamp forests of Indonesia and Malaysia, providing employment, local income, new industries and business opportunities, and contributing to national exchequers, but at the expense of the ecosystem and the environment (Rieley & Page, 2005).

At the present time, and in the absence of human intervention, many tropical deposits are actively accumulating peat or are in a steady state (Brady, 1997a; b), although evidence suggests that climatic and land use conditions are no longer conducive to continued accumulation at many sites (Sieffermann *et al*., 1988; Page *et al*., 1999; Hirano *et al*., 2007). Land use change has altered some of the deposits and their environments significantly, causing the organic matter that accumulated rapidly in the past to undergo decomposition as a result of lowered water tables. Since the 1970s large areas of lowland tropical peatland in Southeast Asia, especially Indonesia, Malaysia and Thailand, have been converted, usually for single sector purposes, especially agriculture and forestry but to a lesser extent for aquaculture, energy and horticulture following forest clearance and drainage (Notohadiprawiro, 1998). Unfortunately, many projects have been unsuccessful and given rise to major problems as a result of land degradation and fire. In Indonesia, for example, agricultural development on thick peat, beyond tidal influence has failed, largely because planners considered peatlands to be just another type of land and did not take into account the special physical and chemical properties of peat soils. The Mega Rice Project in Central Kalimantan, an attempt to convert about one million hectares of wetland (mostly peatland) to rice fields, failed and similar problems have been experienced on peatland elsewhere in the Southeast Asian region (Muhamad & Rieley, 2002).

Much of the recent increased interest in peatlands globally has resulted from their importance as carbon sinks and stores and their role in carbon cycling between the earth's surface and the atmosphere (Immirzi *et al.*, 1992; Hooijer *et al.*, 2006). There is considerable debate about whether or not peatlands globally are net absorbers or emitters of carbon and under what conditions they may sequester or release this environmentally important element. It has been documented that tropical peatland acts as both carbon sequester and producer depending on seasonal changes in precipitation, temperature, the type of vegetation cover and land use. In SE-Asia, in recent years, detailed work has been carried out on carbon gas emissions from tropical peatlands in their natural condition and following degradation and conversion to agriculture and plantations (Hirano *et al*., 2007; Jauhiainen *et al.,* 2004; 2005; Melling *et al.,* 2005 a; b). Tropical forests, especially peat swamp forests, are sensitive, however, to temperature and precipitation changes, and evidence shows that long periods of drought can change peat swamp forests from carbon sinks to carbon sources (Suzuki *et al*., 1999; Hirano *et al.,* 2007).

Tropical peat swamp forest resources and natural functions are being damaged severely as a result of development, illegal logging and fire and may soon be destroyed forever with potentially devastating consequences regionally and globally (Page *et al.,* 2002; Rieley & Page, 2005; Hooijer *et al.,* 2006). Following land clearance and deep drainage the failed Mega Rice Project area became fire prone. Around 56% of this landscape burned in 1997 releasing 150-180 Mt C as gases and particulates to the atmosphere that contributed to climate change processes and also affected human health.

6.1.2. Location and extent of tropical peatlands

Tropical peatlands are found in mainland East Asia, Southeast Asia, the Caribbean and Central America, South America and southern Africa (Table 6.1). The current estimate of the total area of undeveloped tropical peatland is in the range 30 – 45 million hectares, which is approximately 10-12% of the global peatland resource (Immirzi & Maltby, 1992; Rieley *et al.,* 1996). Since most of these peat deposits are situated at low altitude in coastal and sub-coastal locations they are likely to be developed at a faster rate than the peatlands that remain in temperate and boreal zones.

Table 6.1. *Summary Statistics for Tropical Peatlands*[a]

REGION	**AREA** (Mean) (10^6 ha)	**AREA** (Range) (10^6 ha)
Central America	2.437	2.276 – 2.599
South America	4.037	4.037
Africa	2.995	2.995
Asia (mainland)	2.100	1.100 – 3.100
Asia (southeast)	26.216	20.205 – 33.211
The Pacific	0.019	0.019
TOTAL	37.80	30.632 - 45.961

[a] Based on Immirzi & Maltby, 1992; Rieley *et al.*, 1996

6.1.3. Location and extent of peatlands in Southeast Asia

Tropical peatlands in Southeast Asia occupy mostly low altitude coastal and sub-coastal environments and extend inland for distances of more than 150 km along river valleys and across watersheds. Most of these peatlands are located at elevations less than 50 m above mean sea level and cover more than 26 million hectares (~70% of all tropical peatlands). Extensive and fully developed tropical peatlands occur along the coasts of East Sumatra, Kalimantan (Central, East, South and West Kalimantan provinces), West Papua, Papua New Guinea, Brunei, Peninsular Malaysia, Sabah, Sarawak, Southeast Thailand and the Philippines (Figure 6.1; Table 6.2).

6.1.4. Age of lowland peat swamps of Southeast Asia

Based on radiocarbon dates, the onset and development of the present day peatlands in Southeast Asia range from the late Pleistocene to the Holocene (Page *et al.,* 2004). Most of the extensive peatlands along the coastlines, however, originated during the middle to late Holocene and are the youngest peatlands in the region. Peat accumulation of these deposits commenced around 3,500-6,000 cal yrs BP (e.g. Anderson & Muller, 1975; Staub & Esterle, 1994), following stabilisation of sea levels of the last transgression (a period of sea-level rise). In comparison, investigations of sub-coastal and inland peatlands, particularly in Borneo, have revealed much earlier dates for peat formation, ranging from Late Pleistocene (~40,000 ^{14}C yrs BP) in the Danau Sentarum basin of West Kalimantan (Anshari *et al*., 2001; 2004) to ~23,000 ^{14}C yrs BP for inland peat in the Sabangau catchment, Central Kalimantan (Page *et al.*, 2004) through to the early Holocene (10,000 – 7,000 ^{14}C yrs BP) for other deposits within Borneo (Neuzil, 1997; Sieffermann *et al*., 1988). Only a few records show, however, extensive and thick peat accumulation since the late Pleistocene and most records contain at least one hiatus as a result of global climatic changes since the last glacial maximum some 18,000 years ago. Clearly, tropical peatlands were involved in the global carbon cycle well before the boreal and temperate peatlands since the latter did not begin to accumulate until around 7,000 to 8,000 ^{14}C yrs BP (Maltby & Proctor, 1996). Several studies of tropical peatlands show, however, that the formation of contemporary deposits has been a dynamic process and that periods of alternating accumulation and degradation have occurred throughout their history (e.g. Anshari *et al*., 2001; Page *et al*., 2004).

Table 6.2. *Summary Statistics for Pre-development Area of Tropical Peatlands of Southeast Asia*[a]

REGION	**AREA** (Mean) (10^6 ha)
Indonesia	20.073
Malaysia	2.730
Papua New Guinea	2.890
Thailand	0.068
Brunei	0.100
Vietnam	0.183
Philippines	0.172
TOTAL	26.216

[a] Based on Rieley *et al*., 1996.

Figure 6.1. *Distribution of peatlands in SE Asia, where ~70% of global tropical peat deposits occur, and location of selected sites discussed in this chapter.*

6.2. Tropical peatlands and the carbon cycle

In tropical peatlands, both the vegetation and underlying peat constitute a large and highly concentrated carbon pool (Sorensen, 1993). Currently, there is a growing body of information concerning the importance of carbon storage in, and carbon gas emissions from, tropical peatlands and the potential effect on global environmental change processes (Aucour *et al.*, 1999; Page *et al.*, 2004; Kool *et al.*, 2006). The reason for this interest is mainly because land development projects reduce the magnitude of these carbon pools (e.g. Page *et al.*, 2002). Human made ecosystem alterations can cause the natural resource functions of tropical peatlands to fail, converting them from net carbon sinks to net carbon sources.

6.2.1. Peat and carbon accumulation in Central Kalimantan and SE-Asia during the Late Pleistocene and Holocene

Few peatlands in Southeast Asia have been investigated in detail for peat structure, age and development, peat composition, C content, and C accumulation rates (e.g. Neuzil, 1997; Brady, 1997a; Wust, 2001; Page *et al.*, 2004) despite the fact that they account for ~70% of the global tropical peat deposits. Information obtained from four sites across SE-Asia (see Figure 6.1 for site locations) illustrates variations in peat age and C accumulation rates and these are compared with high latitude peatlands.

The carbon storage potential of the lowland peatlands of Central Kalimantan was determined from a 9.5 m long core (SA6.5) obtained from the Sungai Sabangau catchment in 1995 (Page *et al.*, 2004; Figure 6.2). The geochronology, established with 27 AMS (radiocarbon) dates, reveals a record of peat and carbon accumulation over a period of 26,000 years. Initially, there was a relatively rapid rate of peat accumulation of 1.0 mm yr^{-1} between 24,000 – 26,000 cal yrs BP (23,000 – 22,000 ^{14}C yrs BP). This is equivalent to a carbon burial rate of about 54 g C m^{-2} yr^{-1} and may have lasted for several thousand years until about 20,000 cal yrs BP, although some peat may have been lost owing to degradation during the somewhat drier last glacial maximum (LGM; e.g. Flenley, 1997). Peat accumulation rates during and after the LGM fell to an average of 0.04 mm yr^{-1} until ~13,000 cal yrs BP (10,830 ^{14}C yrs BP), with an average carbon accumulation rate of 1.3 g C m^{-2} yr^{-1}. These low peat and C accumulation

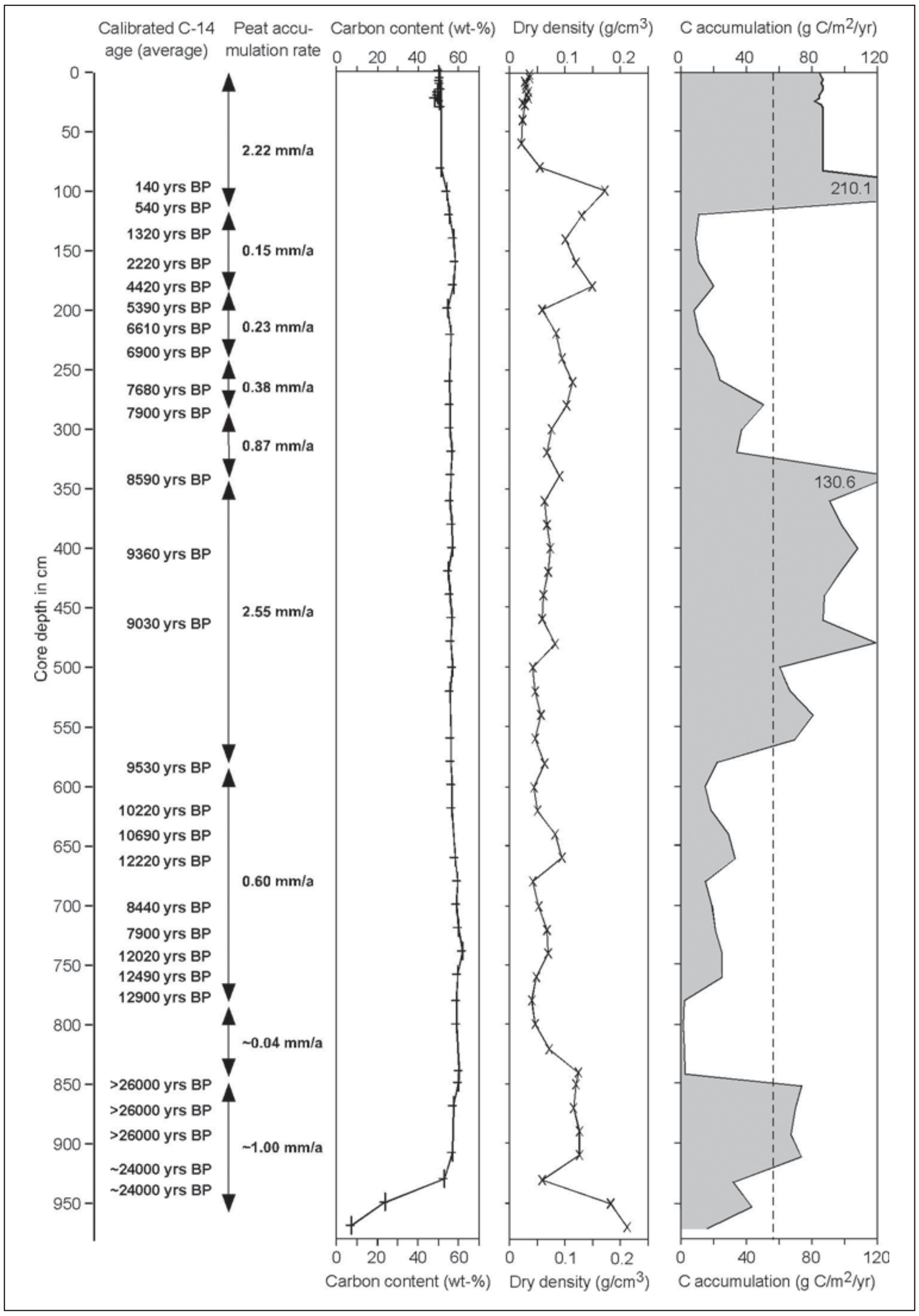

Figure 6.2. *Peat core SA6.5 from Central Kalimantan, Indonesia, showing stratigraphy, stage of peat humification, calibrated 14C ages, peat accumulation rates, carbon contents, dry density and carbon accumulation rates. (Modified after Page et al., 2004).*

rates need to be treated with caution since it is possible that substantially more peat than currently preserved was deposited prior to the LGM but subsequently oxidised during the following 5,000 to 6,000 years when the climate was unfavourable for peat formation and during which the site likely acted as a C source (Koutavas *et al.*, 2002).

The beginning of the Holocene coincided with increased rates of both peat formation and carbon accumulation at the Sabangau site (Figure 6.2). Between 8,540 and 7,820 cal yrs BP the average peat accumulation rate increased from 0.60 to 2.55 mm yr^{-1} and over a ~2,200 year period, starting from 9,060 cal yrs BP, more than 3.5 m of peat accumulated. These values are similar to the range of 1.4 to 2.4 mm yr^{-1} reported by Sieffermann *et al*. (1988), but are higher than Neuzil's (1997), range of 0.3 to 1.2 mm yr^{-1}. The average rate of carbon accumulation during the early Holocene in the Sabangau peatland was 92 g C m^{-2} yr^{-1}, with a maximum rate of 131 g C m^{-2} yr^{-1}, exceeding the early Holocene rates from Sumatra reported by Neuzil (1997), which are in the range of 47 to 75 g C m^{-2} yr^{-1}, and the mid-Holocene highest accumulation rates (20 to 25 g C m^{-2} yr^{-1}) of temperate and boreal bogs from Canada (Turunen & Turunen, 2003).

Around 7,000 years BP rising sea levels stabilised, resulting in exposure of large, relatively flat areas of new coastal environments throughout the Malesian Region (Tjia *et al*., 1984; Hu *et al.*, 2003). The combination of favourable topographic (i.e. low relief) and wet, humid, climatic conditions (as a result of large shallow seas) led to rapid peat accumulation in coastal and sub-coastal areas throughout the region (Staub & Esterle, 1994; Hesp *et al.*, 1998). In the Rajang Delta of Sarawak, for example, 4.45 m of peat accumulated between 6,400 and 2,060 cal yrs BP (5,610 to 2,070 ^{14}C yr BP), equivalent to an average peat accumulation rate of 1.26 mm yr^{-1} whilst, on the east coast of Sumatra, the peatlands of Riau province also underwent very rapid accumulation with initial rates as high as 6 to 13 mm yr^{-1} between 5,300 – 4,300 cal yrs BP (4,700 and 3,900 ^{14}C yrs BP), reducing subsequently to 0.6 to 2.7 mm yr^{-1} (Neuzil, 1997). These rates are significantly higher than the rates for mid- to late Holocene peat accumulation in the Sabangau peatland at this time, which were only 0.15 – 0.23 mm yr^{-1}.

While the Central Kalimantan area around Sg. Sabangau seems to have received less precipitation after 8-8,500 cal yrs BP, and hence peat accumulation rates were reduced, several other sites in Sumatra and Malaysia commenced accumulation (Staub & Esterle, 1994; Neuzil, 1997) illustrating the significance of local and regional climatic changes, which occurred under the influence of raising sea level, sea surface temperature rise, ocean circulation changes in the Sunda Shelf and the Pacific, and the ice sheet collapses in the Northern Hemisphere. The climate variability during the Holocene led to a complex peat accumulation and degradation pattern across all tropical peatlands, best illustrated in the varying peat accumulation rates discussed in the section below. Peat accumulation rates based on 266 radiocarbon dates from sites across Sumatra, West Java, Kalimantan, Sarawak, Peninsular Malaysia, Thailand, Sulawesi, and New Guinea range mainly between 0 – 3 mm yr^{-1} with a median accumulation rate of ~1.3 mm yr^{-1} (Figure 6.3), which is about 2 – 10 times the rate for boreal and subarctic peatlands (0.2 – 0.8 mm yr^{-1}) (Gorham, 1991) and for temperate peatlands of 0.2 to 1 mm yr^{-1} (Aaby & Tauber, 1975). Very few tropical peatland sites have shown accumulation rates >3 mm yr^{-1}, with the highest, 13 mm yr^{-1}, reported from Bengkalis Island, Sumatra (Neuzil, 1997). Other studies have estimated the average accumulation rate for Indonesian peatlands to be between 1 and 2 mm yr^{-1} (Sorensen, 1993).

Peat accumulation rates are essential for determining the carbon sequestration potential of tropical peatlands. Accumulation rates and C content allow the calculation of C accumulation rates both in the past and at present. Interestingly, comparison between thin (2 – 3 m) and very thick (>8 m) peat deposits from Malaysia and Kalimantan shows that C accumulation rates are similar despite the former being minerotrophic and the latter ombrotrophic. The mean C accumulation rates range between ~40 – 90 g C m^{-2} yr^{-1} (Figure 6.4).

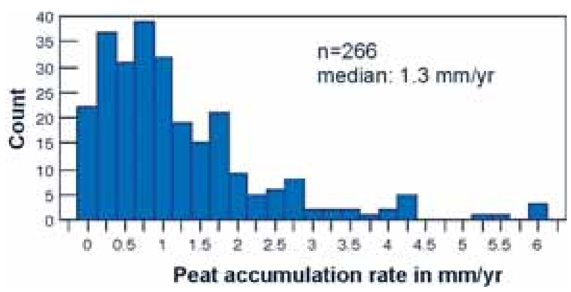

Figure 6.3. *Histogram of peat accumulation rates (showing only the range between 0 – 7 mm yr^{-1}) of 266 samples across sites in Sumatra, West Java, Kalimantan, Sarawak, Peninsular Malaysia, Thailand, Sulawesi and New Guinea. The median accumulation rate is ~1.3 mm yr^{-1} with only a few sites having accumulation rates >3 mm yr^{-1}, while one site on Bengkalis Island, Sumatra has a rate of ~13 mm yr^{-1} (Neuzil, 1997).*

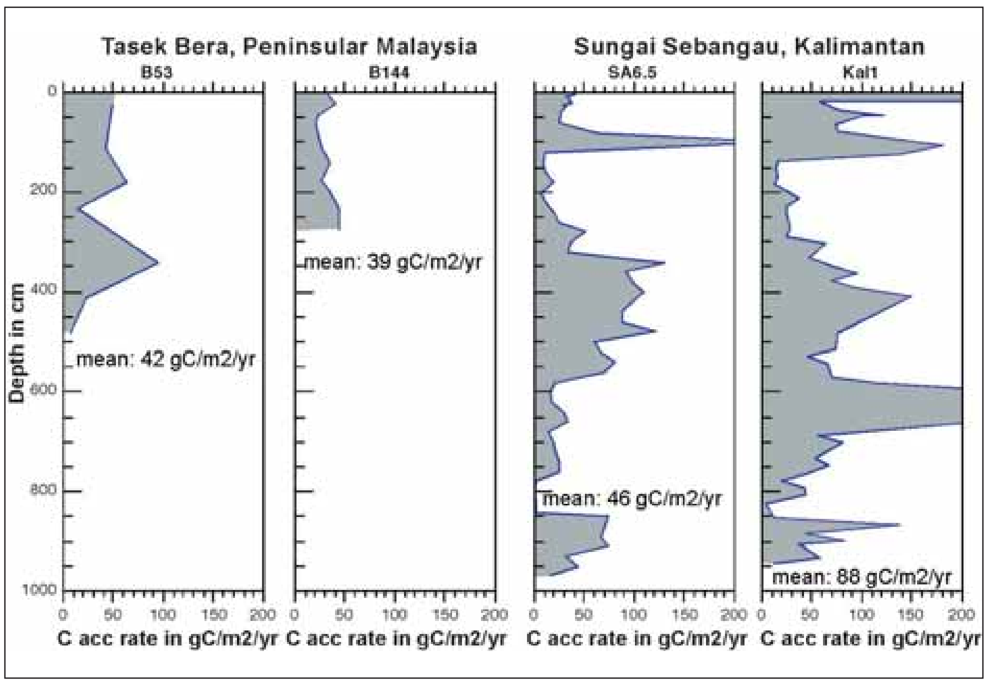

Figure 6.4. *Carbon accumulation rate down cores from two sites in Peninsular Malaysia (Tasek Bera, core B53 and B144) and Kalimantan (Sg. Sabangau; both SA6.5 and Kal1 are located within 1.5 km of each other). Tasek Bera is minerotrophic peat while the Kalimantan site is ombrotrophic.*

Other peat cores from Sumatra, from both the highlands (Tao Sipinggan, Toba Plateau, Figure 6.1) and the lowlands (Siak Kanan, Riau, Figure 6.1) show similar data (Figure 6.5). Peat accumulation rates vary markedly (e.g. between 0.3 – 6.1 mm yr^{-1}) over the history of the peat deposits. The highland peat deposit (Tao Sipinggan) started to accumulate just after Meltwater Pulse 1A (c. 14,500 cal yrs BP) (Liu *et al.*, 2004) while the lowland peat deposits (e.g. SK10) did not initiate until the mid Holocene similar to the peat deposits of Tasek Bera (e.g. B7 and B78). The C accumulation rate ranged from 30 – 50 g C m^{-2} yr^{-1} in the Sumatran highlands, 80 – 270 g C m^{-2} yr^{-1} in the Sumatran lowlands, 30 – 50 g C m^{-2} yr^{-1} in the Tasek Bera area, and 30 – 210 g C m^{-2} yr^{-1} in the Sg. Sabangau region in Central Kalimantan (Figure 6.5).

The peat cores from the various peatlands across SE-Asia and their carbon accumulation rates presented in the above section reveal several important findings. Firstly, they confirm that peat accumulation in both the highlands (Figure 6.5: Toba Plateau; Maloney & McCormac, 1995) and the lowlands (e.g., Kalimantan, Sg. Sabangau peat core SA6.5; Figure 6.4) commenced before the LGM. Since the lowland area of the LGM (when sea level was 125 m below present) is flooded now, the true extent of past lowland peat deposits may never be determined accurately from the limited data and records currently available. In addition, as in the case of the Sg. Sabangau core (Figure 6.2), some of the accumulated organic matter most likely oxidised during the somewhat drier conditions during and shortly after the LGM when the rainforest was markedly reduced in area throughout this region (Flenley, 1998). Other lowland peat deposits, especially coastal peatlands, were inundated during the transgression and this organic matter most likely oxidised except for locations where sediments buried some of the peat. This may be the reason why few submarine thin peat deposits on the Sunda Shelf have been described (Steinke *et al.,* 2003; Liu *et al.*, 2004).

Secondly, the comprehensive radiocarbon record of the Sg. Sabangau core (SA6.5; Figure 6.2), accompanied by a detailed account of peat accumulation, demonstrates that tropical peatlands are complex systems that develop stepwise rather than continuously. Factors influencing the rate of organic matter accumulation include type of vegetation, hydrological setting and climate and environmental changes associated with them. The peat accumulation data implies that, over their lifetime, tropical peat deposits can act naturally as both carbon sinks and carbon sources, although the accumulated peat represents net carbon storage over thousands of years. During the LGM, and towards the end of the Late Pleistocene, for example, the Sabangau deposit probably acted as a carbon source rather than a sink, owing to periods of peat degradation attributable to drier or seasonally variable climatic conditions.

Thirdly, there is evidence of two major periods of peat accumulation in Central Kalimantan during the Late Pleistocene, culminating in a phase of very rapid peat formation and high rates of carbon accumulation during the early Holocene as well as during the last ~600 years (Figure 6.4). Based on this information, the peatlands of Southeast Asia could have played a significant role in the global carbon cycle at those times by acting as a carbon sink from the latter part of the late Pleistocene until about 8,000 – 8,500 yrs BP and then nearer to the present day. This raises the question of how much carbon was stored from the early to mid-Holocene in the peatlands of Kalimantan and in tropical peatlands in general. At the same time, most other lowland and some highland peat deposits commenced peat accumulation only during the mid Holocene (~5,000 cal yrs BP) (Figure 6.5).

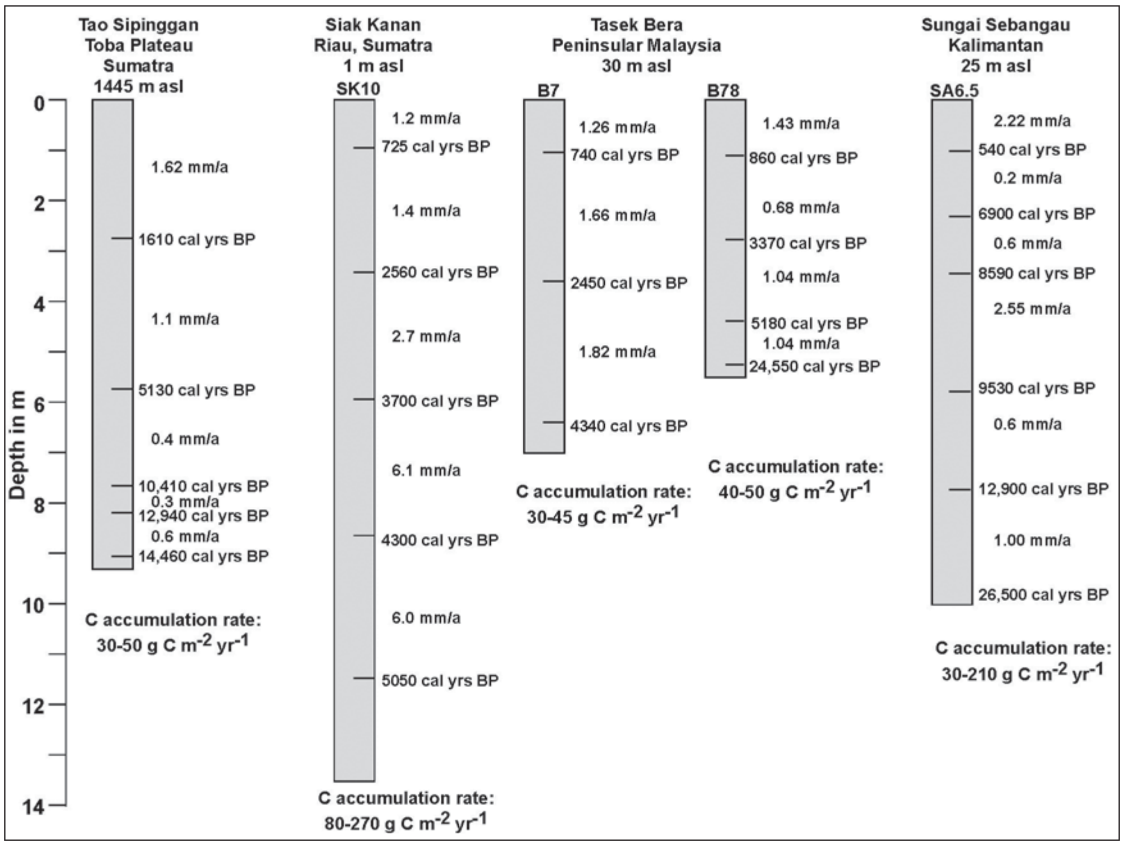

Figure 6.5. *Selected peat sections from various sites in Sumatra, Peninsular Malaysia and Kalimantan showing age of peat accumulation, peat accumulation rates and C accumulation rates that varied between 30 – 270 g C m^{-2} yr^{-1}.*

6.2.2. Contemporary peat and carbon accumulation in the tropics

Peat core-based estimates of present global C deposition within peatlands vary between 0.1 – 0.2 Gt yr^{-1} (Buringh, 1984; Armentano & Verhoeven, 1988), while the share of tropical peat is reported to be about 0.06 – 0.093 Gt yr^{-1} (Immirzi *et al*., 1992; Franzen, 1994).

Estimates of current carbon accumulation rates per unit area in tropical peatlands range from 0.59 – 1.45 t ha^{-1} yr^{-1} (Sorensen, 1993), exceeding the most rapid carbon accumulation rates for boreal and subarctic ombrotrophic bogs of 0.3 and 0.35 t ha^{-1} yr^{-1}, where 1 t ha^{-1} yr^{-1} = 100 g m^{-2} yr^{-1} (Turunen, 2003). Temperate peatlands are likely to be very similar to boreal peatlands (Turunen & Turunen, 2003; Roulet *et al*., 2007). Field research indicates that peat accumulation in the Sabangau peatland of Central Kalimantan, Indonesia is taking place currently at a rate of 2.2 mm yr^{-1} (Figure 6.2) (Page *et al.*, 2004), and thus far exceeds boreal and temperate peat growth rates of 0.2 to 0.8 mm yr^{-1} (Gorham, 1991) and 0.2 to 1 mm yr^{-1} (Aaby & Tauber, 1975), respectively.

The amount of C sequestered by peat swamp forest vegetation and allocated partly to accumulating peat is high in climax peat swamp forest although about 80-90% of the annual biomass produced is decomposed quickly and is unavailable for peat accumulation (Brady, 1997a). Suzuki *et al*. (1999), for example, estimated primary tropical peat swamp forest annual net carbon absorption to be 532 g C m^{-2} yr^{-1} in To-Daeng (Thailand), which is similar to net ecosystem carbon uptake of 516 g C m^{-2} yr^{-1} in Surinam (Williams *et al*., 2001). In contrast Whittaker & Likens (1975) provide a much higher value for 'tropical rain forest' of 990 g C m^{-2} yr^{-1}.

By applying the surface peat carbon accumulation rate of 101 g C m^{-2} yr^{-1} derived from the Sabangau peat core (Page *et al*., 2004; Figure 6.2), to the entire peatland area of Kalimantan (6.788 million hectares) (Rieley *et al*., 1996), the potential (pre-disturbance) carbon sink is estimated to be 6.86 Mt yr^{-1}, where 1 Mt = 10^6 t (Table 6.3). Extending this to the area covered by all of Indonesia's peatlands (20.074 Mha) (Rieley *et al*., 1996), gives a potential peatland carbon sink estimate of 20.28 Mt yr^{-1}. If this is extrapolated to the global area of tropical peatland (37.80 Mha) their carbon sink potential is 38.18 Mt yr^{-1}, which is equivalent to about 58% of temperate, boreal and subarctic peatlands (66.2 Mt yr^{-1}) (Turunen *et al.*, 2002), providing a revised estimate of the potential global peatland carbon sink of 104.38 Mt yr^{-1} to which tropical peatlands contribute 37%. In other words, although representing only 10% aerial coverage of total global peatlands, tropical peatlands represent over

Table 6.3. *Estimates of Carbon Pools and Potential Sinks in Indonesian, Southeast Asia and All Tropical Peatlands*

Location	Area (ha x 10^6)	Total carbon pool (Gt)[a,b]	Current carbon sink (Mt C yr^{-1})[b]
Kalimantan	6.788	15.05	6.86
Sumatra	8.253	18.30	8.34
West Papua	4.624	10.25	4.67
Rest of Indonesia	0.409	0.91	0.41
Total for Indonesia	20.074	44.5	20.28
Total for SE Asia	26.216	58.1	26.48
Total Tropical[c] Peatland	37.80	83.8	38.18

[a] 1 Gt = 10^9 t

[b] These estimates are calculated using values of 0.09 g cm^{-3} for bulk density, 56% for carbon content and 101 g C m^{-2} yr^{-1} of tropical peat derived from a 9.5 m metre peat core in Central Kalimantan (Figure 2 and Page *et al.,* 2004); A peat thickness of 4.4 metres was applied in the calculations derived from 126 peat drillings across several peat domes in Central Kalimantan.

Carbon pool = peatland area x peat dry bulk density x peat carbon content x mean peat thickness

[c] These values are provisional because little is known about the thickness, bulk density and carbon content of tropical peat outside of Southeast Asia. They will be updated as new information becomes available.

Potential carbon sink = peatland area x current carbon accumulation rate a third of the potential global peatland C sink. The value for carbon storage in all tropical peatlands is more than the 34 Mt yr^{-1} calculated by Armentano & Verhoeven (1988) but less than the bottom of the range of 41.5 – 93.4 Mt yr^{-1} suggested by Maltby and Immirzi (1993). It should be noted, however, that all of these values refer to potential rather than actual carbon storage whilst the carbon sequestration function of large areas of tropical peatland has been reduced greatly by deforestation, drainage, agricultural conversion and fire, all of which convert peatland ecosystems from carbon sinks to carbon sources.

6.2.3. Role of tropical peatlands as contemporary carbon sinks and stores

There are major difficulties associated with evaluating the role of tropical peatlands as contemporary carbon pools. Firstly, some peatlands, even under natural conditions, are in a steady-state and no longer accumulating peat, whilst others are undergoing degradation (Sieffermann *et al*., 1988; Moore & Shearer, 1997; Hirano *et al*., 2007). Secondly, large areas of tropical peatland have been drained and burned, which has altered the water table as well as water retention properties, shifting the peatland carbon balance from sink to source (Wösten *et al*., 1997; Page *et al*., 2002; Canadell *et al*., 2007). The numbers presented in Table 6.3 are, therefore, a best estimate of pre-disturbance rather than actual contemporary carbon storage values.

Additional problems are encountered when calculating the carbon pool (store) in tropical peatlands, either nationally (e.g. Indonesia), regionally (e.g. Southeast Asia) or globally. National peatland inventories in tropical countries are inaccurate owing to a lack of resources for survey (remote sensing and aerial photographs), difficulty of separating forested peatland from other forest types (e.g. peat swamp forest from other rain forest types, especially heath forest), peat swamp forest from deforested peatland, developed peatland from non-peatland, and inadequate ground truthing. In addition, areas of tropical peatland cleared of their forest cover and then drained and cultivated are usually no longer regarded officially as peatland and are excluded from inventories, although they may continue to have a considerable thickness of peat and a substantial carbon store for a long time after conversion. Information on peat thickness in all tropical countries is very inadequate making it virtually impossible to estimate peat volumes and carbon pools with precision. Despite these limitations, it is possible to provide reasonably accurate values for the total carbon pool contained within the peatlands of Central Kalimantan, from which to derive approximations for the whole of Indonesia and tropical peatlands globally using information derived from remotely sensed and field checked data for the first (Page *et al.*, 2002), official statistics for the second (RePPProT, 1990, cited in Rieley *et al*., 1996) and published information for the last (Immirzi *et al.*, 1992). These areas, when combined with values for peat thickness, bulk density and carbon content, provide estimates of the different carbon pools (Table 6.3). The peatlands of Kalimantan represent a carbon pool of 15 Gt C, those of Indonesia contain 45 Gt C, whilst the global total is in the region of 84 Gt C. The value for the Indonesian peatland carbon pool is much higher than the range of 16 – 19 Gt suggested by Sorensen (1993), and that for all tropical peatlands is greater than the top of the range of 53 – 70 Gt estimated by Immirzi *et al.* (1992).

6.3. Greenhouse gas (GHG) emissions from natural and degraded tropical peatland

In their natural state, peat swamp forests have the ability to sequester carbon from the atmosphere during photosynthesis, retain this in plant biomass and store part of it in the peat. This process occurs mainly because of the waterlogged condition of the peat, which reduces decomposition significantly and hence the rate of organic matter production exceeds its breakdown. Peatland development, however, requires drainage, brings about changes in the vegetation type, destroys the C sequestration capacity and leads to losses from peat C stores. Carbon is lost especially in the form of carbon dioxide (CO_2) owing to the deeper oxic peat profile caused by water level draw-down. Aerobic conditions and high redox potentials created by drainage are known to favour microbial activity and nitrogen mineralization (Ueda *et al.*, 2000; Jali, 2004), which can enhance C loss by peat oxidation. Peat derived GHG emissions are compared in peat swamp forest and other land use types subject to different cropping vegetation types and peat drainage intensities.

6.3.1. GHG emissions from natural peat swamp forest

Carbon dioxide fluxes

Greenhouse gas release in organic matter decomposition in temperate and boreal peatlands is controlled largely by seasonal changes in temperature, hydrological conditions, and substrate availability and quality (Komulainen *et al.*, 1998; Kettunen, 2002; Vasander & Kettunen, 2006). In the tropics, surface peat temperature is high and promotes rapid organic matter decomposition throughout the year. Although peat temperature can be equable in the tropics, rainfall varies markedly both daily and annually (Takahashi & Yonetani, 1997). The water table in undrained peat swamp forest is above or close to the surface throughout the year and fluctuation is usually small. Draw down of the water table in the dry season is restored quickly at the onset of the subsequent wet season (Takahashi *et al.*, 2000). Periodicity and duration of oxidation-reduction conditions in drying or wetting tropical peat have important roles in the initiation of GHG production (Ueda *et al.*, 2000; Inubushi *et al.*, 2003), but the dynamics of the processes involved are inadequately known.

Few data are available for CO_2 flux rates from the forest floor in peat swamp forests (Chimner, 2004; Jauhiainen *et al.*, 2005; Melling *et al.*, 2005a). The estimated annual CO_2 flux in undrained selectively logged forest in Central Kalimantan under various hydrological conditions is in the range 953±86 – 1061±83 g C m^{-2} yr^{-1} (Jauhiainen *et al.*, 2005), and is comparable with emissions of 1200±430 g C m^{-2} yr^{-1} in a secondary peat swamp forest in South Kalimantan (Inubushi *et al.*, 2003). These values differ greatly, however, from the 2130 g C m^{-2} yr^{-1} estimate for drained peat swamp forest in Sarawak (Melling *et al.*, 2005a). The large variation in peat swamp forest floor CO_2 emission estimates arises mainly from differences in measurement procedures and methods, variation in environmental conditions (especially peat moisture and water table depth), micro site type selection and vegetation characteristics. Therefore measurement conditions should be specified clearly in the estimates.

The ground (peat surface) in peat swamp forest is a complex continuum of micro sites where differing hydrological conditions and sub-soil structure lead to large differences in CO_2 emissions originating from respiration of heterotrophic decomposers and tree root respiration. Microtopography of the ground surface of peat swamp forest is a mosaic of hummocks and hollows. Hummocks consist of tree bases and densely packed small tree roots that accumulate organic debris: their height varies but can be up to 50 cm above the forest floor. The hollows are more open, sparsely vegetated with a variety of pneumatophores and fine breathing roots; their dimension varies in area, shape and depth and they are a prominent feature of the forest floor. The duration of waterlogging differs between hummocks and hollows. The former are water-saturated only after heavy rain while the latter are filled with water frequently, a condition that can last for many months and they can retain moisture throughout the dry season.

According to Jauhiainen *et al*. (2005) CO_2 flux rates in hollows in undrained forest vary from less than 100 mg m^{-2} h^{-1} to almost 900 mg m^{-2} h^{-1} (Figure 6.6). The highest emissions occur in the dry season when the water table falls to 40-50 cm below the surface. Compared to hollows, hummock CO_2 flux rates, under different water table conditions, are relatively uniform (500 – 600 mg m^{-2} h^{-1}) (Jauhiainen *et al*., 2005), (Figure 6.6). Root respiration is an important source of CO_2 especially in hummocks and may form over 50% of the emissions (Hirano, personal communication).

The actual ratio of hummocks to hollows in relation to water table depth over large areas of tropical peatland is complex, variable and difficult to determine. When comparing cumulative forest floor CO_2 fluxes at equal hummock-hollow microtopographical coverage, hummocks are a stronger CO_2 emission source owing to the lower variation in flux rates at different peat water table levels than hollows; high water table conditions clearly lead to reduced cumulative emissions from hollows (Figure 6.7). When the water table is below the peat surface, cumulative flux rates from both hummocks and hollows are similar. Emission rates from both should be included in overall estimates since the ratio of one to the other influences overall CO_2 flux rates. Jauhiainen *et al.* (2005) observed almost 5% change in annual peat swamp forest floor CO_2 emission rate for each 10% change in the proportion of the area of hummocks and hollows.

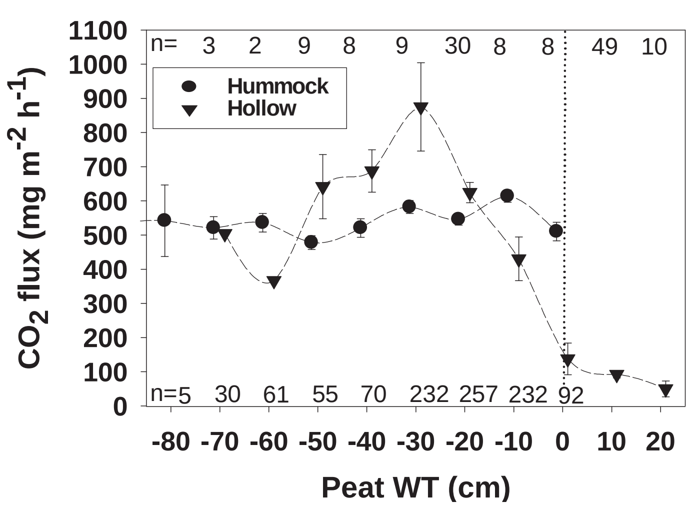

Figure 6.6. *Hummock and hollow mean CO_2 flux rates (mg m^{-2} h^{-1} with standard error) from peat swamp forest in Central Kalimantan, Indonesia at various peat water table (WT) depths. The dotted vertical line shows when the water table is at the peat surface. (Based on Jauhiainen et al., 2005).*

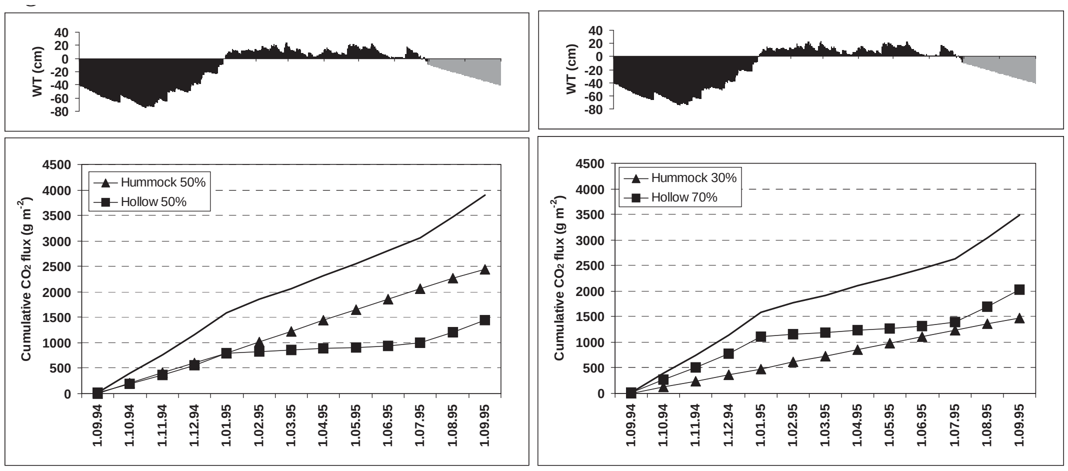

Figure 6.7. *Water table fluctuations (WT) (top) and annual cumulative CO_2 emission (g m^{-2}) (bottom) from mixed peat swamp forest hummocks and hollows (lines with symbols), and combined annual emission (line only) in Sg. Sabangau area, Central Kalimantan. Emissions are presented for 2 hummock-hollow coverage areas; 50:50% on left and 30:70% on right (Based on Jauhiainen et al., 2005).*

Methane fluxes

Methane (CH_4) flux rates from the peat surface in peat swamp forest are between 0.11 and 0.96 mg m^{-2} h^{-1} (Inubushi *et al*., 2003; Jauhiainen *et al*., 2005; Melling *et al*., 2005b). These rates are lower than from boreal *Sphagnum*-dominated bogs, which range from 0.21 to 1.61 mg m^{-2} h^{-1} (Martikainen *et al.*, 1995; Nykänen *et al.*, 1998). Methane formation in peat requires anoxic conditions (waterlogging). When the depth of the oxic surface peat layer increases, as a result of low rainfall or drainage, methane is oxidized to carbon dioxide and emissions decrease to zero. In dry conditions the direction of CH_4 flux can be from the atmosphere into the peat (Figure 6.8).

Methane fluxes in peat swamp forest hollows can be regarded as approximations or slight over-estimates of overall forest floor fluxes because CH_4 is produced only in waterlogged conditions. The water table in hollows is always nearer to the surface than in hummocks and the peat in hollows therefore affords less space for methane oxidation by methanotrophic bacteria than in hummocks. There are no published data on peat swamp forest hummock CH_4 flux rates. Based on flux measurements in hollows, however, the annual CH_4 emission from peat swamp forest floor is less than 1.06±32 – 1.36±57 g CH_4-C m^{-2} yr^{-1} (Jauhiainen *et al*., 2005), while secondary peat swamp forest in South Kalimantan gave a similar value of 1.2±0.4 g CH_4-C m^{-2} yr^{-1} (Inubushi *et al.*, 2003). The estimate of 0.0183 mg CH_4-C m^{-2} yr^{-1} obtained by Melling *et al*. (2005b) from a peat swamp forest in Sarawak, however, is much less and may reflect its drained and drier condition. Annual CH_4 emissions from tropical peat swamp forest floor are small compared to those from undisturbed boreal *Sphagnum* bogs, which vary between 2 and 15 g CH_4-C m^{-2} yr^{-1} (Martikainen *et al.*, 1995; Nykänen *et al.*, 1998; Alm *et al.*, 1999).

The ratio between CH_4 production in anoxic peat and CH_4 consumption in oxic peat determines the gas flux rate at the peat surface (Roulet *et al.*, 1993; Shannon & White, 1994; Komulainen *et al.*, 1998). Maximum CH_4 emission rates from the peat swamp forest floor occur when the water table is near to the peat surface and recently deposited, less decomposed litter (Brady, 1997a) becomes available for anaerobic decomposers, e.g. methanogens (Figure 6.8). In drier conditions oxygen can penetrate into peat pore space and CH_4 consumption by methanotrophic bacteria can balance or slightly exceed CH_4 production, and thus create the potential for CH_4 flux redirection into peat (Figure 6.8). These conditions were increasingly created in peat swamp forest in Central Kalimantan when the water table fell below 20 cm from the surface.

It is possible, however, that some of the CH_4 produced may escape to the atmosphere through vascular plant organs (e.g. leaves and pneumatophores), and thus avoid oxidation in the surface aerobic peat. Remote sensed observations indicate CH_4 is released from tropical forests (Frankenberg *et al.*, 2005; Sinha *et al.*, 2007) but the role of peat swamp forest vegetation in these emissions has still to be clarified. In temperate and boreal wetlands, vascular plants have been noted to have an important role in providing a transport route for CH_4 emissions (Shannon *et al.*, 1996; Frenzel & Rudolph, 1998; Saarnio & Silvola, 1999).

The global warming potential (GWP) of methane emissions from tropical peat is of minor importance compared to that of CO_2. By converting annual CH_4 fluxes into CO_2 equivalents (CO_2-e) by multiplying by 23 (IPCC, 2001; see also Chapter 5), the total CH_4 emissions (31.3 g CO_2-e m^{-2} yr^{-1}) represent only 0.8 – 0.9% of the corresponding CO_2 emissions (3892 – 3493 g CO_2 m^{-2} yr^{-1}) from the ground in undrained forest (Jauhiainen *et al.*, 2005; see also Table 6.4). GWP comparisons using data from Inubushi *et al*. (2003) and Melling *et al*. (2005a; b) provide similar or even smaller contributions by CH_4.

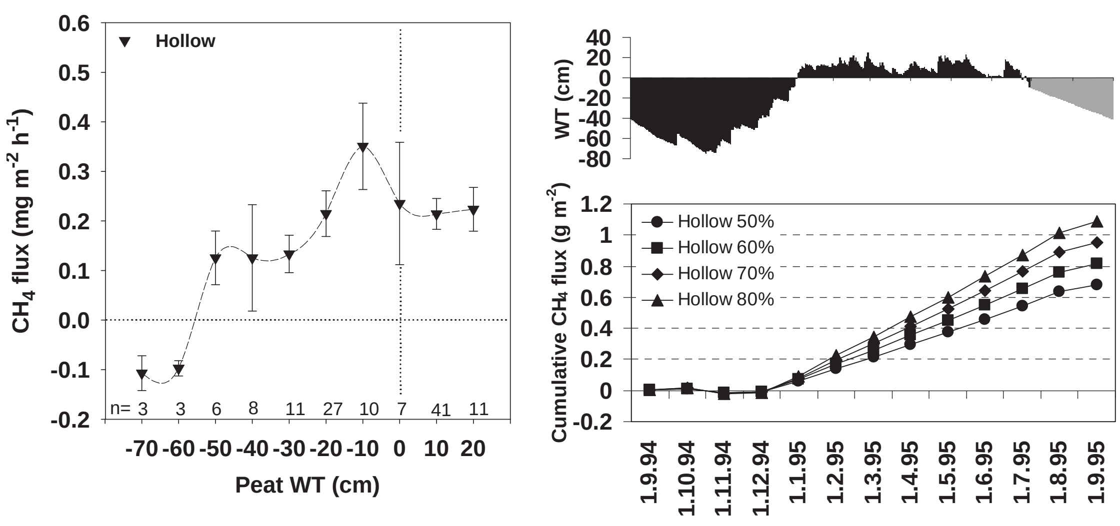

Figure 6.8. *Methane fluxes (mg m^{-2} h^{-1}, with standard error) at various peat water table depths (left) and annual cumulative methane emission (g m^{-2}) (right) from hollows of peat swamp forest in Central Kalimantan, Indonesia. Cumulative emission (1.9.1994 – 31.8.1995) is presented at various hummock-hollow coverage ratios (%). (Based on Jauhiainen et al., 2005).*

Table 6.4. *Carbon Gas Emissions from the Peat Surface in Natural and Degraded Peat Swamp Forest in Central Kalimantan, Indonesia*[a]

	LAND USE	CO_2 EMISSIONS		CH_4 EMISSIONS		TOTAL EMISSIONS
		CO_2 g m^{-2} h^{-1}	CO_2 (CO_2-C) g m^{-2} yr^{-1}	CH_4 mg m^{-2} h^{-1}	CH_4 (CH_4-C) g m^{-2} yr^{-1}	CO_2-e
A	**Undrained peat swamp forest**[b]	43±15 to 689±62	3892±304 (1061±83)	-0.08±0.09 to 0.35±0.01	1.36±0.57 (1.02±0.43)	3892 ± 31.3 = 3923
B	**Drainage affected peat swamp forest**[c]	0±40 to 1404±446	4000 (1091)	-0.08±0.003 to 0.25±0.09	1.3 (0.98)	4000 ± 29.9 = 4030
C	**Clear felled recovering peat swamp forest**	71±18 to 1521±724	3400 (927)	-0.13±0.03 to 0.34±0.06	2 (1.5)	3400 ±46 = 3446
D	**Drained uncultivated agricultural land**	0±44 to 453±19	1928 (526)	-0.04±0.03 to 0.04±0.004	0.12 (0.09)	1928 ± 2.8 = 1931

[a] Temporal and cumulative annual CO_2 and CH_4 flux rates (mean with standard error), and total emissions as CO_2-e global warming potential are given based on data in Jauhiainen *et al*. (2004; 2005).

[b] Numbers for CO_2 are based on 50:50% surface coverage ratio between hummocks and hollows. Numbers for CH_4 are based on hollow emissions assuming 100% surface coverage.

[c] Numbers for CO_2 are based on 30:70% surface coverage ratio between hummocks and hollows.

6.3.2. GHG emissions from degraded tropical peat

Comparison of temporal carbon gas fluxes from three drainage affected tropical peatland site types

Comparison of carbon dioxide and methane fluxes in the upper part of Block C of the former Mega Rice Project in Central Kalimantan, Indonesia shows the effect of different vegetation cover types and land uses (Figure 6.9). This area was the location for intensive land development between 1996 and 1999 and includes drainage affected selectively logged forest, clear felled but recovering (regenerating) forest on drained peat and drained but uncultivated agricultural peatland used previously for growing vegetables. The agricultural area was drained some 20 years prior to the gas flux measurements, and some 15 years earlier than the two other sites. Gas fluxes from these three locations were compared with those from undrained mixed peat swamp forest located in the Sg. Sabangau catchment about 10 km away at a similar distance from the river but on the opposite bank (see Section 6.3.1).

Land use change from peat swamp forest to agriculture affects carbon sequestration markedly because the tree biomass is removed totally and replaced with non peat-forming crop plants. Agriculture requires drainage which creates permanent oxic conditions in peat down to the minimum water table required for optimum crop growth. Variations in precipitation and drainage affect the ability of peat swamp forests to maintain their hydrological integrity causing them to emit CO_2 during times of water draw down (Suzuki *et al*., 1999; Hirano *et al*., 2007). Impairing the water holding capacity of peat increases surface peat oxidation and leads to subsidence and loss of carbon (e.g. Wösten *et al*., 1997; 2006; Jauhiainen *et al*., 2004; Furukawa *et al.*, 2005; Melling *et al.*, 2005a). On drained peat, cultivated plants cannot contribute to C sequestration because of their small biomass, compared to natural forest, most of which is removed when cropped or decomposed rapidly as soon as it is deposited on the peat surface.

The highest CO_2 flux rates were obtained in forested and recovering sites, both of which were drained about 5 years before gas measurements were made (Figure 6.9). Gas flux rates at comparable water table depths in the drainage affected forest floor hollows were slightly higher, and fluxes from hummocks were considerably higher, than emissions from undrained forest (Figures 6.6 & 6.9). These differences in gas flux rate response are caused either by markedly higher autotrophic respiration from tree roots and/or enhanced peat oxidation as a result of drainage. CO_2 flux rates in the clear felled recovering area were similar to the forest hollow fluxes at various water table depths. At both sites, CO_2 flux rates increased down to relatively deep peat water table depths, while the maximum rates in undrained forest were obtained at much shallower water tables (Figures 6.6 & 6.9). This may be a consequence of annually repeated deeper drainage during the dry season, which exposes a thicker peat profile to the air and improves the environment for aerobic decomposers in the drained sites. Uncultivated agricultural land with regulated drainage resulted in the lowest CO_2 flux range of the three sites (Figure 6.9).

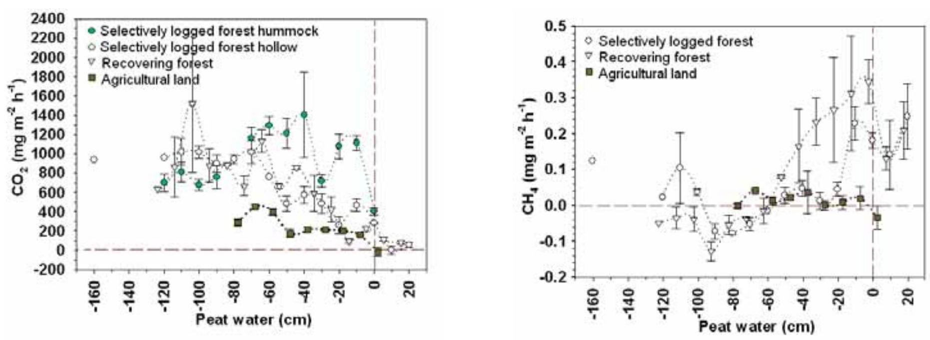

Figure 6.9. *Peat CO_2 flux rates (on left) and CH_4 flux rates (on right) at three tropical peatland sites (mg m^{-2} h^{-1} with standard error) at various peat water table depth classes. The dotted vertical line shows when the water table is at the peat surface and the horizontal line in the CH_4 graph the zero-flux rate. Note the different scales in the graphs. Based on Jauhiainen et al. (2004).*

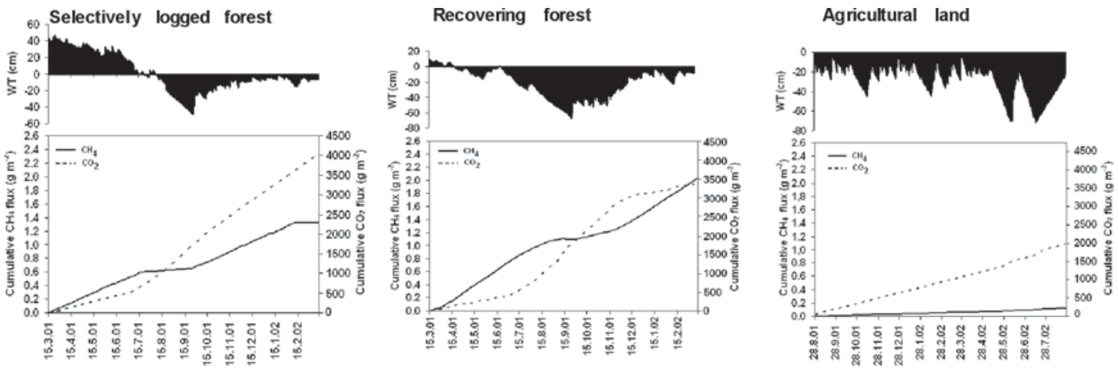

Figure 6.10. *Annual cumulative CH_4 and CO_2 fluxes (g m^{-2}) at the peat surface of three drained/drainage affected sites in Central Kalimantan. The water table (cm) below the surface at the sites is relative to the hollows in peat swamp forest and the almost level surface in the agricultural area. (Based on Jauhiainen et al., 2004).*

Following drainage, the volume of peat experiencing oxic conditions increases considerably and the potential for CH_4 oxidation by methanotrophic bacteria is much greater than in undrained forest peat. Methane flux rate ranges were greatest in the drainage affected forest hollows and in the recovering forest floor (Table 6.4). In these sites, peak CH_4 emissions occurred when the water table was near or above the peat surface (Figure 6.9). On the agricultural land, CH_4 flux rates were almost zero at all peat water table depths (Figure 6.9). The differences in these flux rates can be attributed to a low organic carbon supply and controlled drainage on agricultural land, whereas abundant vegetation of trees and bushes at the two other sites supply litter continuously into the peat (roots) and onto the surface of the peat (leaves and branches) where it can be consumed by methanogenic bacteria in water saturated (anoxic) conditions. CH_4 fluxes at these three site types (see Table 6.4) are similar to those from other land use types on drained peat. For example, CH_4 fluxes from the peat surface in an oil palm plantation are from -0.044 to 0.0056 mg m^{-2} h^{-1} (water table maximum ~-60 cm), whilst in a sago plantation on peat, which requires shallower drainage (water table maximum ~-27 cm) the range is -0.0010 to 0.14 mg m^{-2} h^{-1} (Melling *et al*., 2005b).

Cumulative (annual) gaseous C emissions from three drainage affected site types in 2001/2002

The highest annual CO_2 emission (4000 g m^{-2} yr^{-1}) was recorded in the drained forest (Figure 6.10, Table 6.4) where the CO_2 flux rate from hummocks was very high even in wet conditions (see Figure 6.7, Table 6.4). Annual CO_2 emission in the recovering forest site was slightly lower than in undrained peat swamp forest (Figure 6.10, Table 6.4). There were abundant trees growing at both of these sites, resulting in considerable litter production, so that both root respiration and decomposition would be taking place. Annual fluxes in the drainage affected forest site were similar to the undrained forest site because hydrological conditions on both sites were almost the same. In the drainage affected forest, however, the water table, which was 75 cm below the surface in 2001, fell to much lower depths of -153, -113, -167 and -108 cm in the years 2002 – 2005, respectively, probably as a result of progressive peat degradation. The highest CO_2 emission rates in drainage affected sites occurred where drainage channels were deepest.

The annual CO_2 flux at the agricultural site was considerably lower than at the other two sites (Figure 6.10, Table 6.4). The agricultural land emission (526 g CO_2-C m^{-2} yr^{-1}) was about the same as has been estimated to result from annual subsidence of developed tropical peatland in Johor and Sarawak, Malaysia (Wösten *et al*., 1997). According to Melling *et al*. (2005a), oil palm plantation emissions, including peat decomposition and plant root respiration, were 1540 g CO_2-C m^{-2} yr^{-1} and sago plantation soil emissions 1110 g CO_2-C m^{-2} yr^{-1}, which were more than twice as high as those from bare peat at the Central Kalimantan site but similar to undrained forest soil CO_2 losses.

Cumulative annual CH_4 fluxes were highest in the drainage affected forest and recovering forest sites (Figure 6.10, Table 6.4), in which both periodical anoxic wet conditions in peat and easily decomposable litter were available. At these two sites, peat water table was within 20 cm of the peat surface for similar periods of about 230 days, but higher annual CH_4 emission occurred in the recovering forest because of higher fluxes in these water table conditions. Deep water table conditions at these two sites did not cause notable CH_4 influx to the peat (Figure 6.10). At the uncultivated agricultural site the peat was practically CH_4 neutral on an annual basis (Table 6.4) with cumulative emissions similar to CH_4-C fluxes from grassland (0.073 g m^{-2} yr^{-1}) and vegetable fields (0.046 – 0.192 g m^{-2} yr^{-1}) in the vicinity (Hatano *et al*., 2004). According to Melling *et al*. (2005b), annual peat CH_4 emissions from oil palm and sago plantations in Sarawak are -0.015 g CH_4-C m^{-2} yr^{-1} and 0.18 g CH_4-C m^{-2} yr^{-1}, respectively.

Drainage leads to permanently drier conditions in peat and, consequently, CH_4 emissions decrease. Studies carried out so far have concentrated, however, on peat surface methane fluxes and thus do not take into account other potentially important gas sources in drained tropical peat, for example, the large drains and the drainage water they contain can become anoxic and may constitute a CH_4 source because of the solid and soluble organic residues they contain.

Carbon release can also take place via waterways (streams, rivers and drainage channels) in the form of dissolved organic carbon (DOC), particulate organic carbon (POC), dissolved inorganic carbon (DIC) and dissolved CO_2. Studies of these potential carbon release pathways from tropical peatlands are very limited but a recent one by Baum *et al*. (2007) suggests that Indonesian rivers, particularly those draining peatland areas, transfer large amounts of DOC into the oceans, with an estimated total DOC export of 21 Gt yr^{-1}, representing approximately 10% of the global riverine DOC oceanic input. The character and magnitude of fluvial carbon release from tropical peatlands are the subjects of current, detailed investigations. They are likely to be influenced by a range of biotic and abiotic processes, including land use change. Research on temperate peatlands (Worrall & Burt, 2004), for example, indicates that increases in DOC concentration and flux are associated with major droughts and decreases in the peatland water table, which has implications for carbon release from tropical peatlands under different land management and climate change conditions.

Net peatland C flux is determined largely by the net balance between CO_2 uptake in photosynthesis and C release by ecosystem (autotrophic and heterotrophic) respiration (Table 6.4). Peat carbon gas flux measurements are important in order to provide information on peat C dynamics, but cannot be obtained yet for all major sinks and sources in a forested peatland ecosystem. For example, the lack of accurate data on the amount of CO_2 sequestered by green plants in photosynthesis is a major problem for which suitable methods have yet to be developed. The complex structure of tropical rain forest canopies adds to the magnitude of this problem. The large amount of CO_2 emitted from peat swamp forest floor is likely to be mostly or completely reabsorbed by the vegetation it supports making it CO_2 neutral whilst, if it is accumulating peat, the ecosystem must be CO_2 negative. On the other hand, in degraded and drained peat swamp forest, although it appears to be releasing similar large amounts of CO_2 as undrained forest, its greatly reduced canopy will not be absorbing as much CO_2 and will therefore be a net emitter of this greenhouse gas. The same applies to the recovering forest except, in this case, an even larger proportion of the CO_2 released will enter the atmosphere because it is virtually devoid of trees and the low growing vegetation of ferns and scrub absorbs relatively little CO_2. Virtually all of the smaller amount of CO_2 emitted from the agricultural land will be transferred to the atmosphere because the biomass is removed, one or more times a year in the case of arable crops and after the life cycle time of 8-25 years in the case of plantation crops (e.g. pulp trees and oil palm), and any CO_2 fixed in crop photosynthesis will also be released eventually as products are consumed or used and eventually decompose.

Surface peat CO_2 emissions contribute considerably to total ecosystem respiration, and are influenced greatly by water table depth. Stability of hydrology, forest floor microtopography and vegetation structure are other factors influencing peat CO_2 dynamics in undrained peatland. In contrast, CO_2 dynamics in drained peatland are determined by time from initial drainage, vegetation type, and drainage depth. The role of CH_4 in the tropical peat carbon balance is relatively small on the basis of currently available results, but potentially important CH_4 sources have been identified both in undrained and drained peatland types (Table 6.4), for example, emissions from vegetation in the former and drainage channels in the latter. Carbon losses from fire and groundwater flow were not addressed, although these may be important especially on drained peatlands. Ecosystem-level measurement of gaseous carbon fluxes are needed in order to determine the true overall C gas balances on undrained, degraded and developed tropical peatland.

6.4. Impact of CO_2 emissions from drained peatlands in Southeast Asia on climate change processes

Scientists have understood the link between peatland development and CO_2 emissions for some time (Figure 6.11), but policy makers and peatland managers are still hardly aware of the global implications of local and national peatland management strategies and actions. As a result, CO_2 emissions from SE Asia's drained and burning peatlands are slow to be recognized in the climate change debate, and the decisive international action required to help these countries to manage their peatlands better has yet to start. According to Page *et al.* (2002) the total carbon store in Indonesian peatland is 26-50 Gt, a conservative estimate that could rise considerably when peat thickness variation is known with greater accuracy (Hooijer *et al.*, 2006). A peat carbon content of 50 kg C m^{-3} is considered to be representative for SE Asian peatlands in general and combining this value with peatland area and thickness (Table 6.3), suggests that carbon storage in SE Asian peatlands is in the order of 58 Gt.

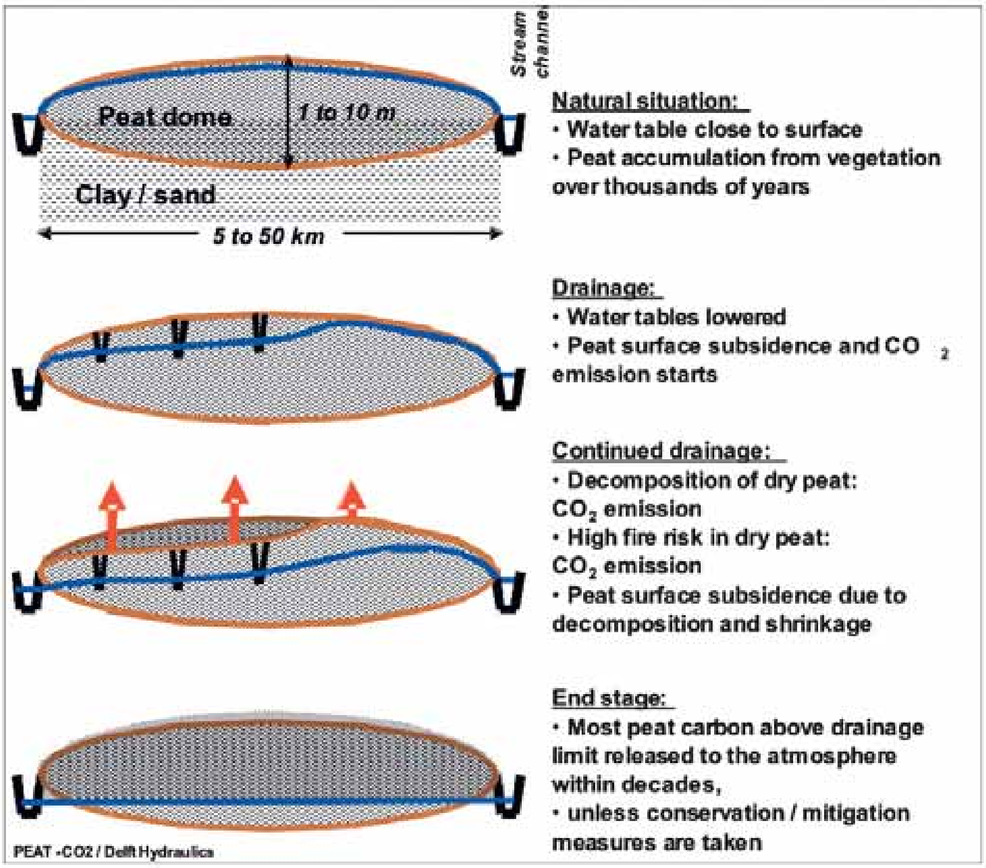

Figure 6.11. *Schematic illustration of CO_2 emission from drained peatland (from PEAT-CO2 Report, Hooijer et al., 2006). The PEAT-CO2 assessment is based on a peatland area of 27.1 Mha, 22.5 Mha of which are in Indonesia, 2 Mha in Malaysia and 2.6 Mha in Papua New Guinea; peat thickness ranged from 0.5 to over 12 metres. In 2000, 61% of these peatlands were covered in forest (JRC, 2003). Only peatlands located less than 300 m above sea level (lowland) were included in the assessment. About 3% of peatland in SE Asia occurs in the highlands of Irian Jaya and PNG but these are shallow and represent less than 1% of the peat carbon store.*

6.4.1. Impact of land use change on tropical peatland sink and store capacities

In their natural condition most tropical peat swamp forests function as C sinks and stores, but forest clearance and drainage can convert them rapidly to C sources. This happens because destruction of the forest cover leads to a decrease in the amount of C allocated into the ecosystem. Agricultural practices require tilling, fertilization, and lowered water tables within the peat, all of which increase surface peat oxidation, leading to subsidence (Figure 6.11).
In the late 1980s, 3.7 million hectares of Indonesian peat swamp forest were developed (Silvius *et al*., 1987), leading to an 18% decrease in peat swamp forest area with a consequent reduction in the C-fixation capacity of 5-9 Mt yr^{-1} (Sorensen, 1993). Deforestation, drainage

and conversion of peatland in Indonesia and Malaysia continued throughout the 1990s and are still occurring. The Mega Rice Project (MRP) in Central Kalimantan was the largest of these peatland development schemes (Muhamad & Rieley, 2002). It was linked to the Indonesian Government's transmigration programme and led to the clearance of lowland peatland forest in order to contribute to the national food supply and accommodate part of the country's rapidly growing population. The MRP commenced in January 1996 and lasted until 1999 when it was abandoned as a failure. By this time around one million hectares of wetland, mostly peatland, had been cleared, more than 4,500 km of drainage and irrigation canals constructed and 60,000 transmigrants settled in one part of it (Rieley & Page, 2005). Almost half a million hectares of this degraded peatland burned in 1997 with the loss of 150-180 Mt C and, since then it has leaked carbon to the atmosphere constantly through peat subsidence and fire. In addition, the carbon sequestration function of this vast peatland has been destroyed.

The basic relationship between peat subsidence and CO_2 emission is that every centimetre of peat subsidence results in a CO_2 emission of approximately 13 t ha^{-1} yr^{-1} (Wösten *et al*., 1997). This value can be combined with information on long-term average relationships between peat subsidence and water table depths for different regions of the world in order to obtain estimates of CO_2 emissions under different environmental conditions (Figure 6.12). An increase in soil temperature and the absence of winter-summer periodicity explain the increase in subsidence rates at all groundwater levels from temperate through to tropical areas in the world. At the same time, lowering of the water table causes a dramatic increase in the release of CO_2 for all peatland locations. In SE Asian peatlands, average water table depth requirements in drained areas are typically between 95 cm in large intensively drained croplands (including oil palm and pulp wood plantations) and 33 cm in smallholder farms (Hooijer *et al.* 2006).

Role of fire in losses of carbon from tropical peatland

Owing to poor management, fires ignited on peatland used for agriculture can spread to adjacent logged forests, destroying the vegetation (Uhl & Kauffman, 1990; Verissimo *et al*., 1995), igniting the peat and increasing the vulnerability of the landscape to subsequent fires (Nepstad *et al*., 1995; Page *et al*., 2002). Emissions from peat fires can release 5,000 – 10,000 g C m^{-2} (Page *et al*., 2000; Siegert *et al*., 2001) but may be as much as 30,000 g C m^{-2} (Page *et al*., 2002). Based on estimates of the total area of fire-affected peatlands in Indonesia in 1997/1998, between 0.8 and 2.6 Gt C were released to the atmosphere as a result of burning peat and vegetation in the 1997 El Niño Southern Oscillation (ENSO) (Page *et al*., 2002; Langenfelds *et al*., 2002). The 1994/1995 ENSO-related fires produced 0.6 – 3.5 Gt C (Langenfelds *et al*., 2002) while a further 0.25 – 0.5 Gt C and 0.66 – 0.77 Gt were released during fires in 2002 (Bechteler & Siegert, 2004) and 2006 (Langner & Siegert, 2007), respectively (Figure 6.13). If CO_2 emissions from drained peatland are included this makes this region, especially Indonesia which is responsible for more than 90% of these emissions, one of the largest contributors to global CO_2 emissions (Hooijer *et al*., 2006).

Severe and long-lasting regional smoke-haze and fire episodes during extreme droughts associated with ENSO events have occurred repeatedly in Southeast Asia over the last two decades (Maltby, 1986; Page *et al*., 2000). The danger of an increased frequency of major fires in years with prolonged dry seasons, and future climate scenarios, suggest there will be an increase in the number of days with high

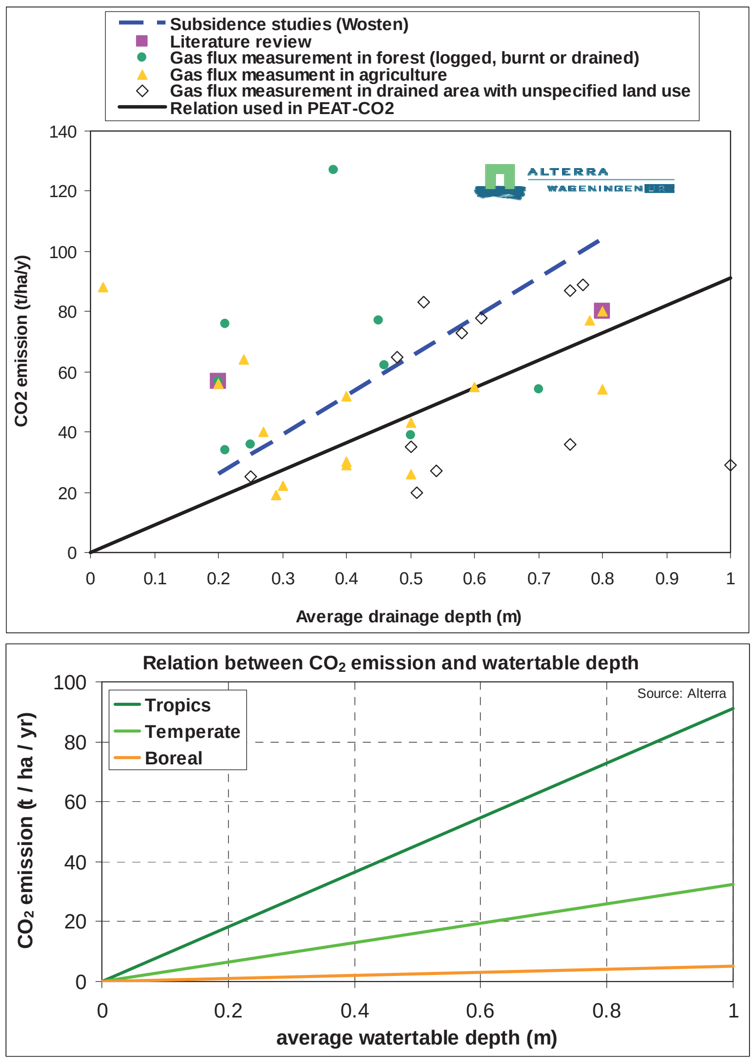

Figure 6.12. *Relationships between drainage depth and CO_2 emission from decomposition (fires excluded) in tropical peatlands (Hooijer et al., 2006). Note that the average water table depth in an undrained peatland is near the peat surface (by definition, as vegetative matter only accumulates to form peat under waterlogged conditions). Top: The relationship for tropical areas, including SE Asia, is based both on long-term subsidence studies and shorter-term gas flux emission studies applying the 'closed chamber method' (Jauhiainen et al., 2005). Results of different methods were combined to derive a linear relationship. This needs to be investigated further since there is evidence to suggest it is probably curved. In reality CO_2 emissions are known to be suppressed at drainage depths up to 0.2 m-0.3 m. Also, CO_2 emissions for a given drainage depth change over time. However, use of a constant and linear relation is deemed acceptable for long-term assessments and for drainage depths between 0.25 m and 1.1 m as applied in this study. Bottom: Tropical drained peatlands have far higher CO_2 emissions than temperate and boreal drained peatlands at the same drainage depth, because of higher decomposition rates in permanently hot and humid climates. Moreover, peatlands in SE Asia are generally drained to much greater depths than is common in temperate and boreal peatlands.*

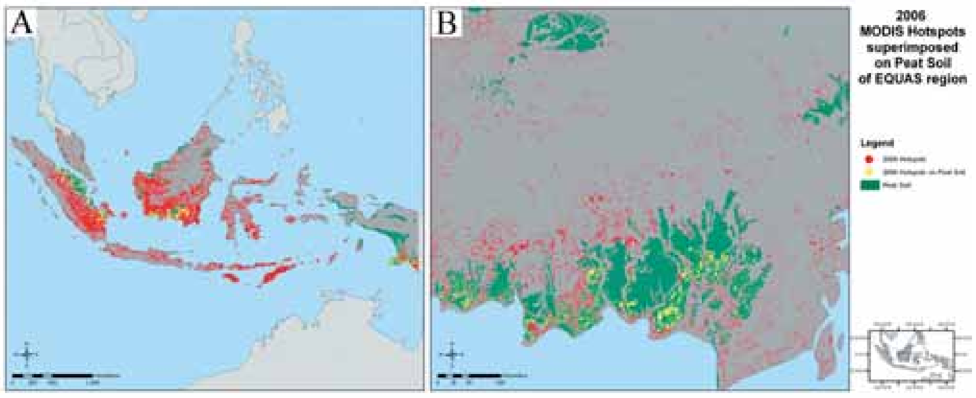

Figure 6.13. *(A) Fires recorded in 2006 superimposed on EQUAS region (Indonesia, Malaysia, Brunei). Peat soils are displayed in green color. Fires on peat soil are shown in yellow color while fires on non peat soil are displayed in red. (B) Subset area of extensive peat areas in Central Kalimantan (Borneo).*

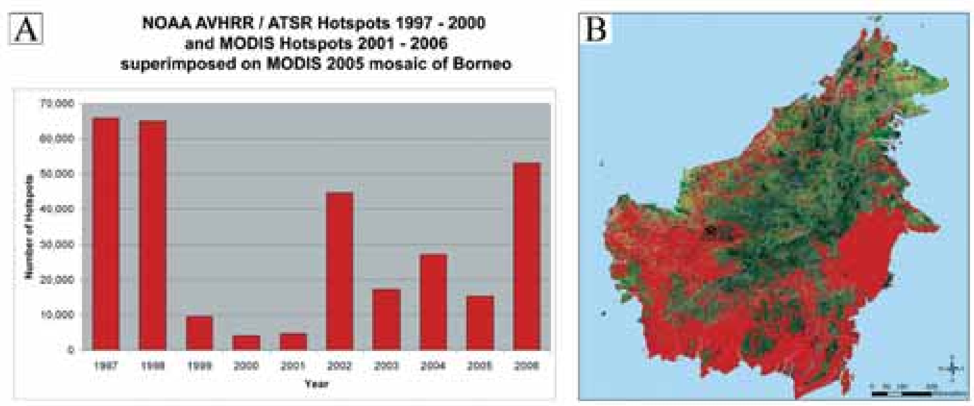

Figure 6.14. *(A) Total number of NOAA AVHRR / ATSR hotspot data from 1997 – 2000 per year and MODIS hotspot data from 2001 – 2006 per year. (B) Total number of hotspots recorded between 1997 and 2006 superimposed on multitemporal composite of Borneo 60 MODIS Surface Reflectance images recorded in 2005.*

risk of fire in tropical areas (Goldammer & Price, 1998; Stocks *et al*., 1998). Some studies suggest an increase in ENSO related tropical storm intensities with CO_2-induced warming in the Asia Pacific region in the future (Royer *et al*., 1998). This is likely to increase the abundance and size of gaps in fragmented forest canopies and areas with long, convoluted boundaries or degraded forest structure resulting from previous fires and logging activities. Storm damage and logging both reduce leaf canopy coverage, thus allowing sunlight to dry out the organic debris on the ground, leading to increased amounts of flammable undergrowth and frequency and intensity of fires with consequent release of large amounts of stored carbon from biomass and peat (Verissimo *et al*., 1995; Holdsworth & Uhl, 1997; Siegert *et al*., 2001).

Compared to the severe El Niño of 1997/1998, the 2002 and 2006 ENSOs were weaker but they still led to severe fire events on the island of Borneo, especially in Central Kalimantan (Figures 6.13 & 6.14). Seventy three per cent of the forest area affected by fire in 2002 occurred in peat swamp forests although their total area is just 23% of the total forest cover. During 2006, fires destroyed 0.76 Mha of peat swamp forests corresponding to 75% of all forest burnt in that year. By focusing on the actual number of fires, the situation becomes even more evident. In 2002, more than ten thousand hotspots occurred in peat swamp forest, corresponding to 81% of all forest fires; in 2006 the number increased to nearly fifteen thousand, which equates to 82% of all forest fires (Langner & Siegert, personal communications). These results show that peat swamp forests are much more prone to fire than any other forest type, probably owing to land clearing activities for the establishment of oil palm and pulp wood plantations. Fires on peatland release much larger amounts of CO_2 into the atmosphere than fires in forests on mineral soils because both the surface vegetation and the underlying peat layer can burn. This is of global importance because the extensive undisturbed peat swamp forests of Southeast Asia are a major C store and sequester of CO_2.

6.4.2. Current and projected CO_2 emissions from drained peat in Indonesia

Present and future emissions from drained peatlands in Indonesia have been quantified recently using the latest data on peat extent

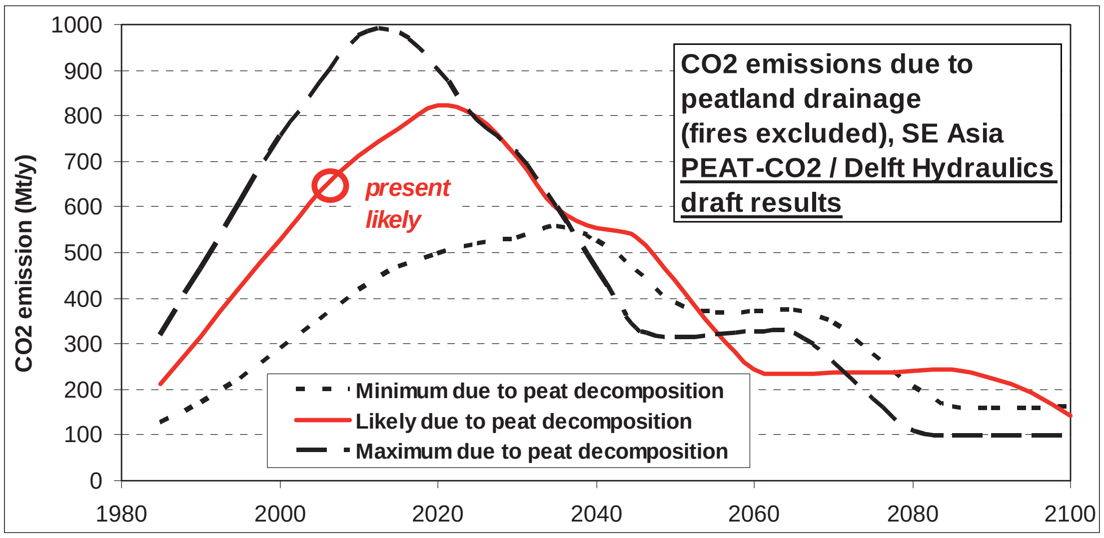

Figure 6.15. *Historical, current and projected CO_2 emissions from peatlands, as a result of drainage (fires excluded). The increase in emissions is caused by progressive deforestation and drainage of peatlands. The decrease after 2020 ('likely' scenario) is caused by shallow peat deposits being depleted, which represent the largest peat extent. The stepwise pattern of this decrease is explained by the discrete peat depth data available (0.25m, 0.75m, 1.5m, 3m, 6m, and 10m). Peat depth data are only available for Indonesia; for other areas conservative estimates were made: 3m for Malaysia and Brunei (similar to Kalimantan) and 1.5m for Papua New Guinea (similar to Irian Jaya). Note that peat extent and thickness data for 1990 (Sumatra) and 2000 (Kalimantan) have been assumed at the starting year of the analysis, in 1985. Considering the uncertainty margin around these data, and the likely systematic underestimation of peat depths, this does not introduce a large additional error in the analysis.*

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and depth, present and projected land uses and water management practices, decomposition rates and fire emissions (PEAT-CO_2 Project: Hooijer *et al.*, 2006). Current CO_2 emissions (2005) caused by decomposition of drained peatlands are estimated to be 632 Mt yr^{-1} (range 355 – 874 Mt yr^{-1}), which will increase in coming decades, and will continue well beyond the 21st century, unless land management practices and peatland development plans are changed. In addition, between 1997 and 2006 an estimated average of 1400 Mt yr^{-1} of CO_2 emission was caused by fires associated with peatland drainage and degradation. The total current CO_2 emissions from tropical peatland of approximately 2000 Mt yr^{-1} equals almost 8% of global emissions from fossil fuel burning. Emissions are likely to increase every year for the first decades after 2000 (Figures 6.15 & 6.16). As shallow peat deposits become depleted, however, and the drained peatland area therefore diminishes, peat subsidence emissions are predicted to peak sometime between 2015 and 2035 at between 557 and 981 Mt yr^{-1} (likely value 823 Mt yr^{-1}), and will decline steadily thereafter. As the deeper peat deposits will take much longer to be depleted, significant CO_2 emission will continue beyond 2100.

6.5. Conclusions and recommendations

The total amount of C in peatlands in Southeast Asia is at least 58 Gt (depending on assumptions of peat thickness and C content), equaling at least 212 Gt of potential CO_2 emissions. Current CO_2 emission rates (fires excluded) from drained tropical peatlands are estimated at between 355 and 874 Mt yr^{-1}, with a most likely value of 632 Mt yr^{-1}. If current rates of tropical peatland conversion and practices of peatland development and degradation continue, this will increase to 823 Mt yr^{-1} in 10 to 30 years time, followed by a steady decline over ensuing centuries as the thicker peat deposits become depleted.

Current CO_2 emissions from Indonesia alone are 516 Mt yr^{-1}, which is equivalent to: 82% of peatland emissions in SE Asia (fires excluded); 58% of estimated global

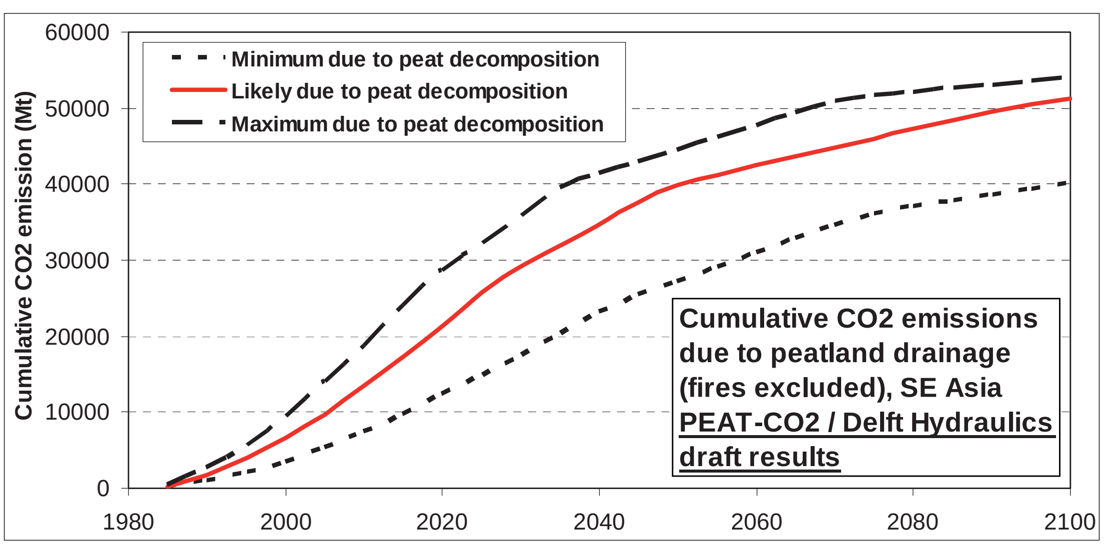

Figure 6.16. *Cumulative CO_2 emissions from SE Asia over 100 years. Note that total storage is at least 206 Gt CO_2 (56 Gt C).*

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peatland emissions, fires excluded; and almost two times the emissions from fossil fuel burning in Indonesia.

Recent developments give little cause for optimism because, while deforestation rates on non-peatlands in SE Asia have decreased somewhat (at least in part owing to depletion of forest resources), those on peatlands have been stable (on average) for up to 20 years. The current (2000-2005) average deforestation rate is 1.5% yr^{-1}. In 2005, 25% of all deforestation in SE Asia was on peatlands. Apart from logging for wood production, an important driver behind peatland deforestation is development of palm oil and timber plantations, which require intensive drainage and cause the highest CO_2 emissions of all land uses. A large proportion (27%) of palm oil concessions (i.e. existing and planned plantations) in Indonesia is on peatlands; a similar percentage is expected to apply in Malaysia. These plantations are expanding at a rapid rate, driven in part by the increasing demand in developed countries for palm oil as a biofuel. Production of 1 tonne of palm oil causes a CO_2 emission of between 10 and 30 tonnes through peat oxidation (assuming production of 3 to 6 tonnes of palm oil per hectare, under fully drained conditions, and excluding fire emissions). The demand for biofuel, aiming to reduce global CO_2 emissions, may actually be causing an increase.

It is essential that future land use of tropical peatland incorporates the principles and practices of sustainable 'wise use', especially with respect to hydrology, water and carbon management. Unfortunately, governments of developing countries in the tropics have higher priorities than maintenance of the natural resource functions of peatlands (Rieley & Page, 2005), despite their proven important role for the global C cycle. This is particularly pertinent given the latest climate change predictions for the Southeast Asian region. The IPCC Fourth Assessment Report predicts that the region will experience a median warming of 2.5°C by the end of the 21st century, accompanied by a predicted mean precipitation increase of about 7% (IPCC, 2007). The strongest and most consistent precipitation increases are forecast to occur over northern Indonesia and Indochina in June, July and August, and over southern Indonesia and Papua New Guinea in December, January and February. The pattern is essentially one of wet season rainfall increase and dry season decrease, with areas experiencing a mean rainfall decrease also likely to experience increases in drought and fire risk. Models indicate that these changes will be strongest and most consistent across south Sumatra and southern Borneo, where there are extensive peatlands. The effect of higher temperatures, decreased dry season rainfall and longer dry periods will be to lower peat water tables more frequently and for longer periods of time, thus exposing remaining peat C stocks to enhanced aerobic decomposition and increased risk of major fires (Hooijer *et al*., 2006).

Inevitably, every type of human intervention on peatland leads to impairment or even loss of natural resource functions (ecology, hydrology, biodiversity, carbon storage). The challenge facing those involved in the management of tropical peatlands in the 21st century is to develop integrated planning and management mechanisms that can balance the conflicting demands on the tropical peatland heritage and its environmental feedback mechanisms to ensure its continued survival to meet the future needs of humankind. This strategy of wise use of tropical peatlands involves evaluation of their functions and uses, impacts caused by and constraints to development so that, by assessment, reasoning and consensus, it should be possible to highlight priorities for their management and use, including mitigation of past and future damage. There are, however, still some critical gaps in our understanding of the carbon dynamics of tropical peatlands. For example, ecosystem-level C budgets under differing hydrology, land management and disturbance regimes require further investigation and elaboration; likewise, we have limited knowledge of how climate change will impact upon the C dynamics of tropical peatlands. Further scientific enquiry will add to our understanding of the role that tropical peatlands have played and continue to play in global environmental change processes, but effective peatland management will also require improved engagement between scientists, policy makers and stakeholder groups, whether they be land development companies or smallholder farmers. New opportunities for protection of the tropical peat carbon store may arise from current negotiations on financial payments for reduced emissions from avoided deforestation and forest degradation (REDD). This could put an economic value on the remaining tropical peat swamp forests and their globally important C stores, and provide an incentive for their protection. It is to be hoped that these initiatives will herald a new era for the fragile tropical peatland ecosystems of Southeast Asia.

6.6. Literature cited

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.

Alm, J., Saarnio, S., Nykänen, H., Silvola, J., Martikainen, P. 1999. Winter CO_2, CH_4 and N_2O fluxes on some natural and drained boreal peatlands, *Biogeochemistry*, 44, 163-186.

Anderson, J.A.R. 1983. The tropical peat swamps of western Malesia, In *Ecosystems of the World 4b - Mires: Swamp, Bog, Fen and Moor*, Gore, A.J.P. (ed.), Elsevier, Amsterdam, pp. 181-199.

Anderson, J.A.R., Muller, J. 1975. Palynological study of a Holocene peat and Miocene coal deposit from Northwest Borneo, *Review of Palaeobotany and Palynology*, 19, 291-351.

Anshari, G., Kershaw, A.P., van der Kaars, S. 2001. A Late Pleistocene and Holocene pollen and charcoal record from peat swamp forest, Lake Sentarum Wildlife Reserve, West Kalimantan, lndonesia, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 171, 213-228.

Anshari, G., Kershaw, A.P., van der Kaars, S., Jacobsen, G. 2004. Environmental change and peatland forest dynamics in the Lake Sentarum area, West Kalimantan, Indonesia, *Journal of Quaternary Science*, 19, 637–655.

Armentano, T.V., Verhoeven, J.T.A. 1988. The contribution of freshwater wetlands to the global biogeochemical cycles of carbon, nitrogen and sulphur, *Wetlands and Shallow Water Bodies*, 1, 1-34.

Aucour, A.-M., Bonnefille, R., Hillaire-Marcel, C. 1999. A Late Pleistocene and Holocene pollen and charcoal record from peat swamp forest, Lake Sentarum Wildlife Reserve, West Kalimantan, Indonesia, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 171, 213-228

Baum, A,, Rixen, T., Samiaji, J. 2007. Relevance of peat draining rivers in central Sumatra for the riverine input of dissolved organic carbon into the ocean, *Estuarine Coastal and Shelf Science*, 73, 563-570.

Bechteler, A., Siegert, F. 2004. Recurrent fires in the tropical peatland of Central Kalimantan, Indonesia. In *Wise Use of Peatlands - Proceedings of the 12th International Peat Congress, 06.-11.06.2004, Tampere*, volume 1, Päivänen, J. (ed.), International Peat Society, Jyväskylä, pp. 607-613.

Brady, M.A. 1997a. Effects of vegetation changes on organic matter dynamics in three coastal peat deposits in Sumatra, Indonesia, In *Biodiversity and sustainability of tropical peatlands - Proceedings of the International Symposium on Tropical Peatlands, 04-08.09.1995, Palangka Raya, Indonesia*, Rieley, J.O., Page, S.E. (eds.), Cardigan, Samara Publishing, pp. 113-134.

Brady, M.A. 1997b. *Organic Matter Dynamics of Coastal Peat Deposits in Sumatra*, Ph.D. Thesis, Faculty of Graduate Studies, Department of Forestry, University of British Columbia, Canada.

Buringh, P. 1984. Organic carbon in soils of the world, In *The Role of Terrestrial Vegetation in the Global Carbon Cycle: Measurement by Remote Sensing*, Woodwell, G.M. (ed.), Wiley, London, pp. 91-109.

Canadell, J.G., Pataki, D.E., Gifford, R., Houghton, R.A., Luo, Y., Raupach, M.R., Smith, P., Steffen, W. 2007. Saturation of the terrestrial carbon sink, In *Terrestrial Ecosystems in a Changing World*, Canadell, J.G., Pataki, D.E, Pitelka, L. (eds.), Springer Verlag, Berlin, pp. 59-78.

Chimner, R.A. 2004. Soil respiration rates of tropical peatlands in Micronesia and Hawaii, *Wetlands*, 24, 51-56.

Flenley, J.R. 1997. The Quaternary in the tropics: an introduction, *Journal of Quaternary Science*, 12, 345-346.

Flenley, J.R. 1998. Tropical forest under the climates of the last 30,000 years, *Climatic Change*, 39, 177-197.

Frankenberg, C., Meirink, J.F., van Weele, M., Platt, U., Wagner, T. 2005. Assessing methane emissions from global space-borne observations, *Science*, 308, 1010-1014.

Franzen, L.G. 1994. Are wetlands the key to the Ice-age cycle enigma?, *Ambio*, 23, 300-308.

Frenzel, P., Rudolph, J. 1998. Methane emission from a wetland plant: the role of CH_4 oxidation in Eriophorum, *Plant and Soil*, 202, 27-32.

Furukawa, Y., Inubushi, K., Ali, M., Itang, A.M., Tsuruta, H. 2005. Effect of changing groundwater levels caused by land-use changes on greenhouse gas fluxes from tropical peat lands, *Nutrient Cycling in Agroecosystems*, 71, 81-91.

Goldammer, J.G., Price, C. 1998. Potential impacts of climate change fire regimes in the tropics based on MAGICC and a GISS GCM-derived lightning model, *Climatic Change*, 39, 273-296.

Gore, A.J.P. (ed.). 1983. *Mires, Swamp, Fen and Moor. Ecosystems of the World, 4B, Regional Studies*, Elsevier Scientific Publishing Company, Amsterdam, 478 pp.

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

Hatano, R., Tomoaki, M., Untung, D., Limin, S.H., Syaiful, A. 2004. Impact of agriculture and wildfire on CO_2, CH_4 and N_2O emissions from tropical peat soil in Central Kalimantan, Indonesia, *Necessity of Establishment of Inventory on Carbon Cycling in Tropical Peatland Ecosystems for Sustainable Agroproduction and Environmental Conservation, Report number 13574012*, Field Science Center for Northern Biosphere, Hokkaido University, Sapporo, pp. 11-14.

Hesp, P.A., Cheng, C.H., Hilton, M., Chou, L.M., Turner, I. 1998. A first tentative Holocene sea level curve for Singapore, *Journal of Coastal Research*, 14, 308-314.

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, 1-14.

Holdsworth, A.R., Uhl, C. 1997. Fire in Amazonian selectively logged rain forest and the potential for fire reduction, *Ecological Applications*, 7, 713-725.

Hooijer, A., Silvius, M., Wösten, H., Page, S. 2006. *PEAT-CO2, Assessment of CO_2 emissions from drained peatlands in SE Asia*, Delft Hydraulics report Q3943.

Hu, J., Peng, P., Fang, D., Jia, G., Jian, Z., Wang, P. 2003. No aridity in Sunda land during the last glaciation: Evidence from molecular-isotopic stratigraphy of long-chain n-alkanes, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 201, 269-281.

Immirzi, C.P., Maltby, E., Clymo, R.S. 1992. *The global status of peatlands and their role in carbon cycling*, Report No. 11, Wetlands Research Group, Friends of the Earth, London, 145 pp.

Inubushi, K., Furukawa, Y., Hadi, A., Purnomo, E., Tsuruta, H. 2003. Seasonal changes of CO_2, CH_4 and N_2O 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*, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (eds.), Cambridge University Press, Cambridge.

IPCC. 2007. *Climate Change 2007 - The Physical Basis*, Contribution of Working Group 1 to the Fourth Assessment Report of the IPCC, Cambridge University Press, Cambridge, UK.

Jali, D. 2004. Nitrogen mineralization in the tropical peat swamps, In *Wise Use of Peatlands - Proceedings of the 12th International Peat Congress, 06.-11.06.2004, Tampere*, volume 1, Päivänen, J. (ed.), International Peat Society, Jyväskylä, pp. 644-652.

Jauhiainen, J., Vasander, H., Jaya, A., Takashi, I., Heikkinen, J., Martikinen, P. 2004. Carbon balance in managed tropical peat in Central Kalimantan, Indonesia. In *Wise Use of Peatlands - Proceedings of the 12th International Peat Congress, 06.-11.06.2004, Tampere*, volume 1, Päivänen, J. (ed.), International Peat Society, Jyväskylä, pp. 653-659.

Jauhiainen, J., Takahashi, H., Heikkinen, J.E.P., Martikainen, P.J., Vasander, H. 2005. Carbon fluxes from a tropical peat swamp forest floor, *Global Change Biology*, 11, 1788-1797.

JRC. 2003. *Global land cover for the year 2000*, European Commission Joint Research Centre publication EUR 20849 EN.

Joosten, H., Clarke, D. 2002. *Wise use of mires and peatlands - Backgrounds and Principles, including a Framework for Decision-making*, International Mire Conservation Group / International Peat Society, Jyväskylä.

Kettunen, A. 2002. *Modelling of microscale variations in methane fluxes*, Thesis, published as Systems Analysis Laboratory Research Reports, A83, Helsinki University of Technology, Helsinki, 38 pp. + appendices.

Komulainen, V.M., Nykänen, H., Martikainen, P.J., Laine, J. 1998. Short-term effect of restoration on vegetation succession and methane emissions from peatlands drained for forestry in southern Finland, *Canadian Journal of Forest Research*, 28, 402-411.

Kool, D.M., Buurman, P., Hoekman, D.H. 2006. Oxidation and compaction of a collapsed peat dome in Central Kalimantan, *Geoderma*, 137, 217-225.

Koutavas, A., Lynch-Stieglitz, J., Marchitto Jr., T.M., Sachs, J.P. 2002. El Niño-like pattern in Ice Age tropical Pacific sea surface temperature, *Science*, 297, 226-230.

Langenfelds, R.L., Francey, R.J., Pak, B.C., Steele, L.P., Lloyd, J., Trudinger, C.M., Allison, C.E. 2002. Interannual growth rate variations of atmospheric CO_2 and its $\delta^{13}C$, H_2, CH_4, and CO between 1992 and 1999 linked to biomass burning, *Global Biogeochemical Cycles*, 16, 1048, doi: 10.1029/2001GB001466.

Langner, A., Siegert, F. 2007. The role of fire on land cover changes in Borneo, *Proceedings of 4th International Wildland Fire Conference, Wildfire2007,* Seville Spain, 13th-17th May 2007.

Liu, Z., Harrison, S.P., Kutzbach, J., Otto-Bliesner, B. 2004. Global monsoons in the mid-Holocene and oceanic feedback, *Climate Dynamics*, 22, 157-182.

Maloney, B.K., McCormac, F.G. 1995. A 30,000-year pollen and radiocarbon record from Highland Sumatra as evidence for climatic change, *Radiocarbon*, 37,181-190.

Maltby, E. 1986. *Waterlogged wealth: Why waste the world's wet places?*, International Institute for Environmental and Development, London.

Maltby, E. 1997. Developing guidelines for the integrated management and sustainable utilization of tropical lowland peatlands, In *Biodiversity and sustainability of tropical peatlands - Proceedings of the International Symposium on Tropical Peatlands, 04-08.09.1995, Palangka Raya, Indonesia*, Rieley, J.O., Page, S.E. (eds.), Samara Publishing, Cardigan, pp. 9-18.

Maltby, E., Immirzi, C.P. 1993. Carbon dynamics in peatlands and other wetland soils. Regional and global perspectives, *Chemosphere*, 27, 999-1023.

Maltby, E., Proctor, M.C.F. 1996. Peatlands: their nature and role in the biosphere, In *Global Peat Resources*, Lappaleinen, E. (ed.), International Peat Society, Jyväskylä.

Martikainen, P.J., Nykänen, H., Alm, J., Silvola, J. 1995. Changes in fluxes of carbon dioxide, methane and nitrous oxide due to forest drainage of mire sites of different trophy, *Plant and Soil*, 168-169, 571-577.

Melling, L., Hatano, R., Kah Joo Goh. 2005a. Soil CO_2 flux from three ecosystems in tropical peatland of Sarawak, Malaysia, *Tellus*, 57, 1-11.

Melling, L., Hatano, R., Kah, Joo Goh. 2005b. Methane fluxes from three ecosystems in tropical peatland of Sarawak, Malaysia, *Soil Biology and Biochemistry*, 37, 1445-1453.

Moore, T.A., Shearer, J.C. 1997. Evidence for aerobic degradation of Palangka Raya peat and implications for its sustainability, In *Biodiversity and sustainability of tropical peatlands - Proceedings of the International Symposium on Tropical Peatlands, 04-08.09.1995, Palangka Raya, Indonesia*, Rieley, J.O., Page, S.E. (eds.), Samara Publishing, Cardigan, pp. 157-167

Morrough-Bernard, H., Husson, S., Page, S.E., Rieley, J.O. 2003. Population status of the Bornean orang utan (*Pongo pygmaeus*) in the Sabangau peat swamp forest, Central Kalimantan, Indonesia, *Biological Conservation*, 110, 141-152.

Muhamad, N.Z., Rieley, J.O. 2002. Mangement of tropical peatlands in Indonesia: mega reclamation project in Central Kalimantan, In *Proceedings of the International Symposium on Tropical Peatlands, 22.08. - 23.08.2001, Jakarta*, Rieley, J.O., Page, S.E. (eds.), BPPT, Jakarta, pp. 155-162.

Nepstad, D.C., Jipp, P., Moutinho, P., Negreiros, G., Vieira, S. 1995. Forest recovery following pasture abandonment in Amazonia: canopy seasonality, fire resistance and ants. In *Evaluating and Monitoring the Health of Large-Scale Ecosystems*, Gaudent, C.L., Calow, P. (eds), Springer Verlag, New York, pp. 333-349.

Neuzil, S.G. 1997. Onset and rate of peat and carbon accumulation in four domed ombrogenous peat deposits, Indonesia, In *Biodiversity and sustainability of tropical peatlands - Proceedings of the International Symposium on Tropical Peatlands, 04-08.09.1995, Palangka Raya, Indonesia*, Rieley, J.O., Page, S.E. (eds.), Samara Publishing, Cardigan, pp. 55-72.

Notohadiprawiro, T. 1998. Conflict between problem-solving and optimising approach to land resources development policies – the case of Central Kalimantan Wetlands, In *Proceedings of the International Symposium: Spirit of Peatlands,* 7-9 September 1998, Jyväskylä, Finland. pp. 14-24.

Nykänen, H., Alm, J., Silvola, J., Tolonen, K., Martikainen, P.J. 1998. Methane fluxes on boreal peatlands of different fertility and the effect of long-term experimental lowering of the water table on flux rates, *Global Biogeochemical Cycles*, 12, 53-69.

Page, S.E., Rieley, J.O. 1998. Tropical peatlands: a review of their natural resource functions, with particular reference to Southeast Asia, *International Peat Journal*, 8, 95-106.

Page, S.E., Rieley, J.O., Böhm, H-D.V., Siegert, F., Muhamad, N. 2000, Impact of the 1997 fires on the peatlands of Central Kalimantan, Indonesia, In *Sustaining our Peatlands - Proceedings of the 11th International Peat Congress, 06.-12.08.2000, Quebec*, Rochefort, L., Daigle, J.-Y. (eds.), Canadian Society for Peat and Peatlands, Edmonton, pp. 962-970.

Page, S.E., Rieley, J.O., Shotyk, W., Weiss, D. 1999. Interdependence of peat and vegetation in a tropical peat swamp forest, *Philosophical Transactions of the Royal Society*, 354, 1885-1897.

Page, S.E., Siegert, F., Rieley, J.O., Boehm, H-D.V., Jaya, A., Limin, S.H. 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., Weiss, D., Rieley, J.O., Shotyk, W., Limin, S.H. 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..

Rieley, J.O., Page, S.E. (eds.). 2005. *Wise Use of Tropical Peatlands - Focus on Southeast Asia*, ALTERRA, Wageningen, 168 pp. + appendices.

Rieley, J.O., Page, S.E. (eds.). 1997. *Biodiversity and Sustainability of Tropical Peatlands - Proceedings of the International Symposium on Biodiversity, Environmental Importance and Sustainability of Tropical Peat and Peatlands, Palangka Raya, 04.-08.09.1995*, Samara Publishing, Cardigan, 370 pp.

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Työ: 4881 Peatsland and climate change [09.05.2008 13:03:15] Peatsland and climate change [09.05.2008 13:03:15] Arkki:179 Front

Rieley, J.O., Ahmad-Shah, A-A. , Brady, M.A. 1996. The extent and nature of tropical peat swamps, In *Tropical Lowland Peatlands of Southeast Asia, Proceedings of a Workshop on Integrated Planning and Management of Tropical Lowland Peatlands*, Cisarua, Indonesia, 3-8 July 1992, Maltby, E., Immirzi, C.P., Safford, R.J. (eds.), IUCN, Gland, Switzerland, x + 294 pp.

Roulet, N.T., Ash, R., Quinion, W., Moore, T. 1993. Methane flux from drained northern peatland: effect of persistent water table lowering on flux, *Global Biogeochemical Cycles*, 7, 749-769.

Roulet, N.T., Lafleur, P.M.,. Richard, P.H., Moore, T.M., Humphreys, E.R., Bubier, J.L. 2007. Contemporary carbon balance and late holocene carbon accumulation in a northern peatland, *Global Change Biology*, 13, 397–411, doi: 10.1111/j.1365-2486.2006.01292.x.

Royer, J.-F., Chauvin, F., Timbal, B., Araspin, P., Grimal, D. 1998. A GCM study of the impact of greenhouse gas increase on the frequency of occurrence of tropical cyclones, *Climatic Change*, 38, 307–343.

Saarnio, S., Silvola, J. 1999. Effects of increased CO_2 and N on CH_4 efflux from a boreal mire: a growth chamber experiment, *Oecologia*, 119, 349-356.

Shannon, R.D., White, J.R. 1994. A three-year study of controls on methane emissions from two Michigan peatlands, *Biogeochemistry*, 27, 35-60.

Shannon, R.D., White, J.R., Lawson, J.E., Gilmour, B.S. 1996. Methane efflux from emergent vegetation in peatlands, *Journal of Ecology*, 84, 239-246.

Sieffermann, R.G., Fournier, M., Triutomo, S., Sadelman, M.T., Semah, A.M. 1988. Velocity of tropical forest peat accumulation in Central Kalimantan Province, Indonesia (Borneo), In *Proceedings of the 8th International Peat Congress, August 1988, Leningrad*, International Peat Society, Jyväskylä, pp. 90-98.

Siegert, F., Ruecker, G., Hindrichs, A., Hoffman, A.A. 2001. Increased damage from fires in logged forests during droughts caused by El Niño, *Nature*, 414, 437-440.

Silvius, M.J., Han, H.I., Ibraham, S. 1987. *Evaluation of the West Coast of Peninsular Malaysia and their importance for natural resources conservation*, Project: MYS 78/85, WWF Malaysia / Forest Research Institute of Malaysia / University of Malaya / Interwader, 189 pp.

Sinha, V., Williams, J., Crutzen, P.J., Lelieveld, J. 2007. Methane emissions from boreal and tropical forest ecosystems derived from in-situ measurements, *Atmospheric Chemistry and Physics Discussions,* 7, 14011-14039.

Sorensen, K.W. 1993. Indonesian peat swamp forests and their role as a carbon sink, *Chemosphere*, 27, 1065-1082.

Staub, J.R., Esterle, J.S. 1994. Peat-accumulating depositional systems of Sarawak, East Malaysia, *Sedimentary Geology*, 89, 91-106.

Steinke, S., Kienast, M., Hanebuth, T. 2003. On the significance of sea-level variations and shelf palaeo-morphology in governing sedimentation in the southern South China Sea during the last deglaciation, *Marine Geology*, 201, 179-206.

Stocks, B.J., Fosberg, M.A., Lynham, T.J., Mearns, L., Wotton, B.M. Yang, Q., Jin, J.Z., Lawrence, K., Hartley, G.R., Mason, J.A., McKenney, D.W. 1998. Climate change and forest fire potential in Russian and Canadian boreal forests, *Climate Change*, 38, 1-13.

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 in Biology*, 37, 115-128.

Takahashi, H., Kayama, M., Limin, S. 2000. The effects of environmental factors on diurnal changes of ground water table in a tropical peat swamp forest, In *Proceedings of the International Symposium on Tropical Peatlands, 22-23.11.1999, Bogor, Indonesia*, Iwakuma, T., Inoue, T., Kohyama, T., Osaki, M., Simbolon, H., Tachibana, H., Takahashi, H., Tanaka, N., Yabe, K. (eds.), Hokkaido University/Indonesian Institute of Sciences, Sapporo, pp. 321-327.

Takahashi, H., Yonetani, Y. 1997. Studies on microclimate and hydrology of peat swamp forest in Central Kalimantan, Indonesia, In *Biodiversity and sustainability of tropical peatlands - Proceedings of the International Symposium on Tropical Peatlands, 04-08.09.1995, Palangka Raya, Indonesia*, Rieley, J.O., Page, S.E. (eds.), Samara Publishing, Cardigan, pp. 179-187.

Tjia, H.D., Sujitno, S., Suklija, Y., Harsono, R.A.F., Rachmat, A., Hainim, J., Djunaedi. 1984. Holocene shorelines in the Indonesian tin islands, *Modern Quaternary Research in SE Asia*, 8, 103-117.

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

Turunen, C., Turunen, J. 2003. Development history and carbon accumulation of a slope bog in oceanic British Columbia, Canada, *Holocene*, 13, 225-238.

Turunen, J., Tomppo, E., Tolonen, K., Reinikainen, E. 2002. Estimating carbon accumulation rates of undrained mires in Finland – application to boreal and subarctic regions, *Holocene*, 12, 79-90.

Ueda, S., Go, C.-S., Yoshioka, T., Yoshida, N., Wada, E., Miyajima, T., Sugimoto, A., Boontanon, N., Vijarnsorn, P., Boonprakub, S. 2000. Dynamics of dissolved O_2, CO_2, CH_4, and N_2O in a tropical coastal swamp in southern Thailand, *Biogeochemistry*, 49, 191-215.

Uhl, C., Kauffman, J.B. 1990. Deforestation, fire susceptibility and potential tree responses to fire in the eastern Amazon, *Ecology*, 71, 437-449.

Vasander, H., Kettunen, A. 2006. Carbon in boreal peatlands, In *Boreal Peatland Ecosystems - Ecological Studies Vol. 188*, Wieder, R.K., Vitt, D. (eds.), Springer Verlag, Berlin, pp. 165-194.

Verissimo, A., Barreto, P., Tarifa, R., Uhl, C. 1995. Extraction of a high-value natural resource from Amazonia: the case of mahogany, *Forest Ecology & Management*, 72, 39-60.

Whittaker, R.H., Likens, G.E. 1975. The biosphere and man, In *Primary Productivity of the Biosphere. Ecological Studies Vol. 14*, Lieth, H., Whittaker, R.H. (eds.), Springer Verlag, Berlin, pp. 305-328.

Williams, J., Fisher, H., Hoor, P., Pöschl, U., Crutzen, P.J., Andreae, M.O., Lelieveld, J. 2001. The influence of the tropical rainforest on atmospheric CO and CO_2 as measured by aircraft over Surinam, South America, *Chemosphere*, 3, 157-170.

Worrall, F., Burt, T.P. 2004. Time series analysis of long term river DOC records, *Hydrological Processes*, 18, 893–911.

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

Wösten, J.H.M., van der Berg, J., van Eijk, P., Gevers, G.J.M., Giesen, W.B.J.T., Hooijer, A., Idris, A., Leenman, P.H., Rais, D.S., Siderius, C., Silvius, M.J., Suryadiputra, N., Wibisono, I.T. 2006. Interrelationships between hydrology and ecology in fire degraded tropical peat swamp forests, *International Journal of Water Resources Development*, 22, 157-174.

Wüst, R.A.J. 2001. *Holocene evolution of the intermontane Tasek Bera peat deposit, Peninsular Malaysia: Controls on composition and accumulation of a tropical freshwater peat deposit*, PhD thesis, Vancouver. B.C., University of British Columbia, Canada, 478 pp.